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An evidence-based assessment of the potential for upscaling prefabricated timber modular building construction in Australia

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ABSTRACT

Timber modular buildings (TMBs) are increasingly promoted as a low-carbon and resource-efficient solution for modern construction. However, despite growing global interest, the feasibility of applying TMBs, particularly multi-storey systems, remains insufficiently understood in the Australian context. The existing literature largely focuses on isolated aspects, such as structural performance and environmental impacts, leaving a significant gap in system-level evaluations that account for the combined implications of design, durability, fire safety, manufacturing and logistics. This study addresses this gap by reviewing case studies and synthesising the key opportunities and challenges associated with large-scale TMB adoption. The review identifies that while TMBs can deliver substantial environmental benefits and reduced construction time, their widespread deployment is limited by fire safety concerns, long-term durability under Australia's climate hazards, structural height and span constraints, and logistical limitations associated with transporting modular units. Thus, this study aims to consolidate these specific building design criteria into feasibility assessments and outline targeted potential solutions. These include enhanced encapsulation and cavity-barrier strategies for fire protection, hazard-specific durability detailing, hybrid and lightweight volumetric modules to manage lifting and transport constraints, and performance-based design approaches tailored to the National Construction Code. Overall, the study provides practical recommendations to support the upscaling of multi-storey TMBs in Australia, highlighting where further research, regulatory refinement, and industry innovation are required to overcome current adoption barriers.

1. Introduction

The construction industry is responsible for more than one-third of global energy consumption and energy-related greenhouse gas (GHG) emissions, with building materials alone contributing approximately 11 % of global energy and process related emissions in 2020 [1]. In Australia, whole-life building carbon emissions attributed to embodied carbon accounted for 19 % in 2019 and are projected to rise to 85 % by 2050 as operational emissions decline due to improved efficiency and grid decarbonisation [2]. Meeting international commitments such as the United Nations Sustainable Development Goals (UN SDGs) [3] requires the sector to pursue comprehensive decarbonisation strategies that extend beyond operational energy reductions to include material manufacturing processes and construction methods [4].

In response, prefabricated modular construction has gained renewed attention as a sustainable construction approach. This method involves manufacturing building components off-site in controlled factory environments and subsequently transporting them to the site for on-site assembly [5,6]. Compared with conventional construction, modular construction offers notable benefits, including shorter construction durations, reduced material waste, improved safety, and enhanced quality control due to industrialised production processes [7–10]. Despite these advantages, adoption in Australia remains limited, representing only around 3 % of the domestic residential housing market [11]. Nevertheless, modular construction has consistently been highlighted in national reforms and strategic industry directions. For example, as one of the eight key visions to improve construction sector performance [5], the 2024 National Construction Code (NCC) will address the nation's housing supply shortfall [12] and support Australia's national trajectory toward zero-energy and zero-carbon-ready buildings by 2050 [13].

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The integration of sustainable and lightweight materials, such as timber has further increased the feasibility of modular systems, particularly for multi-storey applications [14]. Advances in engineered wood products, such as mass timber systems, have reinforced timber's role as a low-carbon alternative to conventional steel and concrete structures in modular construction material selection. Despite timber's environmental benefits, the widespread adoption of multi-storey timber modular buildings (TMBs) remains limited due to several key challenges. These include a lack of design standards, regulations and standardised manufacturing processes [15,16], restricted design flexibility [17], and ongoing concerns around structural integrity and fire safety [18,19]. Furthermore, practical guidance and research on implementing timber in multi-storey modular buildings remains limited. To assess the feasibility, this study adopted building design criteria derived from established frameworks in prior studies by Navaratnam et al. [20], Sharafi et al. [21], and Kamali and Hewage [22], all of which identified critical modular construction considerations through stakeholder surveys involving industry practitioners. From these frameworks, the most relevant criteria for timber building design were selected. This study also evaluates the feasibility of implementing multi-storey TMBs in Australia by analysing the performance of existing timber buildings as a case study. A comprehensive review was focused on the case studies, followed by a discussion of current advantages, including sustainability, off-site manufacturing efficiency, logistics, assembly processes, and design flexibility. This study then identifies current limitations, particularly in relation to fire safety, durability, and constraints related to building height and structural spans. Finally, it presents design recommendations to support effective implementation, outlining key considerations specific to the Australian context.

2. Methods

This study employed a systematic literature review guided by the preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework [23] to examine (a) the advantages and challenges associated with TMB applications and (b) documented case studies of TMB projects in Australia and other countries. The review incorporated both peer-reviewed academic literature and reputable

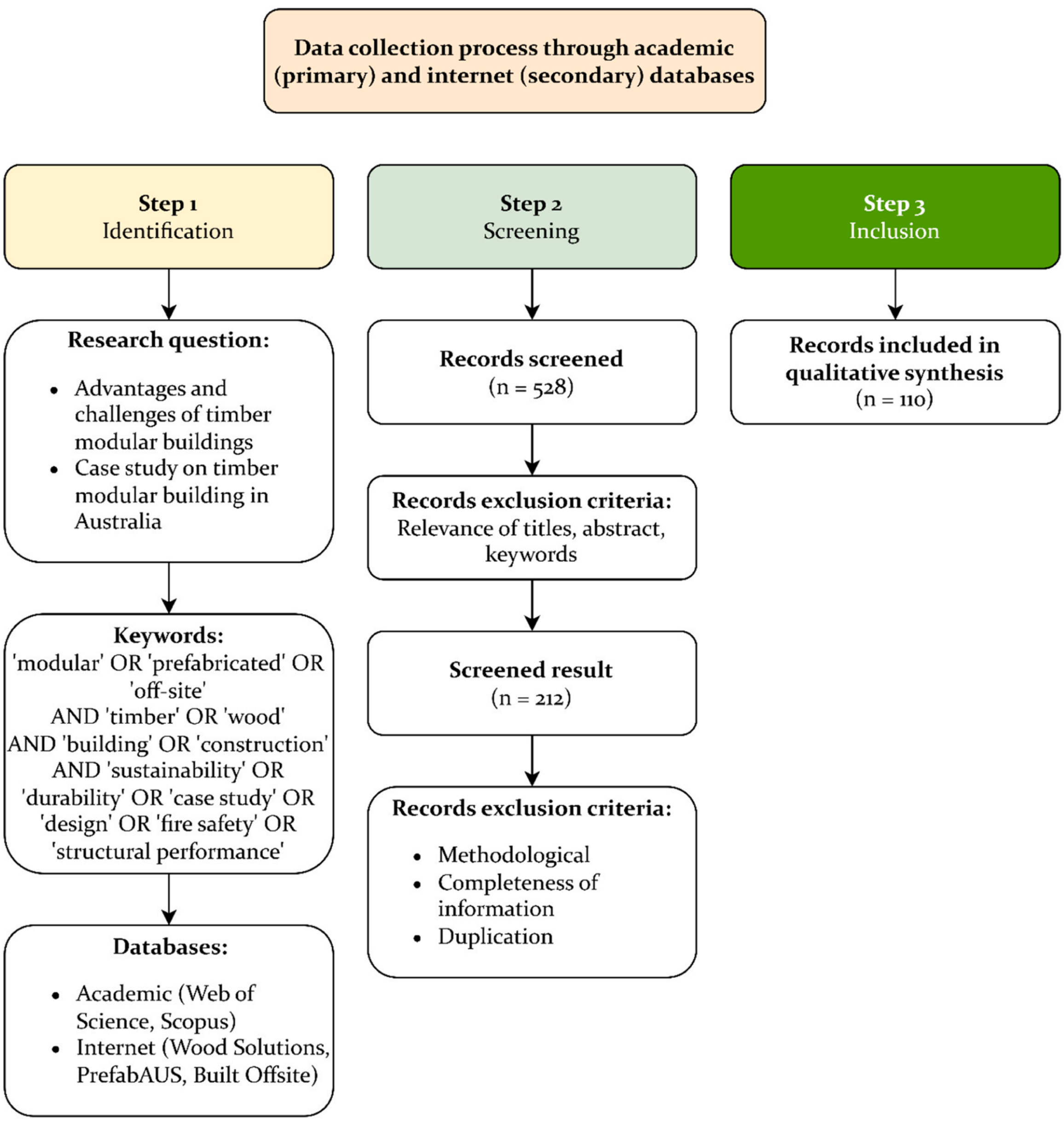


Fig. 1. Data collection process for the comprehensive literature review.

non-academic sources, including architecture and construction press, published books and reports, and professional designers' websites, to ensure comprehensive coverage of current practices. Two major scholarly databases (Scopus and Web of Science) were selected due to their extensive indexing of peer-reviewed publications relevant to the topic of this study. These were supplemented by targeted online searches to capture industry reports and project documentation not available in academic repositories. The review process followed three PRISMA stages: identification, screening, and inclusion, as outlined in Fig. 1.

The identification stage involved constructing a keyword strategy that captured the intersection of modular construction, timber materials, and performance considerations. Search strings combined terms such as "modular", "prefabricated", or "off-site" with "timber" or "wood" to specify material relevance, followed by thematic terms including "sustainability", "durability", "case study", "design", "fire safety", and "structural performance". Publications from 2015 to 2025 were included to ensure relevance. During the screening stage, records were filtered by assessing the relevance of titles, abstracts, and keywords. Full-text screening was then conducted to evaluate methodological soundness, completeness of information, and to remove duplicates. Finally, the inclusion stage retained studies and documents that were directly relevant to the topic of this study.

3. Case studies of TMB

Modular building systems are generally classified into two structural types: load-bearing modules, where loads are transferred through side walls, and corner-supported modules, where loads are carried via edge beams to corner posts [24]. TMBs typically adopt the load-bearing approach, utilising either mass timber or stud wall systems to resist compression. This method is commonly applied to low- to medium-rise buildings, generally limited to four to eight storeys. In terms of prefabrication, TMBs can be categorised by the level of off-site fabrication [25,26]. Salvadori [27] further classifies these systems into one-dimensional (frame-based), two-dimensional (panelised), and three-dimensional (volumetric) modular forms, including hybrid configurations composed of pre-assembled wall and floor components (Fig. 2).

The increasing adoption of engineered timber products, such as cross-laminated timber (CLT), glue-laminated timber (GLT), and laminated veneer lumber (LVL) has facilitated the expansion of TMBs. Several notable projects exemplify this trend, including the Forte building in Melbourne [29], the world's tallest CLT apartment building at its completion, and the International House Sydney [30], a seven-story commercial building constructed using a modular CLT framework. These buildings highlight the growing confidence in mass timber as a structural material for modular construction. Modular timber classrooms have been widely implemented across Victoria [31], providing rapid and sustainable solutions for school expansions. Table 1 provides an overview of notable multi-storey prefabricated TMBs in Australia. The majority of multi-storey TMBs in the country employ mass-engineered timber systems, which offer high strength-to-weight ratios, design flexibility, and prefabrication advantages [14,32]. These buildings predominantly utilise frame and panelised modular systems.

4. Advantages of prefabricated TMBs

TMBs offer several advantages over common construction materials, including steel and concrete. The advantages could be categorised into three topics: (1) Environmental impact; (2) Manufacturing, logistics, and assembly; and (3) Design flexibility.

