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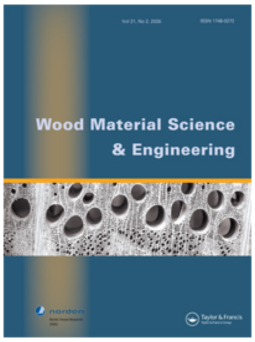

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REVIEW ARTICLE

Cross-laminated timber: a state-of-the-art review of moisture, fire, acoustics, and energy-related aspects

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ABSTRACT
The increasing use of cross-laminated timber (CLT) in construction has encouraged research on moisture, fire, acoustics, and energy performance. These areas are crucial for CLT buildings' functionality and durability and are typically addressed together during design. This study reviewed current knowledge, identifies gaps and explores synergies and conflicts among these areas, while briefly addressing the environmental impact of CLT buildings. Key findings include that airtightness is critical but often overlooked, making field and lab measurements essential. Junctions between CLT elements pose challenges in modeling sound and vibration transfer, and water absorption and removal, necessitating further research on junction robustness. More attention should be given to CLT's limited thermal mass and its impact on overheating risks, cooling demands, and fire development. Enhanced ventilation has a limited impact on off-gassing of volatile organic compounds. Covering CLT panels may be beneficial for energy efficiency, fire safety, and acoustics. Environmental impact assessments of buildings are complex and often neglect operational technical aspects. The aspects identified here are crucial for extending the service life of CLT buildings and enabling the reuse of CLT elements in circular economy value chains. Methodological innovations are needed to enhance evaluation flexibility across entire value chains.

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CLT; mass timber; building physics; hygrothermal performance; fire safety; building acoustics

1. Introduction

The construction sector produces a substantial part of global carbon dioxide emissions. In 2018, it accounted for 39% of energy and process-related carbon dioxide emissions, of which 11% came from building material manufacturing (Global Alliance for Buildings and Construction 2019). A considerable need exists to reduce carbon dioxide emissions from buildings. One way is to replace high-climate-impact construction materials with lower-climate-impact materials. Since trees bind carbon during their growth, the wood used as a construction material stores carbon until it is degraded or burned. Therefore, building with wood could contribute to carbon storage in the built environment and lower the carbon footprint of the construction sector (Churkina *et al*. 2020, Mishra *et al*. 2022). These environmental benefits in combination with the development of modern engineered wood products, have made mass timber, such as cross-laminated timber (CLT), a competitive alternative to reinforced concrete and steel structures for low- and high-rise buildings.

CLT was developed in Europe in the 1990s, building upon earlier inventions in composite lumber (Walsh and Watts 1923), and has since been introduced to the global market. In 2018, the global annual production exceeded 1 million m^3 (Teischinger *et al*. 2023), and in 2020, it was estimated to be 2.8 million m^3 distributed across Europe (43%), North America (43%), Oceania (6%), and Asia (3%) (UNECE/FAO 2022). CLT buildings can be found in the European countries, Canada, USA, South Korea and Singapore (Jeong 2024). CLT comprises an odd number of board layers (lamellas), each being orthogonal to its adjacent layers (Figure 1). This crosswise layering gives a panel with high in-plane dimensional stability and high in-plane and out-of-plane strength and stiffness (Brandner *et al*. 2016, Teischinger *et al*. 2023). Furthermore, the prefabrication enables rapid assembly at the building site where CLT panels can be used for several applications, such as large-sized walls, floor structures, balconies, lift shafts, stairwells, and roof elements (Swedish Wood 2019, Teischinger *et al*. 2023).

CLT comprises long finger-joining, kiln-dried, strength-graded boards to build the layers (Teischinger *et al*. 2023). The layers are glued and pressed together by hydraulic or vacuum compression (Swedish Wood 2019), followed by trimming and customization (e.g. openings for windows or doors) (Teischinger *et al*. 2023). Even though the boards generally are placed in orthogonally altering directions, two adjacent layers can have the same direction for some applications, giving double layers in the outer faces or the core of the panel (Karacabeyli and Douglas 2013). The final panel typically has a width of up to 3 m, a length of up to 18 m, and a thickness of 80–400 mm (Karacabeyli and Douglas 2013, Brandner *et al*. 2016, FPInnovations 2019, Swedish Wood 2019).

The wood species varies with geographical location. Norway spruce (*Picea abies*) is the most common wood species used in Europe (Brandner *et al*. 2016). In North America, various species are used, and the same panel can include several wood species

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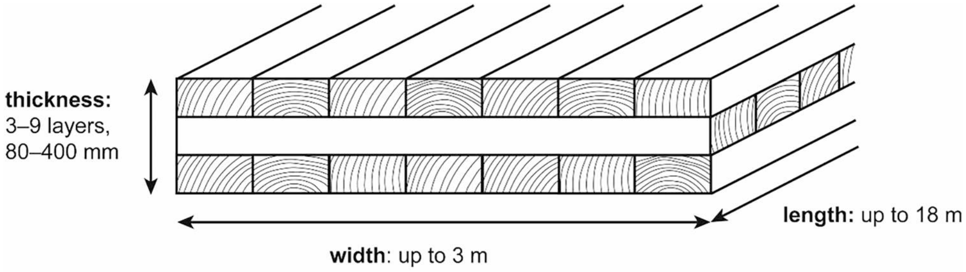

Figure 1. Schematic image of cross-laminated timber, including typical dimensions.

because strength grading is done for species groups rather than single wood species. The panels can consist of wood from the species groups spruce–pine–fir (includes several species of *Picea*, *Pinus* and *Abies*), Douglas fir–larch (*Pseudotsuga menziesii*, *Larix occidentalis*), hemlock–fir (*Tsuga heterophylla*, *Abies* sp.), or southern pine (*Pinus palustris*, *Pinus elliottii*, *Pinus echinata and Pinus taeda*) (ANSI/APA American National Standard 2018, FPInnovations 2019). In Australia, both imported CLT as well as CLT produced by local wood species, such as radiata pine (*Pinus radiata*), are used (Shirmohammadi *et al*. 2021). In other parts of the world, other local wood species might be used (Brandner *et al*. 2016).