4.1. Environmental impact

Minimising the environmental impact of building construction has become a key priority in the industry [42]. Life-cycle assessment (LCA) studies highlight that sustainability can be enhanced through decisions made at all stages, from material selection to construction, operation, and end-of-life management [43]. Timber contributes significantly at the material level by acting as a carbon sink; one cubic metre can sequester approximately 0.9 tonnes of CO_2 [44,45]. In modular construction, where prefabrication is dominant, approximately 80 % of embodied environmental impacts occur during material production [46]. For example, a single volumetric module can store 11.78 tonnes of CO_2, as shown in a case study by Finch Buildings [47]. Depending on the module's design, the timber volume may range from 33.3 to 99.5 m^3, capturing an average of 13.42 tonnes of CO_2 per module [46]. Sourced predominantly from certified forests, timber is also a renewable material that supports sustainable forestry practices [43]. Comparative assessments confirm that timber significantly reduces the carbon footprint compared to concrete and steel [43,48], primarily due to its lower embodied energy. The potential for reusing timber products in design [49] and the near elimination of wood waste through prefabrication, compared to 5–15 % waste in conventional construction [50], further strengthens timber's sustainability benefits.

Furthermore, the reduction of carbon emissions in timber construction also comes from the reduction of using other materials (i.e., concrete, steel) in hybrid structures [51–53]. By employing timber as the primary material for the superstructure, carbon emissions associated with concrete and steel can be significantly reduced through the timber's lightweight characteristics. Timber modules typically weigh between 4–6 kN/m^2, considerably less than concrete modules, which range from 9 to 15 kN/m^2 [54]. This reduced weight lessens the reliance on heavy concrete slabs in the foundation, thereby cutting CO_2 emissions associated with basement construction. Material selection also impacts the assembly process, influencing crane lift capacity and embodied energy requirements during construction [55]. Furthermore, timber-based solutions can lower carbon emissions by up to 25 % per square metre of floor area compared to conventional steel or concrete buildings [56]. Hart et al. [57] study further highlights the significant differences in total embodied carbon, noting that timber frame structures possess approximately one-fifth of concrete frames' embodied carbon and one-third of steel frames.

Although timber's lightweight nature offers embodied environmental benefits, studies show that lightweight timber envelopes can

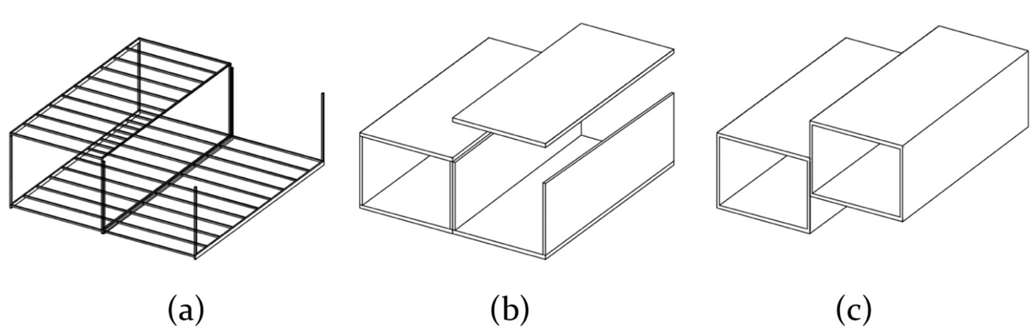


Fig. 2. Modularity in (a) 1D elements, (b) 2D panels, and (c) 3D volumetric modules (reproduced from [28]).

Table 1
Multi-storey prefabricated timber buildings in Australia.

Building name	Modularity type	Structural system	Number of storeys	Completion date	Occupancy	Special features	Reference
T3 Collingwood, Victoria	Frame and panelised	Mass engineered timber	15	2023	Commercial	Australia's largest timber multi-storey building upon completion.	[33]
Xavier College Kostka Building, Victoria	Frame and panelised	Mass engineered timber	3	2023	Educational		[34]
DeFeu Melbourne, Victoria	Fully panelised	Timber panel post-tensioning system	4	2021	Residential	Utilises post-tensioning technology for a fully panelised structure.	[35]
Meyer Timber Office, New South Wales	Frame and panelised	Mass engineered timber	2	2018	Commercial		[36]
25 King Street, Brisbane, Queensland	Frame and panelised	Mass engineered timber	10	2018	Office	One of the tallest timber commercial buildings globally.	[37]
International House Sydney, New South Wales	Frame and panelised	Mass engineered timber	7	2017	Commercial		[30]
Forte Living, Victoria	Frame and panelised	Mass engineered timber	10	2013	Residential	World's tallest modern timber apartment building and the first CLT building in Australia.	[29]
A02 Gillies Hall, Monash University, Victoria	Frame and panelised	Mass engineered timber	6	2019	Residential		[38]
B03 Latrobe University Bundoora Campus, Victoria	Frame and panelised	Mass engineered timber	6	2020	Residential		[39]
Daramu House, New South Wales	Frame and panelised	Mass engineered timber	6	2019	Office		[40]
Macquarie University Incubator, Sydney	Frame and panelised	Mass engineered timber	1	2017	Educational	Lightweight timber roof and floor cassettes allow disassembly.	[41]

exhibit reduced thermal performance in summer due to their low thermal mass, making them more susceptible to overheating compared with heavyweight materials such as concrete or brick [58–60]. In contrast, operational carbon impacts are largely driven by the overall thermal performance of the building envelope and the extent to which mechanical cooling systems are required to maintain indoor comfort [61]. This highlights the need to improve the thermal behaviour of lightweight timber modular envelopes. To address these challenges, previous research has proposed several strategies, including incorporating phase change materials (PCMs) to increase thermal storage capacity [59], enhancing envelope insulation using advanced lightweight composite materials [62], and integrating controlled or intensive ventilation systems to support passive thermal regulation [63].

Another critical approach to maximising sustainability is extending the lifespan of TMBs. Prolonging entire buildings optimises material usage and maximises carbon storage in timber products [64,65]. TMB strongly supports circular economy principles due to its capacity for disassembly and reuse [14,66]. Many TMBs are designed for disassembly (DfD), enabling components to be dismantled and repurposed at the end of the building's lifecycle. This design adaptability significantly reduces the volume of timber waste sent to landfills or incinerated for energy generation, which remains a prevalent practice [67]. One example is the Macquarie University Incubator in New South Wales, which is a TMB designed for easy disassembly, making it suitable for building relocation and repurposing [41,68]. A study by Minnuno et al. [69] observed a potential reduction of carbon emissions by 88 % when a modular building is reassembled and repurposed. Moreover, advancements in prefabrication techniques enhance the flexibility and sustainability of timber modular construction. For example, fully prefabricated timber-concrete composite floors can be manufactured off-site with concrete slabs and connected on-site to timber beams [51]. Similarly, hybrid prefabricated buildings combining GLT frames and CLT panels with steel elements allow for rapid on-site assembly while maintaining the potential for disassembly and reuse [52,70]. The reusable characteristic highlights the environmental advantages of modular timber building systems in promoting sustainable construction practices.

4.1.1. *Environmental impact case studies*

This section presents a comparative analysis of greenhouse gas (GHG) emissions across four case study buildings, examining the impact of material selection and construction methods on sustainability. The comparison evaluates two scenarios: (1) variation in materials and (2) variation in construction methods, emphasising the advantages of timber and the degree of modularity. The GHG emissions data are compiled from the studies of Sandanayake et al. [55] and Rezzag Lebza [56], which involve a quantitative assessment of emissions from material production, transportation of materials, construction or equipment usage, and building operational or electricity consumption. Comprehensive details of the life cycle assessment (LCA) applied can be found in the respective references.

The buildings considered include, as tabulated in Table 2: (1) Case study A (Melbourne, Australia), a conventional on-site construction building utilising reinforced concrete; (2) Case study B (London, UK, hypothetical conditions applied to Australia), a hybrid construction approach combining reinforced concrete for foundations, basement, and ground floors, with timber panels for the superstructure; (3) Case study C (Brumunddal, Norway), a panelised modular construction building utilising a fully timber structure; (4) Case study D (Bergen, Norway), a volumetric modular construction building, also employing a fully timber structure. While the LCA data for case study A is derived from an actual

Table 2
General details of the four case studies.

Detail	Case Study A [71]	Case Study B [71]	Case Study C [72]	Case Study D [72]
Construction method	On-site	On-site & panelised modular	Panelised modular	Volumetric modular
Material	Reinforced concrete	Reinforced concrete & CLT	CLT, GLT, LVL	CLT, GLT
Number of storeys	15	11	18	14
Total height of the building (m)	49.5	33.8	85.6	51
Total construction area (m^2)	17,104	11,960	11,300	5830
Major purpose	Commercial	Residential and Commercial	Residential	Residential

building in Melbourne, the assessment for case study B, though referencing a real building in London, applies hypothetical Australian conditions as outlined by Sandanayake et al. [71]. This means that transportation distances, material availability, and manufacturing context were adjusted to reflect Australian conditions, while the material quantities are taken from the original London building design. The LCA studies of case studies C and D are based on Norwegian conditions from Rezzag Lebza [72].

The total GHG emissions per square metre of building construction area for the four case studies are presented (Fig. 3). The GHG emission density for case study A (conventional reinforced concrete construction) is measured at 526.3 kg Co_2-eq/m^2, while case study B (combined construction of concrete and timber) demonstrates a slightly lower emission density of 508.8 kg Co_2-eq/m^2. The emissions from materials contribute the highest portion, accounting for over 49 % of the total emissions in both cases. The incorporation of timber in case study B reduces material-related emissions by approximately 3 % compared to the fully reinforced concrete structure in case study A.

Case study C, which uses a fully timber structure, observes a more substantial reduction in GHG emissions, resulting in a GHG emission density of 362.9 kg Co_2-eq/m^2. Compared to case study B, timber contributes to a significant reduction in emissions from materials by approximately 66.0 kg Co_2-eq/m^2 for buildings with a similar construction area. This reduction represents a 26 % decrease in GHG emissions specifically attributed to material selection. While differences in transportation-related GHG emissions between case studies B and C are not highlighted due to variations in transportation conditions and methods, emissions from equipment usage and electricity consumption are reported as negligible in all cases. The data demonstrates that timber-based modular buildings can substantially reduce carbon footprints in the production phase compared to reinforced concrete or hybrid construction methods. However, it should be noted that material production may vary across countries depending on processes and capacities, which can affect GHG emissions.

Furthermore, the comparison between case study C (panelised modular construction) and case study D (volumetric modular construction) illustrates how varying construction methods influence GHG emissions in timber buildings. The GHG emission for case study D is recorded at 260.4 kg Co_2-eq/m^2, which is 28 % lower than the GHG emission of case study C. The GHG emission reduction is primarily attributed to the detailed manufacturing process involved in volumetric modular construction, which minimises material waste during the production phase and the demand for on-site activities. It is essential to note that GHG emissions during the production phase are influenced by the degree of prefabrication; volumetric modular systems generally emit more GHG than panellised ones. In case study C, higher material-phase emissions compared to case study D may result from the use of additional materials (i.e., LVL, concrete stiffeners), as noted in the referenced study [72].