Besides ensuring sufficient load-bearing capacity, building codes typically require other technical aspects, such as moisture safety, fire performance, sound environment, and energy performance as illustrated with the examples that follow. Wood is a hygroscopic material, and it is crucial to consider the moisture conditions within and around the wooden elements because wood-degrading fungi, which can reduce the load-bearing capacity, and mold fungi, which can affect the indoor environment, require elevated moisture levels. Moisture intrusion in CLT structures and the consequences thereof have been highlighted as a vital aspect to consider (Cappellazzi *et al*. 2020, Udele *et al*. 2021, Ayanleye *et al*. 2022). Regarding fire performance, studies have shown that when wood is adequately protected against fire, the contribution of the material to the fuel load is negligible (Li *et al*. 2015, Su *et al*. 2018). However, protection failure will result in an increased fuel load and the involvement of the CLT in a potential fire (Brandon and Östman 2016). Hence, ensuring sufficient fire protection is critical in the design of CLT structures. Furthermore, a sound-proofed home and working environment is imperative for comfort and health (World Health Organization 2018). However, obtaining sufficient sound insulation is challenging in CLT buildings (Lolli and Lien 2019) due to the inherent sound properties of CLT panels but also in regard how they perform as systems, including flanking transmission. For buildings based on wood, including CLT, or other light materials, a lack of sound insulation at low frequencies is common (Vardaxis *et al*. 2018, Di Bella and Mitrovic 2020, Ljunggren and Simmons 2022). Finally, ensuring sufficient energy performance of CLT buildings is crucial for both comfort and sustainability. While the comfort is considered through the operational energy demand for heating, cooling, and related power demands, the sustainability is reflected through the embodied energy, which is the total energy consumption during a building's lifecycle.

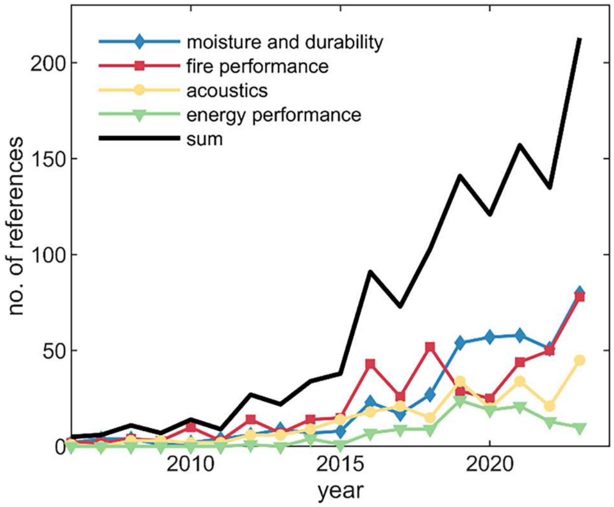

Figure 2. The number of publications over time: the figure includes the number of hits for the databases Scopus, Web of Science, and Google Scholar for "cross-laminated timber" or "cross laminated timber" or "CLT" in combinations with words related to the topics of this review (Figure 3).

Parallel to the increased interest in CLT, research in the field has increased. Figure 2 shows the number of publications over time within the technical aspects (moisture, fire, acoustics, and energy). These four areas are central to the functionality and durability of CLT buildings, and being inherently interconnected, they are typically addressed simultaneously during the building design process. However, review papers usually address these technical aspects separately. Substantial review papers on CLT for these individual topics have been published, not least regarding energy related to lifecycle analysis (LCA), where the amount of review papers is substantial (Duan *et al*. 2022, Shin *et al*. 2023). Since 2020, CLT review papers have also addressed moisture and durability (Cappellazzi *et al*. 2020, Udele *et al*. 2021, Ayanleye *et al*. 2022), fire (Ronquillo *et al*. 2021, Liu and Fischer 2022, 2024, Mitchell *et al*. 2022, Xu *et al*. 2022), and acoustics (Di Bella and Mitrovic 2020). Despite comprehensive reviews on these topics and their rapid increase (Figure 2), a review combining all four areas has not yet been published. The rapid increase in publications (Figure 2) motivates a review that includes several technical aspects. Such a study is essential for highlighting possible questions that require further research.

As a step forward, this paper addresses all four technical areas, providing a state-of-the-art review of the moisture, fire, acoustics, and energy aspects of CLT buildings, while briefly addressing their environmental impact. The results aim to identify individual trends and common questions deserving further

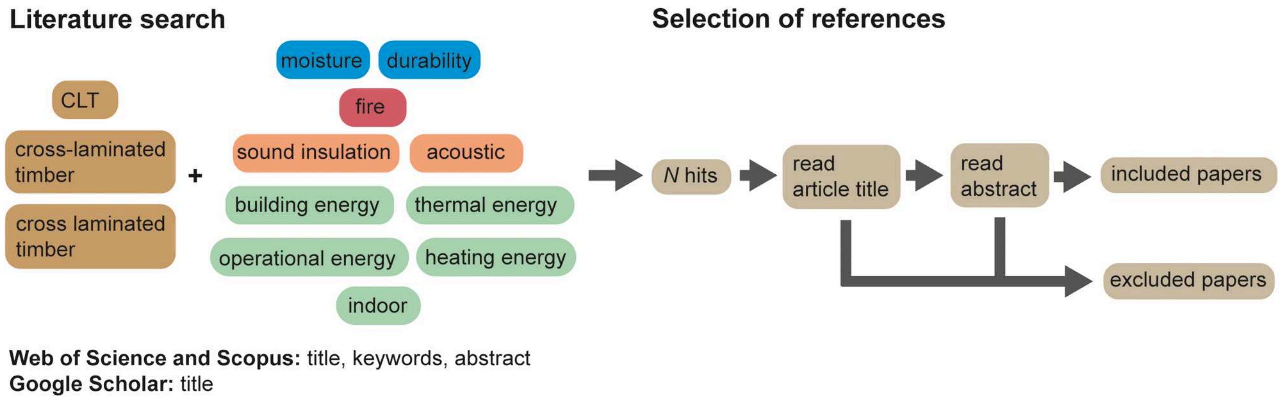

Figure 3. An overview of the methodology used for the literature search and the selection of publications to include.

research rather than going deeply into each area. The study also highlights knowledge gaps in these areas and potential conflicts regarding meeting various technical requirements. Other aspects, e.g. mechanical properties, load-bearing capacity, and seismic behavior, are outside the scope of this review. Furthermore, the review focuses more on general construction techniques and material properties rather than the specific requirements mandated by national building regulations.

2. Method

The databases *Scopus*, *Web of Science* and *Google Scholar* were used to find relevant publications according to the process shown in Figure 3. The keywords "CLT," "cross laminated timber," or "cross-laminated timber" were used in all searches, with specified keywords for different subject areas: moisture: "moisture" or "durability," fire: "fire," acoustics: "acoustic" or "sound insulation," and energy: "thermal energy," "operational energy," "heating energy," "indoor," or "building energy." For Scopus and Web of Science, the search was made for article title, abstract, and keywords (called topic in Web of Science), whereas for Google Scholar, the search was made for article title only. The search results were reviewed, and the relevant references were selected after reading the article title and abstract. Some listed references have a different origin than the described search procedure. It applies to standards, references found in already referenced publications, and articles of particular interest known to the authors. The references were to a high extent collected and reviewed within each domain independently. Parts that reserve considerations in at least two different domains were discussed between the authors and formed the basis for the conclusions. Although keywords related to "massive timber" were deliberately left out in the search process, the experience from this study is that relatively few search matches would have been added upon inclusion, and that the likelihood of the additional references significantly affecting the main results of the study is small.

3. Moisture

Wood is a hygroscopic material, meaning it can absorb water vapor from the air. Furthermore, wood takes up liquid water by capillary absorption, and due to its anisotropic structure, the capillary absorption rate is particularly high in the longitudinal direction. Several sources of moisture exist in CLT buildings, from the construction phase to when the building is in service (Shirmohammadi *et al*. 2021). For example, although CLT elements are dried after manufacturing, they can be remoistened if not sufficiently protected during transport and storage or be wetted by precipitation during construction (Wang *et al*. 2018, Shirmohammadi *et al*. 2021). Additionally, inadequate design regarding the thickness and position of insulation and impermeable layers can cause elevated humidity levels and/or condensation inside a wall structure when the building is in service (Kukk *et al*. 2022a, Strang 2023).

There are several reasons why the moisture content in a wood structure must be kept at sufficient levels. The moisture content of wood affects its mechanical properties, and changes in moisture content cause dimensional changes (swelling/shrinkage) and moisture-induced stresses and cracks (Kukk *et al*. 2017). Furthermore, elevated moisture levels in CLT elements and subsequent drying can cause delamination (Kalbe *et al*. 2022). In addition, wood-degrading fungi degrade wood if it is exposed to elevated moisture contents during extended periods (Schmidt 2006, Brischke and Alfredsen 2020), and elevated humidity levels can cause mold growth on surfaces (Viitanen *et al*. 2010, Johansson *et al*. 2012).

This part of the review (section 3. Moisture) focuses on research related to moisture and CLT, including hygrothermal performance, wetting and drying of CLT elements, and the durability and long-term performance of CLT structures. Although moisture also affects mechanical properties, it is not covered here since mechanical performance is outside the scope of this review paper.

3.1. Hygrothermal performance and modeling of CLT assemblies

The optimal design of a CLT wall assembly depends on the climate the building is exposed to (Strang *et al*. 2021). In colder climates, a wall is generally designed to prevent warm air from the interior side of the wall to be transported to the colder side and condensate. However, in warmer and more humid climates, the challenges are different, and the focus is rather to prevent moist air from being transported inwards and condensate (Strang *et al*. 2021). The design of a moisture-safe CLT wall assembly depends on which climate zone the building is placed in. Studies of the hygrothermal performance of CLT structures and the influence of different wall designs exist for various climates globally: Estonia (Kukk *et al*. 2022a), Australia (Strang 2023, Strang *et al*. 2023, 2021), Oregon, US (Kordziel *et al*. 2020), South Korea (Chang *et al*. 2020, Yoo *et al*. 2021, 2019), and Italy (Urso *et al*. 2022).

Kukk *et al*. (2022a) studied the impact of the vapor permeability of the insulation material (mineral wool, polyisocyanurate (PIR), and cellulose-based), the interior layer of the wall, and the façade orientation on the hygrothermal performance of CLT walls. They did measurements as well as simulations for five wall types in the Estonian climate. Strang *et al*. (2021) evaluated the performance of different wall assemblies in various Australian climates by hygrothermal simulations. They studied the influence of different insulation layer positions, different insulation materials (mineral wool, expanded polystyrene, and wood fiber), and different positions and vapor permeability properties of the weather-resistive barrier (preventing air convection and moisture ingress into the CLT structure). The hygrothermal simulations in Strang *et al*. (2021) were additionally validated by Strang *et al*. (2023) in laboratory and field measurements. The recommendations from Strang *et al*. (2021) for moisture-safe wall assemblies differed for the different climates in Australia, highlighting the importance of considering the local climate conditions. These studies showed that it is possible to design CLT buildings for Australian hot and humid climates if a climate-specific design of the wall assembly is applied and appropriate stormwater management practices are used. A flow chart for moisture-safe design and stormwater management strategies for moisture-safe CLT structures in hot–humid climates was compiled by Strang (2023).

Kordziel *et al*. (2020) evaluated the hygrothermal performance of CLT structures by laboratory measurements, field measurements, and modeling. They acquired data for North American wood species and implemented these in a one-dimensional transient hygrothermal model. By implementing an equation for determination of the liquid water transport coefficient for suction based on the liquid water absorption coefficient and the water content at free saturation, it was possible to simulate the wetting and drying of CLT elements exposed to water in a laboratory. The simulations correlated well with field measurements of a roof assembly in a CLT building. Their approach could be extended using hygrothermal data for other wood species and other CLT layer configurations. Modeling of liquid water uptake and drying in CLT elements have also been addressed by Brandstätter *et al*. (2023) and Buck *et al*. (2023).