The volumetric modular construction method results in a slight increase in transportation-related GHG emissions due to the higher volume of prefabricated modules requiring transportation. Despite this, the reduction in on-site assembly time and fewer assembly steps associated with volumetric construction contribute to lower GHG emissions from equipment usage. These findings suggest that volumetric modular construction is more environmentally efficient than panelised construction for multi-storey timber buildings, particularly in minimising material waste and reducing overall GHG emissions. The higher degree of modularity associated with volumetric systems also enhances sustainability by supporting greater efficiency in manufacturing and assembly processes.

4.2. Manufacturing, logistics, and assembly

The application of modularisation in construction and design aims to achieve streamlined objectives by minimising variations in building components through mass customisation [73]. This method prioritises reducing the diversity of elements within a project, thereby fostering standardisation and allowing for flexibility in customisation [15]. A notable advantage of modularising timber structures is the elimination of construction delays inherent to conventional methods, as off-site assembly allows the superstructure to be constructed concurrently with foundation works [74]. Case studies of mass timber buildings or panelised timber construction have demonstrated that they can reduce project timelines by 20–50 % compared to the conventional on-site construction [75]. One prominent example is the Forte Living building in Melbourne, completed in 2013 [29]. At the time, it was the largest timber apartment complex globally, comprising 10 storeys, achieving a 30 % reduction in construction time compared to similar structures built with conventional materials [76]. Further, a report from the Engineered Wood Association (APA) [77] indicates that prefabricated wood panels can lead to even more significant assembly time reductions, exceeding 50 % compared to conventional construction techniques.

In terms of the degree of modularity, the majority of current TMBs in Australia were made with a panelised system. While panelised timber components and volumetric timber modules differ significantly in installation methods, volumetric modular timber projects streamline off-site fabrication and facilitate faster integration of mechanical, electrical,

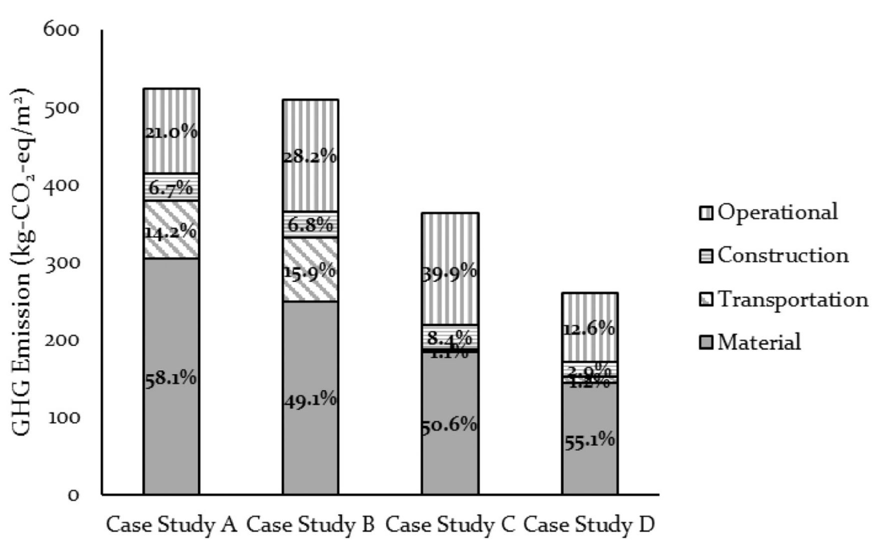


Fig. 3. Comparison of GHG emissions in building life cycle stages of case studies.

and plumbing (MEP) systems [46]. This reduces labour demands and installation time. Case studies comparing construction methods reveal that projects employing the volumetric modular technique were completed 16 % faster than those using panelised approaches [78]. Although transportation challenges associated with volumetric modules may present greater logistical complexity than panelised systems, the time savings achieved through volumetric construction methods outweigh these challenges without compromising construction quality [78]. Further research is needed to address the technical details of adopting full timber elements in timber volumetric modules to address the challenges of these modules.

Expanding on the efficiencies provided by modular timber construction, another significant benefit is the reduction in overall project costs. This benefit is achieved by standardising components instead of relying on fully customised timber designs, leading to savings in both production and scheduling [79]. According to a report by McKinsey [80], modular construction techniques significantly reduce the overall cost of housing projects compared to on-site construction. Among these techniques, the volumetric modular approach achieves the most significant cost savings, with up to 24 % reductions compared to 17 % for panelised modular systems. A pilot project in Lausanne highlights the economic advantages of modular timber construction, reporting cost savings of approximately 20 % [81]. Similarly, models of mass timber modular school buildings in Austria and Germany demonstrate that timber reduces costs by 25 % compared to conventional materials such as concrete and steel [82].

4.3. Design flexibility

Timber modular construction offers unparalleled design flexibility and customisation potential, making it a standout approach in modern building practices [83]. The recent standard of ISO 20887 [84] pushed the principles of sustainability with DfD design examples, acknowledging the wide array of tools and methodologies to support the idea. Modular systems enable unique architectural designs while supporting mass customisation, facilitated by advanced technologies such as building information modelling (BIM) and computer numerical cutting (CNC) [85]. These tools efficiently produce timber elements, such as CLT panels, in off-site facilities tailored to specific project requirements [83,85]. For instance, the Stadthaus in London, a nine-story TMB, exemplifies the potential of CLT panels to achieve both bespoke designs and high efficiency. The project highlights how modular timber systems can deliver architectural innovation alongside structural and environmental performance [86]. Another example of design flexibility in TMB can be found in the Macquarie University Incubator [41]. The roof and floor cassettes were made with lightweight CLT, allowing quick assembly and disassembly for future relocation.

Moreover, flexibility in TMBs extends beyond initial design to encompass adaptability throughout a building's lifecycle. This flexibility is defined as accommodating diverse social uses or modifying physical arrangements, which is integral to modern construction practices [87,88]. Timber's compatibility with DfD principles further enhances its utility, enabling components to be easily repurposed at the end of their lifecycle [89] (Fig. 4). Case studies from Ostapska et al. [89] highlight timber's dominance in DfD applications, accounting for over 50 % of 151 analysed projects. For example, Little Finlandia in Finland exemplifies adaptability, with its modular design allowing for disassembly, relocation, and repurposing as a school building after three years of use as a public hall [90].

Reversibility in DfD is primarily achieved through the use of reversible joints and connections. These connections allow building components or structural members to be disassembled and reused in their entirety, provided they remain within their elastic behaviour or are combined with a reversible fuse that can be replaced when necessary [91]. Several studies have reviewed reversible connection types specifically for timber structures in the context of DfD, including studies from Pozzi [92] and Ottenhaus et al. [91]. Study from Li & Tsavdaridis [93] focused particularly on interlocking connections for volumetric structures.

In the application of timber within DfD, where the goal is to reuse timber components following disassembly, the load history of the material is a critical factor affecting durability. This issue is especially prevalent in joints and connections, but it also influences the mechanical properties of the timber itself [91]. To address these challenges, various standards, guidelines, and studies have been developed to assess and grade reclaimed timber from existing buildings.

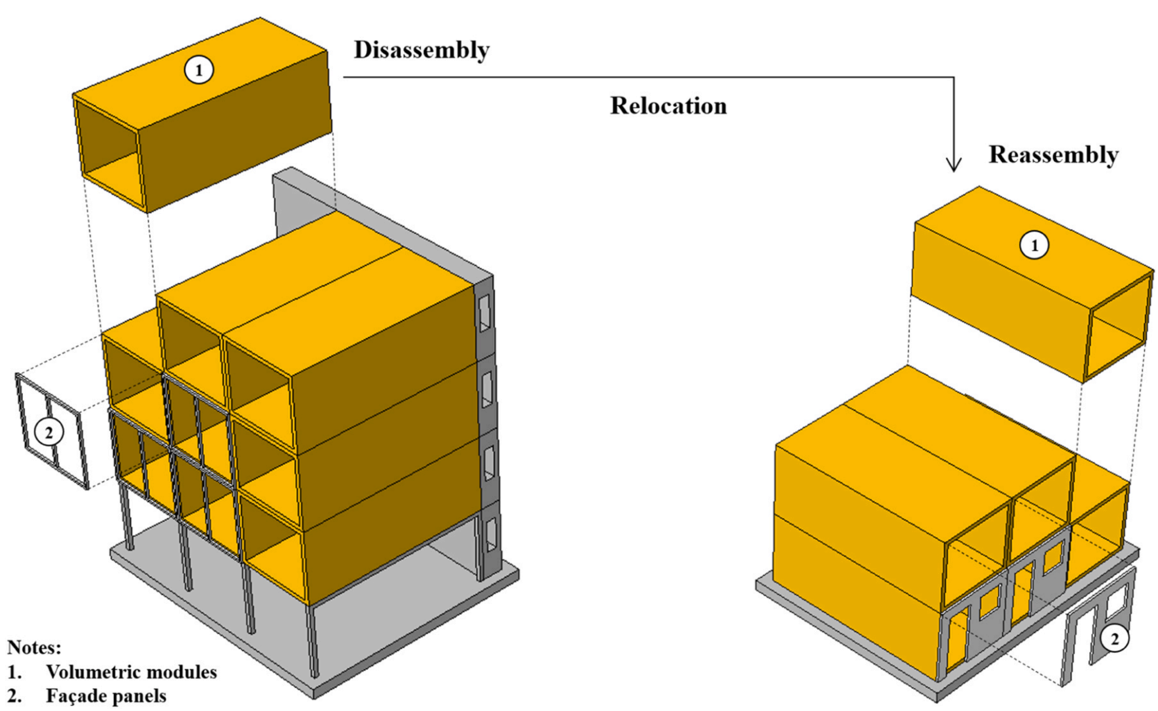


Fig. 4. Illustration of DfD in timber volumetric modular building designs.

A study by David et al. [66] compiled a review of these efforts, including the Australian industry interim standard for recycled timber [94], which provides guidance on the grading of recycled hardwood timber, outlining design rules and methods for defining the mechanical properties of reclaimed timber. Furthermore, the Italian standard UNI 11119 [78] provides guidelines for on-site inspections to diagnose the structural condition of timber members. The European standard EN 17121 [95] also offers guidelines for the on-site assessment of load-bearing timber structures. Moreover, the studies combining visual grading, non-destructive assessment and bending tests like those by Arriaga et al. [96] and Kauniste et al. [97] can be used to assess the structural and material performance of timber.

5. Challenges in the applications of timber modular

Several researchers have noted several challenges in using timber modular in buildings. These barriers could be identified into three topics, namely (1) fire safety, (2) durability, and (3) design integration.

5.1. Fire safety

5.1.1. Fire safety characteristics

In fire safety, TMBs encounter similar challenges to those associated with conventional timber structures [98]. Numerous research studies have been conducted and are still ongoing on the fire safety of timber structures. These progressions give insight into the challenges in satisfying the fire safety of TMBs. During a fire, exposed timber can act as fuel, contributing to the heat release rate and fire propagation [99]. Therefore, the time available for safe evacuation is directly affected. Thus, compared to modular construction using non-combustible materials, TMBs need to consider the participation of exposed timber components in a fire during the design of modular units. The exposed surfaces of solid timber undergo thermal degradation, starting around 100°C to 200°C [83], which converts the timber into char. This process is known as charring and is deemed to be complete at temperatures ranging from 300°C to 400°C [100–102]. This degradation results in stiffness reduction in the structural components, leading to a loss of structural capacity [103,104]. Similarly, engineered timber also undergoes charring. However, due to the involvement of structural adhesives between the laminated timber layers, losing the integrity of the adhesives at around 200 °C results in delamination [105,106]. This delamination exposes the inner timber layers to the fire, increasing inner layer charring. Crielaard et al. [107] demonstrated that such delamination has the risk of creating a second flashover within the compartment. It has been identified that engineered timber made using polyurethane (PUR) adhesives is more vulnerable to delamination under fire [108,109].