Water vapor diffusion and liquid water transport data are needed in hygrothermal modeling. Chiniforush *et al*. (2019) measured the water vapor diffusivity of Norway spruce CLT as a function of temperature and moisture content in three directions. The adhesive layer was estimated to reduce the diffusion coefficient by 28% perpendicular to the plane of the CLT panel. Kordziel *et al*. (2020) measured water vapor diffusion coefficients at three relative humidity (RH) levels and liquid water absorption for Douglas fir and spruce–pine–fir CLT. Similar to Chiniforush *et al*. (2019), they found an influence of the adhesive layer on water vapor diffusion, except for the lowest RH level of 25%.

3.2. Drying after exposure to liquid water

Several studies have noted high moisture contents in CLT elements during construction (Liisma *et al*. 2019, Schmidt and Riggio 2019, Humar *et al*. 2020, Poblete *et al*. 2022); therefore, it is relevant to investigate the possibility of a CLT structure to dry out if it is exposed to rain during construction, which was studied by e.g. Kalbe *et al*. (2022) and Kukk *et al*. (2019, 2022a, 2022b). Kukk *et al*. (2022a, 2022b) studied the influence of the initial moisture content of CLT elements. They included CLT walls with different drying capacities by varying the insulation type and the water vapor permeability of the interior layer. Their results showed that in cases of high initial moisture contents, vapor-permeable materials were beneficial since the time for drying was reduced. This result aligns with Kukk *et al*. (2019), who studied the influence of the permeability of the interior layer on drying-out capacity. Kukk *et al*. (2022b) further evaluated the probability of mold growth using the model by Viitanen (1997). They found that if CLT elements were exposed to rain during construction, the vapor permeability of the different layers in the wall assembly influenced the probability of mold growth. As expected, a high initial moisture content in combination with coverage with vapor-tight layers created a high risk for mold growth. Furthermore, Kukk *et al*. (2021) found that an additional drawback of high initial moisture contents is that the airtightness of the CLT panel can be reduced because of crack formation during drying.

Kalbe *et al*. (2022) followed six CLT buildings in Estonia during construction. They identified end-grain surfaces as critical points, especially the bottom edges of wall panels where end-grain wetting was found in all studied buildings. Long drying times of wetted areas were seen in the studied buildings, further confirmed by laboratory experiments. Delamination and cracks were identified in the studied buildings in areas where wetting had occurred.

Schmidt *et al*. (2019) exposed CLT elements to cyclic wetting and drying periods. They found that water tended to accumulate between the two upper plies because of the small gaps between the boards in the upper layer. They also found that the joint between two CLT panels acted as a trap that allowed water to accumulate. Kordziel *et al*. (2020) simulated the wetting and drying of CLT flooring elements using two methods: one where samples were hanging in water and one where the upper surface of a CLT element was exposed to a pond of water. A higher water uptake was seen when the upper surface was exposed to water, presumably because the water could penetrate gaps to a greater extent as observed by Schmidt *et al*. (2019). Several studies highlight that the time required to dry out a wet CLT element or part of a CLT element is substantially longer than the time required to reach high moisture contents (Schmidt and Riggio 2019, Shirmohammadi and Faircloth 2023, Udele *et al*. 2023), especially if layers with low water vapor permeability hinder drying (McClung *et al*. 2014).

Several studies (Schmidt *et al*. 2019, Kalbe *et al*. 2022, Olsson *et al*. 2023) point to end-grain surfaces and joints as critical points. The possibility of preventing water absorption through end-grain surfaces has been investigated through on-site observations (Kalbe *et al*. 2022) as well as in laboratory experiments (Buck *et al*. 2023). Kalbe *et al*. (2022) noted from on-site observations that bitumen foil did not provide sufficient protection for end-grain surfaces. Buck *et al*. (2023) studied the performance of ten coatings for their use as end-grain sealants. X-ray computed tomography was used to evaluate moisture contents after water uptake, and the results showed that two of the coatings efficiently decreased the end-grain water absorption.

3.3. Durability and long-term performance

Wood-degrading fungi degrade wood if it is exposed to moisture contents above 25–26% for long periods of time (Schmidt 2006, Brischke and Alfredsen 2020). Such degradation reduces the load-bearing capacity because wood-degrading fungi degrades the cellulose, hemicellulose, and lignin of which the wood is composed. However, mold growth can occur also after short-term wetting and already at lower moisture levels (Wang *et al*. 2018). Mold growth is related to the RH at the surface rather than the bulk moisture content, and limit states around 75–80% RH at favorable temperatures are given in the literature (Viitanen *et al*. 2010, Johansson *et al*. 2012). Mold does not degrade the wood itself, but it is still problematic because it can cause indoor air quality problems and health issues for the inhabitants (Johansson *et al*. 2012, Wang *et al*. 2018).

The wood species used for CLT are primarily low-durability softwoods (durability class 4 in EN350-2) (SSI Swedish Standards Institute 1994, Shirmohammadi *et al*. 2021). Therefore, moisture management and protecting the wood from moisture are crucial when using CLT (Shirmohammadi *et al*. 2021). Moisture intrusion because of precipitation during construction, construction errors, or undetected leakages from pipes (Ott and Aondio 2020) can increase the moisture content to such an extent that it causes fungal growth (Austigard and Mattsson 2020, Ott and Aondio 2020). Austigard and Mattsson (2020) studied CLT buildings in Norway and found both mold growth and wood-degrading fungi. These damages were caused either by precipitation during construction or construction errors (Austigard and Mattsson 2020). Sinha *et al*. (2020) presented a laboratory method to assess the effects of wetting and subsequent fungal attack on CLT connections, including CLT-specific aspects such as large dimensions.