To make these timber structures adequate to fire by reducing their participation in combustion, fire-rated sheathing can be used [110], and as a secondary benefit, it can also reduce the charring rate [111,112], which is beneficial in maintaining the strength of structural timber elements. By varying the protection sheathing type (gypsum plasterboard, cement fibre sheet), their thickness as well as the design (single or multiple layers of gypsum plasterboard, gypsum plasterboard and mineral wool), participation of timber in fire and the charring of the timber components can be managed to satisfy safety [110–112]. However, despite the use of fire protection, the connection/bond between the protective material and the timber elements may be compromised during a fire, leading to the loss of fire protection layers. Such sudden failures have been shown to lead to an increase in heat release rate (HRR) and temperature [113].

As the compartment fire progresses, the flaming at the surface of the timber ceases [113] due to the insufficient volatile gases transferred through the char layer acting as insulation between the compartment fire and the inner timber. However, even after the cessation of flaming, heterogeneous oxidation of the char layer leads to slow flameless combustion known as smouldering [18]. This leads to further charring of the inside timber. However, the charring rate under smouldering combustion is much lower than under flaming combustion. However, over time, continued degradation can lead to a loss of structural integrity. Indications for this hazard can be found in the fire test by Mitchell et al. [114], which studied smouldering combustion of timber structures over 48 h following the cessation of flaming. During one test under continued smouldering, a charred GLT column failed, highlighting the importance of considering the continued charring of structural elements.

Due to these general challenges arising from the behaviour of timber material under fire, the timber connections between timber elements and modules can further challenge the structural fire safety of TMBs [115,116]. These timber connections often incorporate steel fasteners [117,118]. Such heat-conducting components can lead to ignition or detachment [100]. Apart from components made solely of timber, composite wall panels, such as Structural Insulated Panels (SIPs), have been incorporated into timber modular constructions. For example, these composite panels are made of EPS insulation sandwiched between Oriented Strand Boards (OSB). The vulnerability of such combustible SIPs has been confirmed through real-scale fire testing [119]. The combustion of the OSB layers initiates the burning of the EPS layers, compromising their composite action and potentially leading to structural collapse. Apart from the heat exposure and combustion, smoke behaviour during fire events challenges the fire safety of building occupants. The combustibility of treated/engineered timber can contribute to smoke toxicity [120]. Despite their lower content compared to other materials in use, almost every polymer adhesive can generate toxic gases during combustion. For example, it has been verified that the adhesives containing phenol, resorcinol, and formaldehyde (PRF) used in the production of CLT elements can emit toxic gases [102, 103] during combustion. Moreover, under fire conditions, the connections between engineered timber panels can result in smoke leakage [111], leading to a loss of compartmentalisation.

In addition to the above-discussed challenges, the unique configuration of modular buildings can pose challenges to fire safety. TMBs often feature continuous cavities (Fig. 5), resulting from the assembly of 3D volumetric units [6,121]. These cavities, referred to as "intermodular cavities," can be classified into vertical and horizontal categories. Vertical intermodular cavities (Fig. 6a) are formed between the walls of adjacent modular units. These gaps typically arise from connection details at the eight corners of the modular units or to accommodate tolerances during the manufacturing and assembly processes. The standard width of these cavities is 50 mm, although they may range from 20 mm to 50 mm [6]. In contrast, horizontal intermodular cavities (Fig. 6b) are necessary to provide access to intermodular connections and install service lines. These cavities' height (or depth) can vary from 20 mm to 500 mm [6]. The main fire safety concern associated with such continuous cavity spaces lies in their potential to facilitate fire and smoke spread throughout a building [98]. Several fire incidents related to cavity fires in TMBS have been reported (Table 3). Just et al. [122] have reviewed cavity fires in TMBS, identifying several common challenges. Cavities constructed from combustible materials allow fire to spread, even with restricted airflow. Combustible adhesives in ceiling cavities to

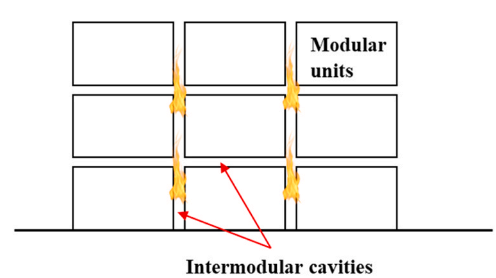


Fig. 5. Cavities in modular construction units [121].

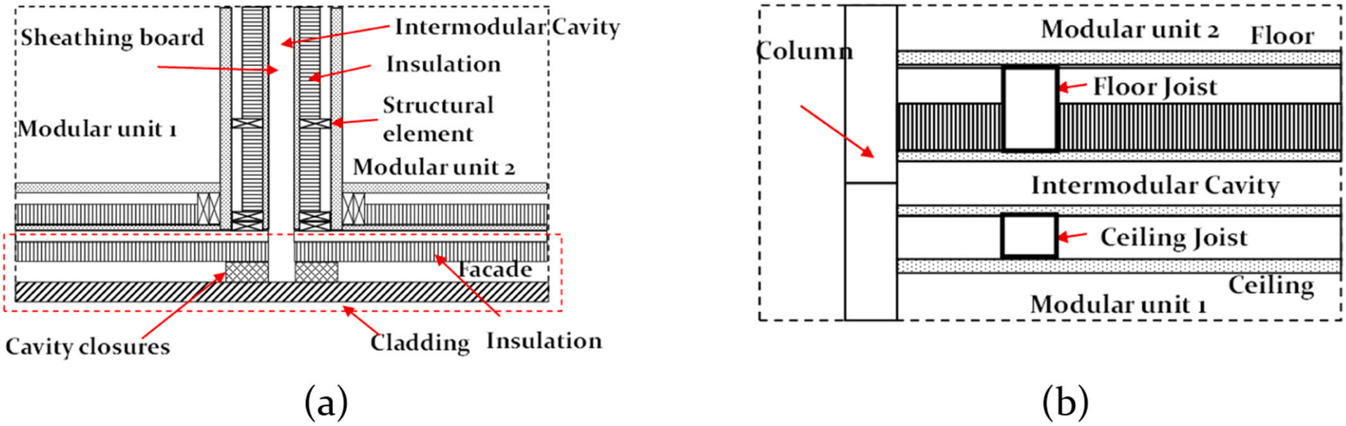
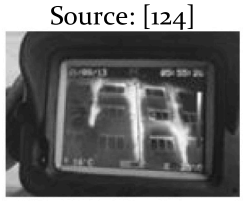
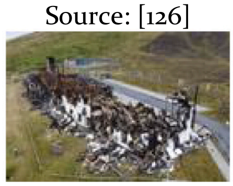


Fig. 6. Intermodular cavity formation: (a) vertical intermodular cavity [6] and (b) horizontal intermodular cavity [6].

Table 3
Fire accidents in modular buildings are related to cavity fire spread [122–128].

Building	Image	Year	Description
Two-story colonial-style home, Acushnet, Massachusetts [123, 124]	 Full building involved in the fire. Source: [124]	2008	The fire spread quickly through a 500 mm deep ceiling cavity due to the flammable polyurethane foam adhesive used for the gypsum board, with holes aligned to the void space.
Five-story Light Timber student apartments. Luleå, Klintbacken Sweden [122]	 Fire spreading through cavities. Source: [122]	2013	The fire started from ignited oil in a saucepan on the top floor and spread through the ventilation system to the attic and other cavities. A combustible plastic layer in the mineral wool barrier allowed the fire to progress beyond it.
Fair Isle Bird Observatory, Shetland, Scotland [125]	 Fire spreading throughout the building. Source: [126]	2019	The fire started on the roof and spread through the cavity of the exterior timber cladding system. The building has been constructed from glue-laminated timber joists.
Moorfield Hotel, Shetland, Scotland [126-128]	 Structure after the fire. Source: [126]	2020	The fire started on the roof and spread through the cavities. The building comprised structural insulated panels (SIPs) with combustible polyurethane insulation between two oriented strand board sheets.

secure board materials [123,124] to structural or supporting members have been reported as a reason for fire spreading within cavities. Notably, this concealed fire propagation can persist for several hours beyond the duration of compartment fires, frequently leading to the reignition of compartments [122] even after they have been extinguished. Importantly, extinguishing such hidden fire propagation can be challenging, resulting in greater damage to the building.

In 2013, a two-story modular home in West Haverstraw, New York, was destroyed by a rapid-fire [123]. Additionally, another modular home in Carmel, New York, was involved in a fire in 2012 that resulted in four fatalities [123]. However, detailed information regarding these two incidents has not been thoroughly reported.

5.1.2. Pathways to overcome fire safety-related challenges

The above-discussed challenges in fire safety can hinder the acceptance of TMBs as a sustainable construction approach. However, the existing research and knowledge provide insight into overcoming the challenges in fire safety. The National Construction Code (NCC) [129] Australia indirectly allows the incorporation of timber elements in modular buildings by categorising them under timber construction (NCC Volume 1, Part CL.13). It accepts timber construction under the achievement of deemed-to-satisfy solutions for Class 2, 3, and 5 buildings, provided that several measures are taken to overcome fire safety-related challenges. This section discusses all these options for adopting TMBs as a sustainable construction approach in Australian conditions.

Three main approaches can be identified to enhance the fire resistance of structural components in TMBs full-encapsulation, partial encapsulation and usage of sacrificial depths [130]. Fig. 7 illustrates the standard detailing of these three approaches.

The first method considers fully encapsulating the timber elements with fire-protective layers and is the most widely used approach. Avoiding charring and delamination by this encapsulation using fire-protective layers is a logical way to improve fire resistance [131]. Fire resistance tests conducted on timber connections underscore the significance of these protective layers for compliance with building codes [116]. Options for protective layers include fire-rated gypsum plasterboards, cement-fibre boards, intumescent flame-retardant coatings, and flame-retardant nano-coatings [132]. Experimental research [112] has demonstrated that encapsulation of mass timber with single and double layers of gypsum plasterboard can protect the timber from direct heat exposure for up to 39 min and in excess of 53 min, respectively. Experimental evidence [133] shows that proper protection for timber slab walls can compartmentalise the ignited compartment from another compartment. NCC [129] stipulates the performance targets shown in Table 4 to achieve fire resistance to the incipient fire spread. The acceptance criteria are developed based on the temperature increase observed at the interface between the fire protection layer and the timber element. Consequently, it is specified that the temperature of the timber must not surpass 300 °C during a fire resistance test.