Furthermore, decay models developed for service life prediction of outdoor structures have been applied to CLT structures (Libralato *et al*. 2021). Libralato *et al*. (2021) applied two wood decay models (the model by Viitanen (1997) and the simplified logistic dose–response model by Isaksson *et al*. (2013)) on CLT walls of three designs and investigated the effect of including sorption hysteresis when predicting the service life of CLT structures. The modeling was performed at seven locations globally. They found that the estimated decay ratings and predicted service life were affected by the inclusion of sorption hysteresis at high moisture loads.

While long-term wetting is required for degradation by decay fungi, short-term wetting can induce mold growth (Wang *et al*. 2018). Olsson (2021) studied mold growth in four CLT buildings in Sweden during construction without weather protection and concluded that it was difficult to avoid microbial growth if no weather protection was used during construction. Out of 200 measurement points, approximately half of them had varying degrees of mold growth. Tengberg and Bolmsvik (2021) presented a case study for one building in Sweden where full weather protection was used during construction, and no mold growth was detected. In warm and humid climates, Strang (2023) suggests adding a weather-resistive barrier at the CLT factory along with end-grain protection, if full weather protection during construction is impossible. Furthermore, Time *et al*. (2023) adapted an extensive moisture monitoring program for a CLT building erected without weather protection. They found that the moisture content decreased and stabilized at reasonable levels during the first year but detected some moisture damages, such as visible mold growth where the vapor barrier was mounted early in the construction process, as well as some minor cracking. In laboratory experiments, Olsson *et al*. (2023) further studied mold growth in pieces of CLT panels and CLT connections under simulated Swedish/Nordic climate conditions to investigate which moisture loads induced mold growth. They found that one day of moisture load and preceding drying gave elevated moisture levels in joints where drying was hindered but did not induce mold growth. However, one week of moisture load and subsequent drying resulted in mold growth.

While mold growth (Olsson 2021, Olsson *et al*. 2023) and wood-degrading fungi (Austigard and Mattsson 2020) present challenges in colder climates, termites present an additional challenge in warmer climates (Udele *et al*. 2021). CLT buildings have been constructed in regions where termites are present, and protecting buildings from termite damage includes separating the timber structure from the soil (Shirmohammadi *et al*. 2023) or using physical barriers (Neupane *et al*. 2023). Shirmohammadi *et al*. (2023) used micro-X-ray computed tomography to visualize termite damage in CLT specimens and study the influence of the layered CLT structure on termite damage.

In challenging environments (such as warm and humid climate) and/or when building regulations require it, it might be necessary to apply some protection to prevent fungal degradation (Singh *et al*. 2019). Ayanleye *et al*. (2022), Wang *et al*. (2018), and Cappellazzi *et al*. (2020) reviewed the possibilities of and challenges associated with applying available wood protection techniques, such as preservative treatments and wood modification techniques, for CLT applications in regions with high moisture loads. Pressure treatment with preservatives is effective (Bagheri *et al*. 2022) but may be questioned due to health and environmental concerns associated with most wood preservatives (Wang *et al*. 2018, Cappellazzi *et al*. 2020). Chemical wood modifications (e.g. acetylation and furfurylation) are costly but substantially increase durability as well as dimensional stability and have advantages regarding environmental concerns (Wang *et al*. 2018, Cappellazzi *et al*. 2020, Ayanleye *et al*. 2022). However, changes in mechanical properties from chemical wood modification as well as influence on bonding strength need to be further investigated (Ayanleye *et al*. 2022). Thermal modification is another technique used to improve the durability of wood, especially for façades. However, the high temperature exposure results in reduced mechanical performance and alters surface properties, potentially affecting adhesive bonding (Ayanleye *et al*. 2022). Furthermore, Cappellazzi *et al*. (2020) highlight the need to identify the degree to which structural element protection is needed.

4. Fire

A major problem with using wood as a building material is its combustibility. Solid wood discolors and decomposes at elevated temperatures and chars from 200°C to 250°C, forming a char layer (Figure 4). Thermal decomposition at low temperatures does not necessarily signify combustion. However, smoldering is a distinct process characterized by slow, low-temperature, and flameless combustion (Ohlemiller 1985). As the temperature increases, cracks appear in the char, allowing combustible gases to escape from the underlying wood through pyrolysis. (Drysdale 2011). Charred wood surfaces can reach 800°C; however, the primary pyrolysis of wood begins above 225°C and ends below 500°C (Sweet 1993).

Cross-laminated timber undergoes the same type of thermal decomposition in a fire as normal timber even though the design of CLT introduces additional considerations for fire safety. This section focuses on four critical aspects of CLT and fire: the influence of CLT on compartment fire dynamics, charring and self-extinguishment, char fall-off and heat delamination, and fire protection.

These aspects have shaped the structure of this literature review and the development of inclusion and exclusion criteria. Notably, the review does not analyze CLT's structural response to fire.

4.1. The influence of CLT on compartment fire dynamics

The quantity and arrangement of the CLT panels, i.e. whether they are used for all walls, for two parallel walls, in the ceiling, etc., will affect the heat release rate (HRR). The arrangement (Medina Hevia 2014, Barber *et al*. 2016, Bøe *et al*. 2023a, 2023b) and the amount of timber influence the fire development regarding the HRR and temperature. Su *et al*. (2018) and Medina Hevia (2014) performed compartment fire tests with varying amounts of exposed CLT. In tests with CLT walls covered with gypsum boards, the CLT panels were never involved in the burning, and the fire self-extinguished after the temporary fuel load in the room was consumed (Medina Hevia 2014). When all the interior CLT surfaces were exposed, the fire burned vigorously after the fuel was consumed (Medina Hevia 2014). Generally, with fewer exposed surfaces, the fire is less intense, and it has been concluded (Medina Hevia 2014, Barber *et al*. 2016) that if only one wall was exposed to the fire performance, the fire intensity would be more like in a fully protected room, resulting in self-extinguishment after the room contents were consumed (Medina Hevia 2014, Barber *et al*. 2016). Other studies (Barber *et al*. 2016, Hadden *et al*. 2017) have proposed that limited areas of exposed timber can be accommodated within a fire-safe design. Although the studies mentioned show similar results, it should be noted that the findings depend on their respective experimental conditions.