When it is necessary to keep timber elements fully exposed without any protective layers for aesthetic reasons, fire resistance can be

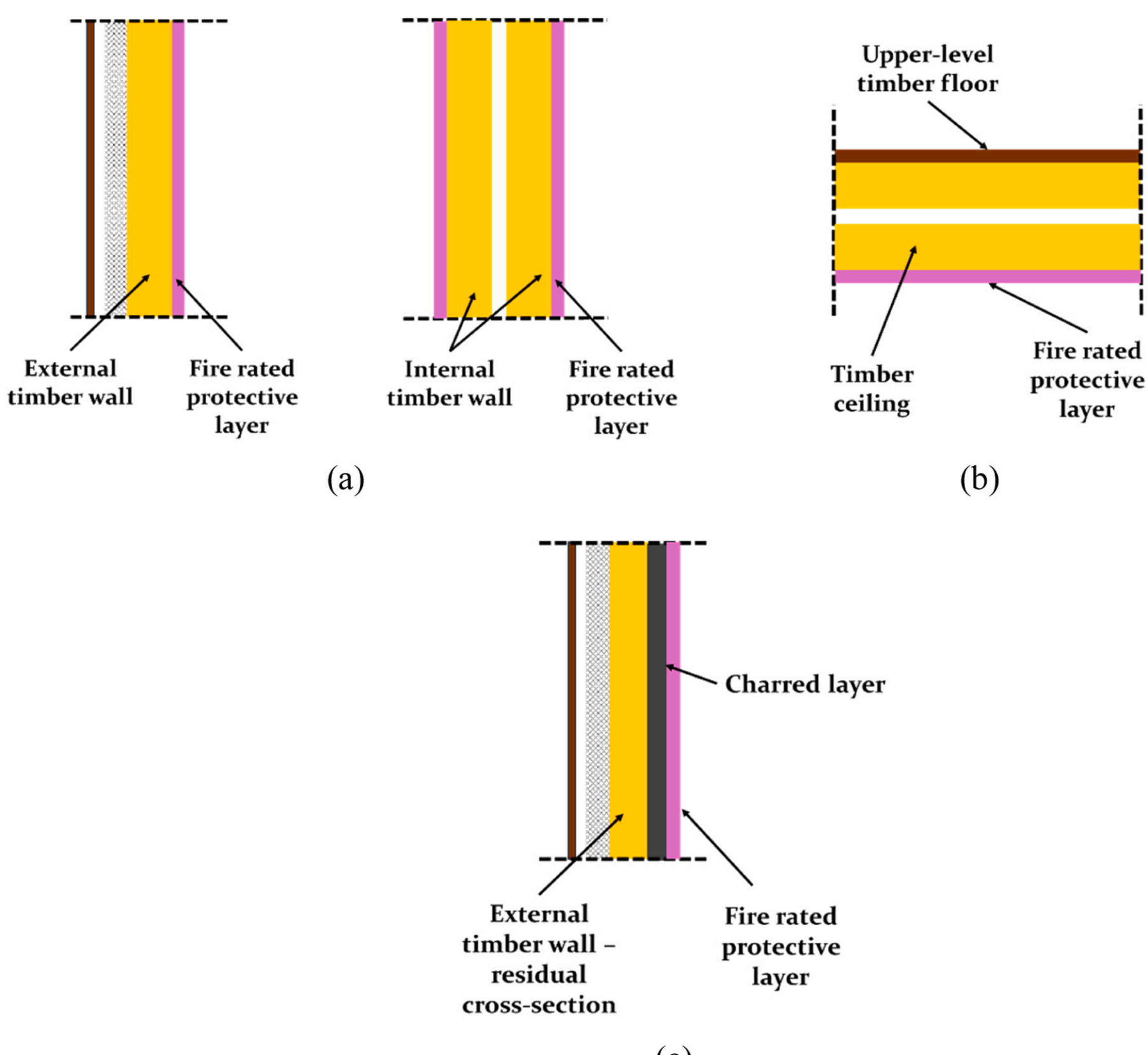


Fig. 7. Standard detailing for improving fire resistance of structural elements: (a) full encapsulation for walls; (b) full encapsulation for ceilings; and (c) limited encapsulation for walls [130].

Table 4
Performance targets and required minimum thicknesses of plasterboard for fire resistance of elements in timber (modular) buildings [129].

Application	Time without timber interface exceeding 300° C (mins)	Minimum plasterboard thickness (mm)
Fire-isolated stairway/lift shaft	20	13
External walls	45	13 + 13
All other applications	30	16

achieved by utilising larger cross-sections that allow for sacrificial charring depths. In terms of delamination, Crielaard et al. [107] highlighted the need for thicker timber layers to avoid delamination/charr fall-off. This second method of achieving fire resistance through sacrificial charring depths can provide fire resistance for 90–120 min and can be incorporated into robust designs [134]. The third approach for fire resistance combines the first two, integrating protective layers and sacrificial depths for charring, considering that protection falls off during the fire. This partial encapsulation [135] allows the reduction of the usage of protective layers, leading to reduced costs and CO_2 footprint. Therefore, this option has the potential to overcome fire safety challenges while improving the sustainability of the modular building. However, as highlighted earlier, this method also has concerns about second flashovers after the protection falls off, which can promote fire [96]. Therefore, such strategies should not be adopted unless verified through full-scale experiments. Even under verification, there should be a clear idea regarding the protective layer's failure. Fig. 8 summarises experimental data [136–139] available on the fall-off times of different protective layers. Based on these data, it can be suggested that minimum thicknesses of 13 mm, 16 mm, 32 mm and 48 mm of Gypsum plasterboard layers can withstand fire exposure up to 30, 60, 90 and 120 min, respectively. Moreover, Intumescent, Rockfiber, cement fibre, Chipboard and MDF protective layers can withstand a fire exposure of 30 mins when the thickness is greater than 60 mm, 51 mm, 10 mm, 32 mm and 48 mm, respectively. If the integrity of the fire protective board is necessary for prolonged periods beyond hours, options like spray-applied fire-resistant materials [136] can be considered. However, as discussed under cavity fire-related challenges, the usage of combustible Chipboards and MDF protective layers inside the cavity spaces cannot be recommended as they can increase the cavity fire spread. Inside the compartments, those protection layers can be used, but their addition to the combustible load needs to be taken into consideration. Thus, for the fire protective layers, it is safe to consider only non-combustible materials.

Apart from these three approaches, controlling delamination with suitable adhesives that have a proven glue line integrity [18] can be considered to meet the fire resistance of modular construction based on engineered timber. At the same time, consideration should be given to reducing the risk of toxic smoke generation when selecting suitable adhesives for engineered timber production. For example, Lee et al. [140] researched on reducing the toxic gas generation in CLT elements by using ethylene vinyl acetate as a substitute for adhesive within CLT. Moreover, novel techniques using modified timber treatments with nanocarbon materials are being developed to enhance flame-retardant and mechanical properties [141].

The fire resistance of timber connections can be achieved through encapsulation with fire-resistant compounds [132]. The requirement of such fire resistance enhancement is highlighted by the fact that unprotected timber connections have a fire rating of less than 30 min [142]. Replacing steel fasteners with ceramic bolts has enhanced the fire resistance of timber connections [132]. Other traditional approaches to improve the fire resistance of timber connections include increasing the thickness of the wood components or reducing the applied load ratio [142].

The fire resistance levels of construction elements are typically assessed by subjecting individual components to heating conditions. However, this method may not accurately represent the overall performance of the entire system [7,100]. The combination, arrangement, and quantity of combustible materials within the system can significantly influence its result [100]. For example, using combustible integrated panels (SIPs), unencapsulated mass timber, and combustible cavity spaces can impact the system's performance rather than as isolated components. Furthermore, existing test methodologies do not necessarily consider the effect of prolonged smouldering combustion [143] corresponding to a post-decay stage of a compartment fire. Therefore, new testing procedures need to be identified. Moreover, when protection boards are used, the integrity of those layers needs to be considered

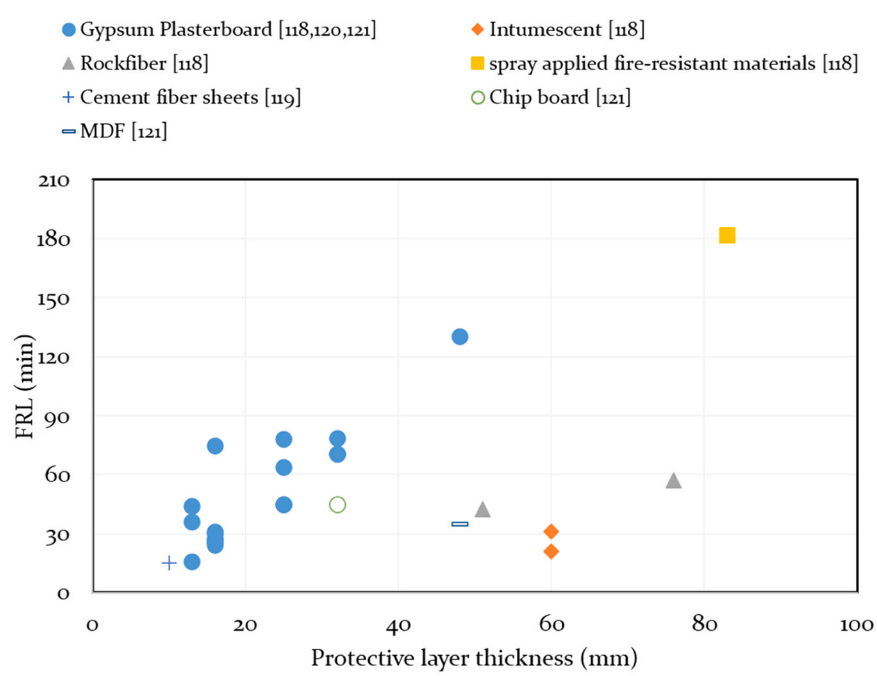


Fig. 8. Experimental data on fire protective layer fall-off under fire exposure.

during the transportation of the modules, as vibrations can cause damage [144].

In the deemed to satisfy solutions in NCC [129], the challenge of fire spread in tall timber constructions is addressed by imposing an effective building height restriction of 25 m. Construction of high-rise structures from timber is a challenge. Being combustible can lead to uncontrollable fire spread, impacting evacuation and fire suppression. Thus, height limitations for timber structures are necessary for the deemed to satisfy the provisions provided in NCC [129]. However, the unique configuration of TMBs can substantially differ from conventional timber structures, especially in the context of continuous cavities. For example, rapid fire in modular timber buildings has been identified by firefighters, resulting in severe damage to the structures within a short time and the time taken to extinguish [106,127], which can compromise the safety of occupants' evacuation, as well as to a greater extent. Therefore, additional research is essential to identify the impact of building height on the fire performance of timber modular structures and to verify whether the current building height restrictions, deemed to satisfy solutions in the NCC [110], are adequate. In the meantime, to control the spread of fire over combustible timber elements, further research is warranted on the treatment/production of engineered timber with materials that can suppress combustion.

The intermodular cavity-related fire safety risks can be controlled by carefully detailing cavity spaces. NCC [129] acknowledges the risk of concealed fire propagation within cavity spaces in timber construction. Therefore, the NCC [129] prohibits combustible insulation materials within such cavity spaces to reduce the potential for cavity fire spread. Apart from that, intermodular cavities in modular buildings are required to be sealed with cavity barriers (Fig. 9) at each module boundary [6,145,146]. In addition, NCC [129] specifies the following locations that require cavity barriers in timber (modular) construction.