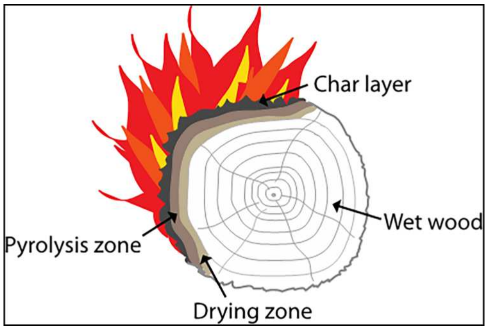

Figure 4. When solid wood burns, a char layer will form; underneath the char layer, combustible gases leave the wood through pyrolysis.

Large-scale experiments have shown that when an exposed CLT ceiling is ignited, the fire spreads rapidly, and the fire dynamics change (Kotsovinos *et al*. 2023, Bøe *et al*. 2023b). Another parameter is the presence of beams or other down stands that can increase the smoke layer thickness and heat fluxes, increasing the HRR (Nothard *et al*. 2022, Hopkin *et al*. 2023).

Mitchell *et al*. (2022) noted that the temperatures inside a timber compartment are greater than in a traditional noncombustible compartment because of the greater insulating capability of timber and its contribution to the fuel load. It is not the fuel load that directly leads to higher temperatures, but rather the rate at which energy is released, which is primarily determined by the area that is burning. However, other publications (Medina Hevia 2014, Li *et al*. 2016, Hadden *et al*. 2017, Hoehler *et al*. 2018, Su *et al*. 2018, Gorska *et al*. 2021) indicate that compartment temperatures are similar for compartments with and without exposed CLT. This result is probably because the room temperature will only increase to a specific level because the energy that can be released in the room will depend on oxygen availability, a function of the opening (e.g. doors or windows) size. A smaller opening provides a longer duration than a larger opening because the fire becomes restricted by the available ventilation (Kawagoe 1958, Heselden 1961).

The flammable gases emitted from the exposed CLT that cannot combust within the compartment will flow out and, if hot enough, ignite upon encountering oxygen. The energy released outside the compartment will depend on the situation. For example, Li *et al*. (2016) saw that external burning produced over 75% of the total heat release in a 16 m^2 compartment with exposed CLT. Even though the results depend on experimental factors such as compartment geometry, ventilation conditions, and extent of exposed CLT, the heat flux to the exterior façade will still be higher when more CLT is exposed (Gorska Putynska *et al*. 2017, Su *et al*. 2018), resulting in a higher probability for ignition of a combustible façade or fire spreading to overhead spaces.

4.2. Charring and self-extinguishment

The reduced cross-section model is a popular and simplified design concept for timber structures (Schmid *et al*. 2012).

proposing that the wood will gradually char and lose itSs load-bearing properties. A fictitious zero-strength layer is removed from the original cross-section, and the remaining cross-section is assumed to have normal strength and stiffness properties. The method is implemented in the current Eurocode 5 (CEN 2004) as the reduced cross-section method.

Once a char layer has formed, it will start functioning as an insulator for the unexposed wood, resulting in a slower charring rate (Li *et al*. 2016). The thermal properties of the timber will significantly impact the resulting charring rates (Dagenais 2016) and have been seen to decrease with increasing density, particularly for timber densities above 700 kg/m^3 (Liu and Fischer 2024).

By reviewing existing research, Liu and Fischer (2024) concluded that a linear charring rate could be used for CLT exposed to a standard fire if no char fall-off occurred. However, Mindeguia *et al*. (2021) noted that the charring behavior of CLT exposed to natural fires is more challenging to predict than when exposed to heat during standardized fire tests. Experiments have indicated that a slow-growing fire with a longer duration might have more severe effects on the structural capacity than a shorter, more intense fire (Wiesner *et al*. 2021). Bartlett *et al*. (2015a) saw that the charring rate guidance in the Eurocode was unconservative for alternative heating scenarios compared to a standard fire. It has also been found essential to include the decay phase when evaluating the performance of CLT for natural fires due to the continued charring and mechanical behavior of timber systems during cooling (Gernay *et al*. 2022, Wiesner *et al*. 2022, Vairo *et al*. 2023).

Other factors influencing the charring rate are the location of timber elements within a compartment, the ventilation conditions, and furnishing (temporary fuel load) (Mitchell *et al*. 2022). The orientation of the CLT layers, the applied loading, and the CLT panel thickness do not seem to affect the charring rate (Ronquillo *et al*. 2021).

When the fire consumes the temporary fuel load and if the heat flux toward the charred timber is below a specific threshold, self-extinguishment can occur (Gorska *et al*. 2017, Emberley *et al*. 2017a, Crielaard *et al*. 2019, Hopkin *et al*. 2022). Therefore, the burning declines and transits from flaming to smoldering combustion and, finally, from smoldering to self-extinguishment. CLT can self-extinguish due to the formation of a char layer before the temporary fuel load is fully consumed (Bøe *et al*. 2023b). A prerequisite is that the char and the lamellas stay in place. If debonding occurs or gaps form, reignition can occur (Emberley 2017).

Calderón (2022) performed bench-scale tests and saw that the heat flux threshold was 15 kW/m^2. However, in a large-scale test with an exposed wall and ceiling, self-extinction occurred when the heat flux was reduced below 45 kW/m^2 (Emberley *et al*. 2017b), and in another large-scale test, self-extinction occurred at 70–84 kW/m^2 (Bøe *et al*. 2023a). This extensive range depends on how the test is arranged, the type of wood species (Emberley *et al*. 2017a), and the thickness of the char layer formed (Bøe *et al*. 2023a). Hadden *et al*. (2017) observed self-extinguishment in compartment fire tests with two exposed timber surfaces. In another study, self-extinguishment was observed in one test, but when the test was repeated under identical conditions, it was not observed (Hadden *et al*. 2017). It is challenging to determine if self-extinguishment will occur because of factors such as the timber moisture content (Cuevas and Maluk 2023), the thermal penetration time of the timber layers (Hadden *et al*. 2017), the compartment size, and ventilation (Bøe *et al*. 2023b).