- At concealed cavities adjacent to junctions between fire-resisting floor/ceiling assemblies and fire-resisting walls.
- At concealed cavities adjacent to junctions between fire-resisting floor/ceiling assemblies and fire-resisting or non-combustible external walls.
- At concealed cavities adjacent to junctions between fire-resisting walls and fire-resisting or non-combustible external walls.
- Around the perimeter of door and window openings in fire-resisting construction.

In these areas, horizontal cavity barriers should be installed at intervals not exceeding 5 m, while vertical cavity barriers should be placed no more than 10 m apart. Alternatively, window or door frames may serve as cavity barriers around openings, provided they are made of either steel or timber (complying with the minimum cavity barrier thickness specified in Table 5) and are securely fitted to a rigid construction through mechanical fastening.

These cavity barriers can be installed at off-site preparations within the modular units or directly on-site [122,147]. The general installation

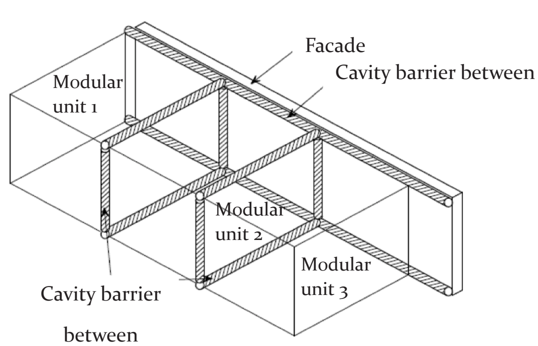


Fig. 9. Cavity barriers in modular construction (reproduced from [145]).

Table 5
NCC [129] specifies cavity barrier requirements.

System FRL	-/60/60 or -/90/90	-/120/120, -/180/180 or -/240/240
Cavity barrier FRL	-/45/45	-/60/60
Minimum thickness (Timber/ Mineral wool)	45 mm	60 mm

methods for these cavity barriers are illustrated in Fig. 10. According to the NCC [129], permissible materials for cavity barriers include timber, polythene-sleeved mineral wool, or mineral wool slabs and strips. These must meet specific requirements in terms of minimum thickness and fire resistance level (FRL). The required FRL and minimum thickness rely on the highest FRL of the elements they are installed within or sealed against, as detailed in Table 5. Although the NCC [129] permits the use of polythene-sleeved mineral wool cavity barriers, the fire incident that occurred in Luleå, Klintbacken, Sweden [103] (Table 3) highlights the potential hazards associated with such combustible sleeves. Research conducted by Just and Brandon [122] demonstrated that the combustible plastic layer in the mineral wool cavity barriers facilitates the movement of hot gases beyond the barriers, leading to smouldering combustion. Therefore, further investigation is necessary to assess the appropriateness of polythene-sleeved cavity barriers in timber modular constructions.

Several factors can compromise the effectiveness of cavity barriers in timber modular construction. Due to the narrowness of the cavity spaces and the orientation of the modules in all three dimensions, limited accessibility [100] poses challenges for the practical on-site application of cavity barriers. Furthermore, inspecting cavity barriers to confirm the proper installation is complicated, regardless of whether the barriers are applied off-site or on-site. Manufacturing tolerances, deformation during transportation, the positioning of modular units with cranes, and the shrinkage of timber modules can lead to alignment issues [6]. In modular construction, two types of alignment issues can occur as vertical and horizontal (Fig. 11) [6,121]. Such misalignments can compromise cavity barrier performance, resulting in gaps that may permit smoke and flame to pass through. Deformations in structural systems due to earthquakes and high wind conditions can also be crucial. The NCC [129] requirements emphasise that cavity barriers must be installed in a manner that prevents thermal expansion and structural movement from compromising their sealing capability for fire and smoke spread. Therefore, further research in structural deformation mechanisms is beneficial in identifying its impact on compromising cavity barrier performance. As a solution for the cavity fire/smoke spread under unexpected tolerances/gap formations, cavity barriers and fire stops with intumescent coatings can be investigated.

According to NCC guidelines, the FRL of cavity barriers must be determined following Section 10 of AS 1530.4 [148]. However, whether the same testing standards utilised for conventional cavity barriers are suitable for modular buildings remains uncertain. For example, double cavity barriers (Fig. 10e) are not a conventional method for cavity barrier application. It is essential to test the joint formed by two separate cavity barriers to evaluate their effectiveness in preventing hot gases. Moreover, affordable and user-friendly in situ testing methods need attention to identify cavity barrier defects. If feasible, testing should be undertaken to measure how effectively the cavity barrier design contributes to fire safety, particularly in light of these defects. Additionally, when cavity barriers, fire stop systems, or sealants are utilised with combustible substrates, it is imperative to consider the combustibility of the substrates rather than solely relying on the fire rating of the substrate (e.g., wall or floor systems) [100]. This consideration is especially significant when unencapsulated timber substrates are involved. Just et al. [122] also highlighted concerns regarding the adequacy of current cavity barrier testing methods in accurately representing actual fire conditions during cavity fire spread. These existing methods do not

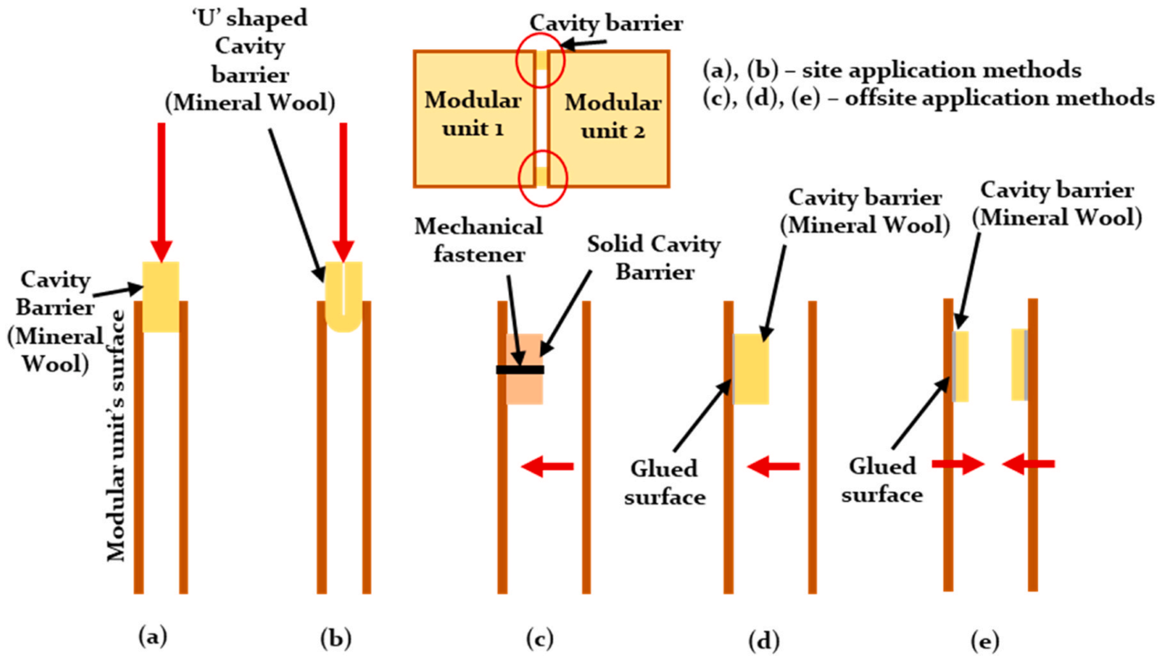


Fig. 10. Cavity barrier installation methods used in modular buildings [122].

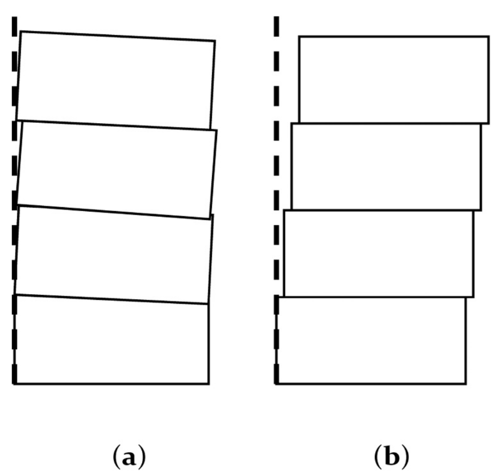


Fig. 11. Module alignment issues [6] (a) Vertical misalignment; (b) Horizontal misalignment.

consider the possibility of air heating within cavity barriers, which can lead to smouldering combustion. Therefore, Just et al. [122] recommended using two-cavity barriers with combustible boundaries, when applicable, to assess the performance of cavity barriers. Furthermore, as documented in various cavity fire incidents, it is essential to account for the possibility of reignition within cavity spaces, even after the visible fire has been extinguished. Just et al. [122] introduced a potential fire curve divided into three phases. These three phases include a heating phase (standard fire curve in Eurocode), a cooling phase (without heating), and the reignition phase (allowing airflow).

5.2. Durability

TMBS are widely being researched in terms of durability due to the challenges arising from the natural behaviour of timber. Material quality and design, moisture and decay resistance, and structural integrity are key considerations in the efficiency and long-term durability of timber. In general, all timber buildings, including TMBs, utilise high-quality materials and adopt advanced design standards, resulting in significant durability levels. Scandinavian and Canadian technologies have demonstrated that modular wooden buildings can last up to 200–300 years when certain parameters, such as wood density, are maintained [149]. The durability of TMBs depends on factors such as wood treatment, proper maintenance and design practices, with some structures potentially lasting up to 200–300 years under optimal conditions [149,150]. Proper maintenance entails a systematic process of regular inspection, protection, cleaning, repair, and pest control designed to preserve the structural integrity, safety, and visual appeal of timber components. Timber-cork modular systems for lightweight temporary housing have higher sustainability than common container houses, with lower greenhouse gas emissions and biogenic carbon storage values [151]. This higher sustainability of TMBs is attributed to the use of responsibly sourced renewable timber materials, minimised embodied energy and carbon emissions, enhanced energy efficiency, and adaptability through modular design. Moreover, carbon sequestration benefits, healthier indoor environments, and the capacity for disassembly and reuse collectively contribute to reduced ecological impact, resource conservation, occupant well-being, and long-term resilience, adding up to higher sustainability in terms of all the pillars of sustainability.

Most widely used timber species in TMBs in Australia include both hardwood and softwood. Blackbutt, spotted gum, and Jarrah are the most used hardwoods, while Radiata Pine and Cypress Pine are common softwoods. The natural deterioration of these timber species is a function of exposed weather conditions, and studies have been conducted to evaluate the median specimen life for these timber species in different locations across Australia [152]. According to Cookson [152], the observed median specimen life for the most widely used timber species in TMBs is compared below in Fig. 12.

Moreover, Table A1 in the Appendix compares the durability classes of various timber species used in TMBs, along with their expected lifespans and relevant applications. The different timber species used in TMBs are categorised into four durability classes, with applications ranging from structural framing to non-structural components, including partitions, doors, and windows.