Smoldering combustion might persist following a flaming fire and endure for extended periods, potentially resulting in partial collapse. Furthermore, a smoldering fire might unexpectedly reignite into flames, even after initial extinguishment (Mitchell *et al*. 2023).

4.3. Char fall-off and heat delamination

Self-extinction will not occur if virgin timber is exposed during the fire; if that happens, more fuel will be available, increasing the intensity of the fire. Timber fall-off can occur due to char fall-off or heat delamination (Figure 5). Char fall-off occurs when charred wood detaches and heat delamination occurs near the bond line, resulting in failure within the adhesive or between the adhesive and timber (Čolic *et al*. 2021, Čolić 2021). Therefore, heat delamination occurs when lamella detaching occurs before complete charring (Ronquillo *et al*. 2021).

When charred layers fall-off, an increased charring rate can be observed (Frangi *et al*. 2009, Dagenais 2016), and when no fall-off occurs, the fire behavior is more like that of homogeneous timber panels (Dagenais 2016). Char layer fall-off is poorly understood, and it occurs seemingly randomly at and after the adhesive line (Čolic *et al*. 2021, Čolić 2021).

In some instances, heat delamination can cause a second flashover (Medina Hevia 2014, Craft *et al*. 2018, Su *et al*. 2018, Ronquillo *et al*. 2021, Mitchell *et al*. 2022, Bøe *et al*. 2023a), terminate the decay phase of the fire, and extend its duration (Johansson and Svenningsson 2018). Figure 6 illustrates different possible temperature scenarios resulting from heat delamination or char fall-off.

Several studies have investigated heat delamination and its relation to the type of adhesive used (Bartlett *et al*. 2015a, Brandon and Dagenais 2018, Barber *et al*. 2021, Čolic *et al*. 2021, Čolić 2021). The type of adhesive can significantly impact whether a CLT element delaminates or not (Johansson and Svenningsson 2018). Aguanno *et al*. (2013) state that using thermoset adhesives rather than thermoplastic adhesives will reduce the risk of delamination and increase the fire resistance times of CLT. A study by Johansson and Svenningsson (2018) showed that CLT with older polyurethane (PU)-based adhesives was more prone to delamination than other types; however, the difference between the two types of PU-based adhesives is not presented. Other studies have shown that some PU-based adhesives are more prone to delamination than, for example, melamine-formaldehyde (MF), melamine-urea formaldehyde (MUF), and phenol-resorcinol-formaldehyde (PRF)-based adhesives (Miyamoto *et al*. 2021, Ronquillo *et al*. 2021, Wiesner *et al*. 2022). However, there can be other adverse effects of the adhesives in a fire; for example, PRF can release toxic gases, resulting in severe health effects (Lee *et al*. 2020).

Dovetail massive wooden boards are timber elements without adhesive and metal fasteners. In a study (Ilgın *et al*.

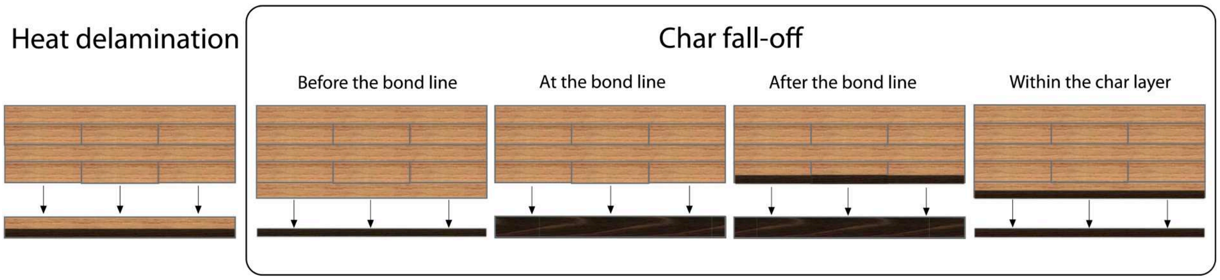

Figure 5. An illustration of heat delamination and char fall-off; the illustration is redrawn from Čolić (2021).

2023), the performance of such boards was compared to CLT with PU adhesives. The dovetail elements were charred like solid timber and had no char fall-off, whereas the more standard CLT had a higher charring rate due to char fall-off.

Heat delamination can occur at a wide range of bond-line temperatures. Čolić *et al*. (2021) saw that it occurred at 150 ± 80°C, and in another study, it varied from 78°C to 235°C, depending on the type of adhesive (Čolić 2021). Furthermore, preconditioned (dried) samples are more prone to delamination (Čolic *et al*. 2021, Čolić 2021). Increasing the thickness and number of layers in a panel can increase the fire resistance and reduce the frequency of heat delamination (Frangi *et al*. 2009, Aguanno *et al*. 2013, Crielaard *et al*. 2019, Wang *et al*. 2020). The charring front is not the sole indicator of the performance of fire-exposed CLT slabs because the global mechanical behavior of the slabs also depends on the decay of mechanical properties due to heating (Mindeguia *et al*. 2021). The effect of combinations of the number of layers and layer thickness on the fire performance of CLT is not trivial. Wiesner *et al*. (2022) saw that three-ply specimens (40–20–40 mm) failed earlier than five-ply specimens (20–20–20–20–20) because the orthogonal timber layers in the five-ply configuration act as sacrificial layers, not significantly contributing to the load-bearing capacity.

Different methods have been explored to investigate whether small- or medium-scale tests can yield similar results as standardized tests or even full-scale compartment fire tests (Aguanno *et al*. 2013, Brandon and Dagenais 2018, Barber *et al*. 2021, Čolić 2021, Gorska *et al*. 2021) because reduced-scale tests are less resource-demanding. The results vary, but studies show that reduced-scale tests can yield similar results as large-scale tests.