5.2.1. Moisture and pest resistance

The moisture and termite resistance are critical factors affecting the

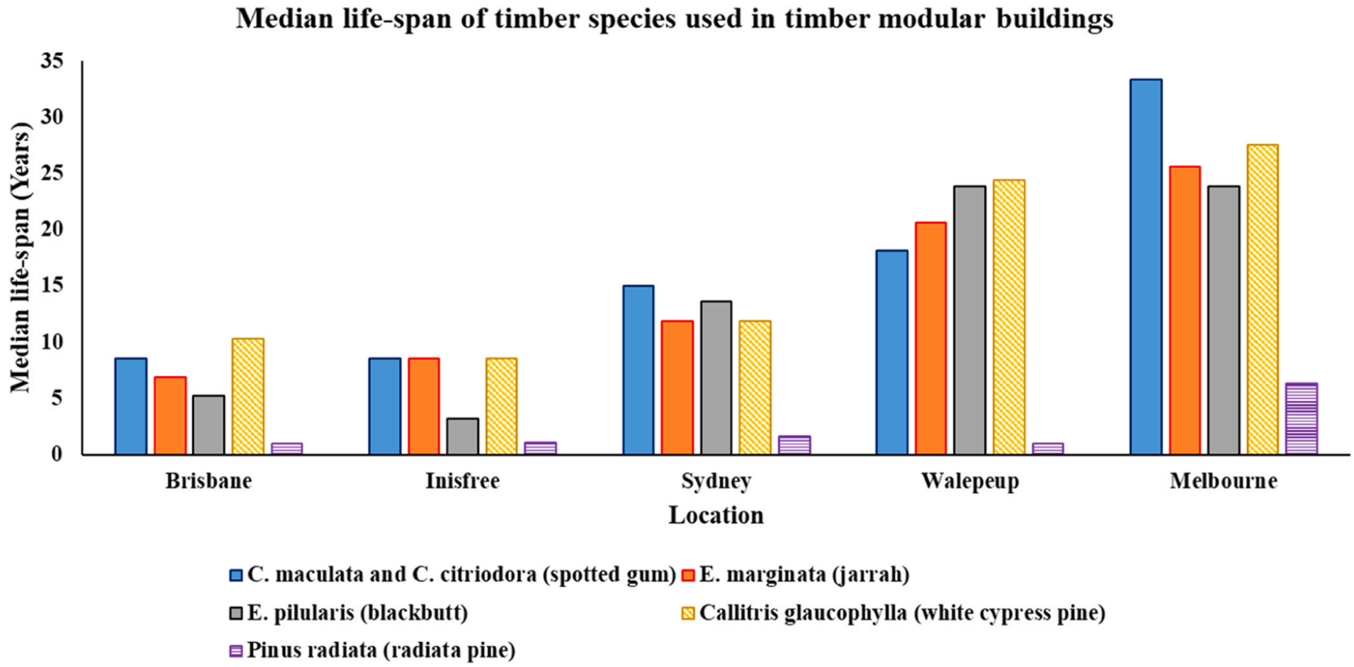


Fig. 12. Specimen life for the different timber species in Australia [152].

durability and longevity of TMBs. Hence, effective strategies for moisture management and termite attack control are essential to prevent biological degradation and ensure the structural integrity of the structure. This section focuses on the effects of moisture and termite attacks on TMBs, moisture control methods, termite resistance strategies, and possible monitoring techniques that can be incorporated into TMBs. Moisture is a fundamental concern in timber construction, and this consideration is equally relevant for modular timber buildings. Timber is regarded as a hygroscopic material by nature, which makes it undergo structural property changes in response to changes in moisture content [153]. Among the various types of timber used in TMBs, CLT is frequently employed due to its high bearing capacity, stiffness, and sustainable construction method [154]. Consequently, the effect of moisture represents a significant concern for modular timber buildings. With the ingress of moisture into GLT, CLT, LVL, and mass plywood panels (MPP), the adhesive bond is susceptible to physical changes, subsequently diminishing the structural integrity [155,156]. Moreover, moisture ingress may result in creep and dimensional instability [157].

Moisture conditions also significantly influence pest infestation in timber [158]. Maintaining appropriate moisture levels helps enhance resistance to biological attacks, ensuring the structural integrity and serviceability of TMBs [159]. The TMBs can achieve moisture and pest resistance by isolating timber from mineral elements using non-bituminous systems or incorporating fungicidal fillers in the building elements [160]. Elevated moisture conditions increase the likelihood of pest infestation in timber, compromising structural integrity; thus, moisture control is essential for pest resistance in TMBs [159]. A moisture and pest-resistant barrier for TMBs using a synthetic resin emulsion combined with anti-fungal agents and pesticides is proposed to combat adverse effects due to moisture in buildings [161]. Moisture monitoring in timber elements helps prevent timber decay and pest infestation, ensuring long-term functionality and durability in TMBs, especially in challenging hygrothermal conditions [162]. TMBs are sensitive to moisture, which can lead to mould and pest issues; thus, moisture-safe construction methods and weather protection are essential for durability and health safety [163].

Delamination is a key durability concern in engineered timber, particularly GLT, as it compromises structural integrity. This moisture-related delamination differs from heat-induced delamination in fire and is typically caused by moisture fluctuations, poor adhesive performance, or mechanical stresses. Changes in moisture content lead to dimensional movement and separation within or between timber layers, reducing stiffness and strength [15–17]. Prolonged wetting can also cause staining, mould, and decay in TMB applications [18]. Inadequate or incompatible adhesives further increase the risk of glue-line failure [19,20], while factors such as high temperatures and improper surface preparation can exacerbate delamination.

5.2.2. *Long-term structural serviceability*

Given that TMBs offer numerous benefits, they present several challenges regarding long-term structural serviceability, primarily due to material properties and design considerations. These issues can affect the durability and serviceability of such structures over time. Generally, aligning with the common benchmarks outlined for permanent structures under Eurocode 5 [164] and the NCC [129], the design life of TMBs is typically around 50 years. The selection of adequate materials, facilitating protection from environmental exposure conditions, and adherence to proper construction and maintenance practices are key factors in ensuring the stated design life for TMBs [165,166]. The design life is reduced to 25–40 years for temporary or relocatable TMBs due to their desired short-term utilisation [167]. Although the use of high-quality engineered timber products, such as CLT and GLT, can enhance the design life, the long-term durability and structural performance of these structures are critically governed by factors including moisture ingress, intermodular connections, and design for disassembly. The design life variation of modular systems varies with the type of material due to the associated durability constraints. Generally, timber has a design life of around 50 years; however, its durability is significantly affected by biological decay induced by moisture [32,168,169].

Timber frame modules are typically used in educational buildings and houses as 1–2 storey buildings [170]. In addition to the timber modules, prefabricated engineered wood panels, such as CLT, are well-suited for modular structures due to their enhanced structural integrity, lightweight nature, design flexibility, and thermal and acoustic insulation [79]. Long-term structural performance issues in TMBs may include susceptibility to creep, moisture-related deformations [171]. Additionally, interactions between non-structural components affect the overall stability and serviceability [171].

Variations in racking stiffness and strength, along with the need for stronger inter-module connections, may impact the long-term structural performance of TMBs [172]. Moreover, long-term structural performance concerns for TMBs include potential stress concentration in joints, susceptibility to moisture-related issues, and challenges in maintaining uniform stress distribution over time [173]. Modular timber buildings may face challenges in long-term structural performance due to potential joint weaknesses, moisture variability, and the complexity of interactions between different materials affecting durability and safety [174].

Impacts due to different natural hazards prevalent in Australia are another key aspect to consider regarding the long-term performance of TMBs. Since Australia's geographic location and varied climate conditions subject buildings to numerous natural hazards, including bushfires, earthquakes, cyclones, and floods, it is essential to ensure these TMBs are designed to withstand these hazards. Table 6 below summarises the specific natural hazards occurring in Australia and suggested design measures to cater for them in TMBs.

In addition to the above-discussed material-oriented constraints affecting the long-term structural performance of modular timber buildings, several non-material-related factors also hinder the design life of modular timber buildings [175]. These include the lack of long-term performance data, limitations in insurance coverage, negative risk perceptions, conservative regulations, and often accompanied by delays in updating relevant standards. The available empirical evidence on the long-term performance of mass timber and modular timber buildings is limited [175]. This has resulted in conservative design assumptions and cautious regulatory approaches. Additionally, the experimental data on the long-term hygrothermal and mechanical behaviour of timber systems are limited compared to steel and concrete [7,176]. Particularly, connections in composite CLT/GLT structures remain insufficient [177], highlighting the requirement for further research to support reliable design practices. Additionally, limitations in insurance coverage have arisen due to the lack of loss history and established risk assessment frameworks for these buildings [178]. Hence, the adoption of conservative approaches, such as considering total loss scenarios, has resulted in higher premiums or more restrictive coverage terms. This could limit the broader adoption of timber modular solutions.

5.2.3. *Maintenance considerations*

TMBs present several maintenance challenges that can impact their long-term viability. While modular designs offer advantages in assembly and disassembly, they also introduce complexities that can complicate maintenance efforts. Perceived challenges of modular timber buildings include increased maintenance costs and concerns regarding durability and stability, which contribute to resistance to their adoption for multi-storey construction [179]. These buildings also face challenges in maintenance due to potential moisture movement, connection system vulnerabilities, and the requirements for specialised knowledge for effective upkeep and repairs. The major drawback of traditional modular designs is the neglect of maintenance needs, leading to difficulties in accessing and servicing components [180]. The integration of MEP systems in timber structures is more complex than using timber as a conventional material, increasing the risk of moisture damage and complicating repairs [181]. According to industry surveys, the higher maintenance costs associated with timber structures limit their widespread adoption [179]. Hence, effective maintenance strategies need to be considered during the design phase, although it has not been well prioritised. In TMBs, disassembly operations significantly impact the degradation processes of components in modular buildings, especially the intermodular connections, and this poses a common challenge for the timber modular system as well [179].

Table 6
Design standards and measures to cater for different natural hazards in Australia.

Natural hazard	State	Complying code	Adopted design measures
Bushfire		AS 3959 (Construction of Buildings in Bushfire-Prone Areas)	Using non-combustible cladding/ bushfire-resistant timber/materials with specific fire-resistant levels. Minimising ignition points around joints.
Cyclones and wind resistance	Queensland Northern territory	AS 4055 (Wind Loads for Housing)	Using wind-resistant cladding. Use of sturdier connections.
Flooding	Low-lying areas on the East Coast and the Northern parts		Elevated foundations, waterproof coatings, moisture barriers to prevent water from coming into direct contact with the timber structure, using damp-proof membranes, designing drainage systems.

5.3. *Building design-related constraints*

5.3.1. *Structural design limitations*

Modular timber buildings face structural limitations related to stability configurations, reliance on linear assembly processes, and challenges in achieving verticality compared to traditional materials like steel and concrete [15]. Additionally, modular timber buildings face limitations such as the need for external cladding, moisture protection during erection, low practical experience, and fire safety concerns in high-rise applications [154]. Structural limitations such as sensitivity to overturning, bending-shear deformations under earthquake loads, and vibrations from strong winds necessitate robust shear wall designs for the stability of TMBs [182]. Furthermore, challenges in seismic analysis, fire performance, and the structural behaviour of walls, floors, and columns, affecting overall durability and safety, are included [183]. The lack of efficient structural systems for lateral load transfer is a significant limitation in TMBs. This issue impacts their widespread application and performance and has been identified as a structural drawback pertaining to TMBs [184]. Significant variation in racking stiffness and strength, along with the need for stiffer mechanical inter-module connections, highlights structural limitations in TMBs under combined loading conditions [185].

Modular timber buildings face limitations in connection design, energy dissipation during seismic events, and potential overdesign due to the use of conservative analytical models, which can affect structural performance and efficiency [93]. The physical characteristics of timber limit its structural use in TMBs, particularly in high-rise and large-span structures [15,186]. The strength and design of inter- and intra-module connections significantly influence the structural performance of TMBs, as weak connections can lead to stability and robustness issues, particularly in high-rise applications [154,170,187]. Moreover, as timber is a combustible material, fire safety is a critical concern of modular timber buildings, where the risk of buckling inside walls during a fire limits the maximum height and slenderness of TMBs [154]. Moreover, apart from the constraints imposed by the timber material properties, these modular assemblies undergo significant deformations and uneven force distributions, which affect their overall structural integrity. Particularly for CLT, bending and rotation of stabilisation walls result in maximum deformation [154]. In addition, these TMBs face challenges in design and modularity, which limit the flexibility of architectural design. Timber structures are generally rectilinear and symmetric, with repetitive extrusions, which may hinder the fulfilment of architectural or functional requirements [15,186].

5.3.2. Potential solutions to overcome structural design limitations

Prefabricated timber components are integrated with existing structures to extend or retrofit current buildings. This enhances the sustainability and efficiency of construction due to the potential of this approach in reducing carbon footprints and adapting to urban densification challenges. Urban densification poses a significant challenge for many cities worldwide. The vertical expansion (Fig. 13) of existing buildings comes as a viable solution in creating usable spaces by vertically expanding the existing buildings, without exerting additional burden on the ground [188]. Several concerns draw attention to expanding existing structures, including the load-bearing capacity of the existing structure, construction time, and convenience in construction [188]. Prefabricated timber frame construction is prominently utilised in the domain of adding vertical extensions to existing buildings, given its ability to adapt to existing structures, typologies and architectures, in terms of façade expression.

By combining timber with other materials, such as steel, to form a hybrid system, the structural capabilities of these TMBs are enhanced. Moreover, these hybrid systems have been identified as lightweight, seismic-resistant solutions that are more sustainable and efficient [189, 190]. Construction systems with excellent performance and architectural flexibility are developed using CLT panels combined with steel frames and beams [52]. This is shown in Fig. 14 and reflects the potential of integrating with existing building retrofitting.

However, although these timber space modules offer the potential to replicate themselves due to their fixed dimensions, several constraints have been noted when integrating these modules into existing structures. These adaptability and integration challenges include fixed dimensions, architectural constraints, and load-transferring systems. The fixed dimensions of timber modules limit their adaptability to existing structures, further constraining architectural integration [173,174]. Ensuring proper load transfer is necessary when integrating modular timber components with existing structures, and this requires specific load-transferring systems to effectively accommodate the structural loads [174,175].

6. Summary and recommendations

This study provides an integrated assessment of timber modular buildings (TMBs) and addresses the current research gap in understanding their system-level feasibility for multi-storey applications in Australia. While the benefits of timber and off-site construction are well established, the literature remains fragmented, often examining structural, environmental, or material aspects in isolation. This review synthesises these domains to highlight the key opportunities and significant barriers that must be resolved for broader adoption. Findings confirm that TMBs offer meaningful sustainability advantages, including notable reductions in greenhouse gas emissions, approximately 26 % with panelised systems and up to 28 % with volumetric systems. The circular economy potential can also be observed through the timber's suitability for design for disassembly and adaptation (DfD). However, the novelty of this study lies in identifying the critical challenges that constrain large-scale deployment and outlining targeted pathways for improvement. Fire safety, long-term durability under Australia's hazard-prone conditions, structural limits for taller buildings, and logistical constraints remain the central barriers to upscaling TMBs.

To address these challenges, several solution pathways are proposed. Fire safety can be improved through effective encapsulation, enhanced cavity barrier design, and performance-based fire assessments that consider the entire modular system rather than individual elements. Further research is required into alternative fire protection layers, adhesive performance to mitigate delamination, and heat-resistant fastener technologies. Durability can be strengthened through hazard-specific detailing, appropriate timber species selection, protective treatments, and maintenance planning. Structural and logistical barriers may be overcome by adopting lightweight or hybrid volumetric modules and improving transport-tolerant connection systems. Eliminating or better controlling intermodular cavity spaces also represents a key research direction. Overall, the study recommends prioritising volumetric modular systems, supported by hybrid lightweight materials, digital design integration (e.g., BIM), design for disassembly, standardised component interfaces, and validation through performance-based design. Strengthened regulations, expanded long-term performance data, and improved insurance frameworks will be essential to accelerate the adoption of multi-storey TMBs in Australia and internationally.

Limitations: This study is limited by its focus on building design criteria related specifically to the use of timber in multi-storey modular buildings and therefore does not encompass broader systemic factors such as regulatory frameworks, economic conditions, industry capability, or supply-chain maturity. These aspects represent important areas for further investigation to provide a more comprehensive understanding of the challenges and opportunities associated with scaling up TMBs.

CRediT authorship contribution statement

Satheeskumar Navaratnam: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alvin Setiawan Rahardjo:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Rajeendra Godakandage:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Sathya Bandaranayake:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation.

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.

Fig. 13. Application of timber modular structure as a vertical extension to an existing building [188].

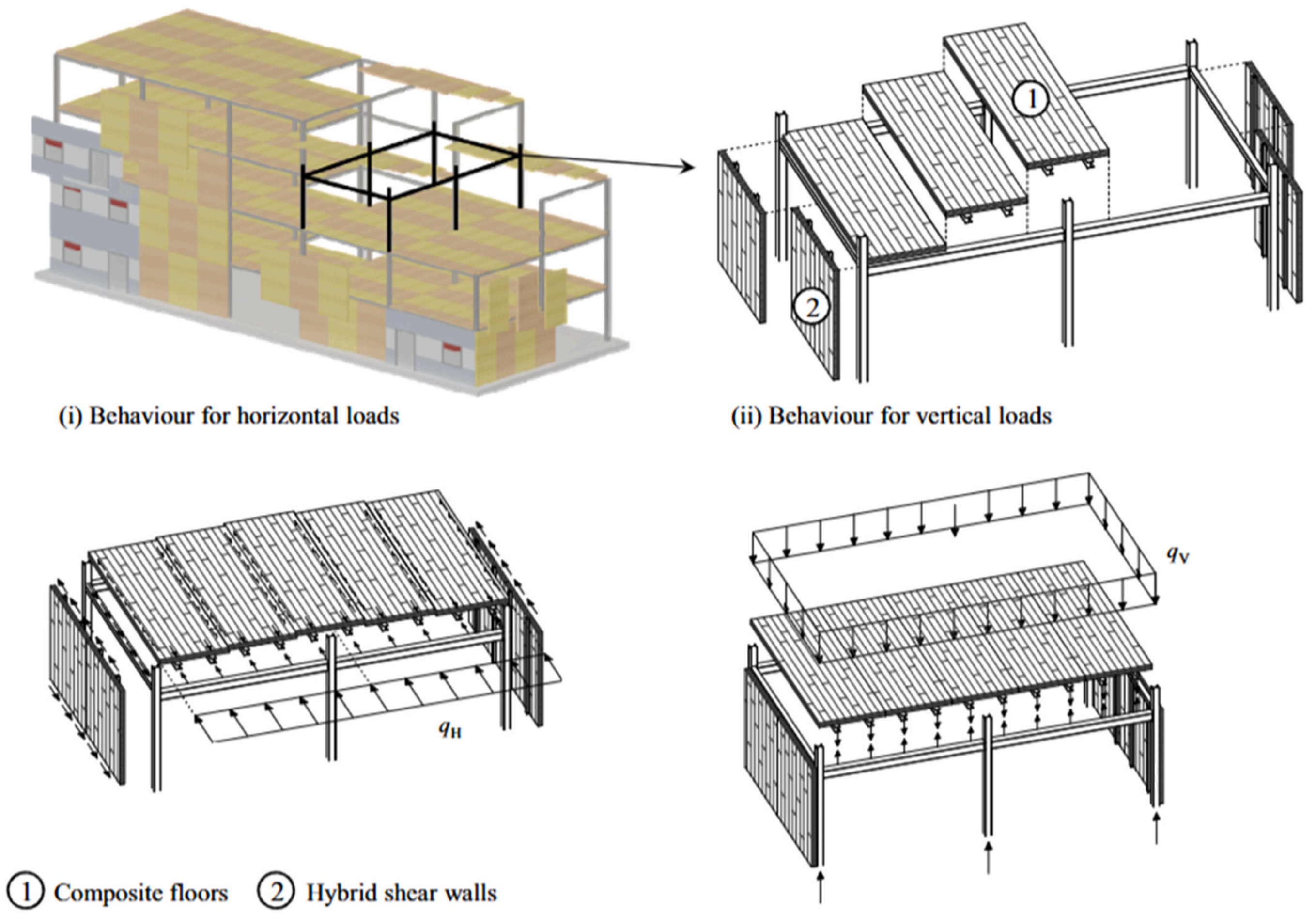


Fig. 14. Hybrid timber-steel system [190].

Appendix

Table A1
Durability classes of different timber species utilised in TMBs [191]

Durability class	Timber species	Expected lifespan (Above ground)	Expected lifespan (In-ground)	Applications in modular buildings	Typical hazard class	Treatment type	Remarks
Class 1 (Highly durable)	Spotted Gum	40 + years	25 + years	Structural framing, cladding, decking, exposed beams	H3 -H4	Often untreated/ preservative coated	Naturally durable, used externally without treatment
	Ironbark				H3 - H5	Untreated/light oil treatment	High resistance to rot/insects
	Tallowwood				H3	Often used untreated	Not suitable for in-ground use without treatment
Class 2 (Durable)	Blackbutt	15–40 years 15–25 years		Flooring, external walls, window frames	H2–H4	H3 -Light organic solvent preservatives/ Alkaline Copper Quaternary	Used for outdoor/in-ground after treatment
	Jarrah				H3–H4	Oil-based or copper preservatives	Durable/ additional advantages from treatment
Class 3 (Moderately durable)	Victorian Ash Tasmanian Oak	7–15 years	5–15 years	Interior walls, ceilings,	H1-H2 (Treated) H1–H2	Boron (interior), not recommended for H3 Boron	Not suitable for outdoor use untreated

(continued on next page)

Table A1 (*continued*)

Durability class	Timber species	Expected lifespan (Above ground)	Expected lifespan (In-ground)	Applications in modular buildings	Typical hazard class	Treatment type	Remarks
Class 4 (Non-durable, must be treated)	Radiata Pine Hoop Pine	< 7 years	< 5 years	Internal framework treated for external use	H1–H5 (with treatment) H1–H3 (with treatment)	H1- Boron; H3-Light organic solvent preservatives Alkaline Copper Quaternary; H4 Copper Chrome Arsenate or Copper Azole	Must be treated for any external use Used structurally when treated

H1: Low risk (indoor, dry areas) H2: Termite risk (dry areas) H3: Moderate decay & insect risk (above ground, outdoor) H4: Severe decay risk (in-ground contact) H5: Extreme decay & insect risk (in-ground, wet areas) H6: Marine exposure (saltwater)

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