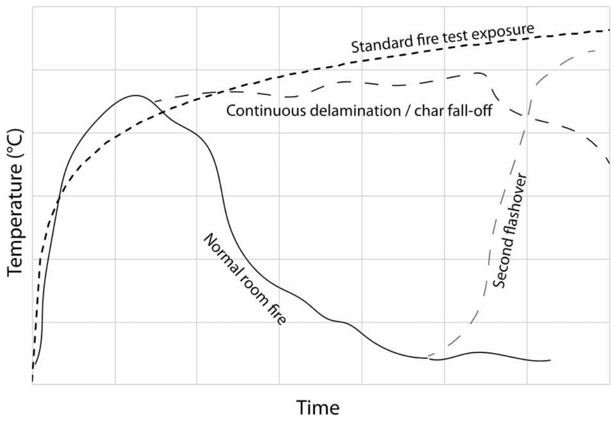

Figure 6. Different types of fire scenarios of cross-laminated timber compartments, based on information from various sources including Bøe *et al*. (2023a), Craft *et al*. (2018), Medina Hevia (2014) and Mitchell *et al*. (2022).

4.4. Fire protection

Encapsulating CLT can reduce or prevent flaming combustion. (Li *et al*. 2016, Hoehler *et al*. 2018, Su *et al*. 2018, Hopkin *et al*. 2022, Kotsovinos *et al*. 2023). Hopkin *et al*. (2022) saw in a set of large-scale experiments that compartments with exposed CLT ceilings had a peak HRR up to three times larger than that of the plasterboard-lined reference scenario. Kotsovinos *et al*. (2023) noted that the HRR was reduced by 38% when a CLT ceiling was partially protected with plasterboards. A single fire-rated gypsum board can delay CLT charring by 30 minutes (Yasir and Macilwraith 2023), and two layers of fire-rated gypsum board can delay charring by more than 40 minutes (Li *et al*. 2016). The thickness of the protective boards required for a specific performance criterion depends on the fire severity and the position of the CLT; less protection might be necessary on the floor than on the ceiling (Christensen *et al*. 2023). Furthermore, it cannot be relied on that charring or smoldering is avoided, even though protective claddings can significantly delay the onset of charring and improve the fire performance of CLT panels (Li *et al*. 2016, Hoehler *et al*. 2018, Su *et al*. 2018, Hopkin *et al*. 2022, Kotsovinos *et al*. 2023).

A CLT panel normally has the Euroclass rating D-s2,d0. However, wood products can also be treated through impregnation or surface treatment to reduce their ignitability and combustibility. It has also been seen that pre-charred surfaces can improve fire performance by reducing the HRR significantly (Lin *et al*. 2023). Questions have been raised about whether fire impregnation might affect the bondability of the CLT lamella. In a study (Mahnert and Bertelsen 2023), no influence of fire-retardant treatment on the bondability of spruce lamellae was seen; however, it was concluded that further investigations should be conducted.

The behavior of connections and joints between CLT panels and how they can be protected have also been studied (Dagenais 2015, Cato 2022). The connections and joints between CLT panels should be sealed to prevent smoke and flames from spreading to adjacent compartments (Ronquillo *et al*. 2021). Cato (2022) evaluated different types of joints using a fire furnace and concluded that all joints studied met the integrity and insulation criteria, even though smoke penetrated some joints. Other full-scale fire tests showed integrity is the predominant failure mode of CLT floors under load (Dagenais 2015).

Another measure to mitigate charring and control fire spreading is automatic water sprinklers (Ronquillo *et al*. 2021, Mitchell *et al*. 2022). A potential problem is that the water can damage timber components. However, properly design and installation of the sprinkler system should address this potential issue.

5. Acoustics

The research on acoustics related to CLT and CLT buildings has been extensive. One reason is the potentially insufficient sound insulation in CLT buildings, as demonstrated in various studies. Wahlstrøm *et al*. (2020) reported that acoustic regulations are a primary barrier to a more widespread use of CLT buildings. Ilgin and Karjalainen (2023) addressed the need for an intricate solution to achieve effective sound insulation in apartment buildings. In a comfort assessment study by Lolli and Lien (2019) involving two CLT buildings, the indoor noise level was one of the most common issues. This result relates to the work by Ljunggren and Simmons (2022), where impact sound insulation measured in wooden buildings, including those made of CLT, showed a poor correlation to how the residents in multifamily houses experience (in terms of annoyance) the sound environment in the home. Bare CLT panels must be combined with other elements, i.e. linings or toppings/ceilings, to meet normative acoustic requirements (Mahn and Müller-Trapet 2019, Di Bella and Mitrovic 2020, Santos *et al*. 2021).

Most published research within acoustics is found within the following four topics: measured sound insulation of bare CLT panels and panels with linings, fundamental vibroacoustic properties of CLT panels, modeling and predicting sound and vibration transmission through CLT structures, and modeling and quantifying vibrations transferred into adjacent construction parts in a building, i.e. flanking transmission.

5.1. Measured sound insulation

Measuring and reporting sound insulation performance is crucial for validation and understanding. Considering the measurements of bare panels performed in laboratory environments, Loriggiola *et al*. (2020) and Vardaxis *et al*. (2022) reported airborne sound insulation for panel thicknesses of 100–180 mm with $R_W = 32–35$ dB. Homb *et al*. (2017), Vardaxis *et al*. (2022), and Zeitler *et al*. (2014) have reported corresponding impact sound insulation for panel thicknesses of 102–245 mm with $L_{\mathrm{n,w}} = 80–87$ dB. Besides the sound insulation of bare panels, the referred studies also present results obtained with different linings and toppings (coverings) applied for walls and floors; the latter is also found in studies by Zhang *et al*. (2020) and Zhao *et al*. (2021). The additions include dry materials, such as mineral wool and gypsum boards, and wet, such as concrete screeds. A frequent method to increase the sound insulation further is mounting the linings elastically, such as floating floors and suspended ceilings, reducing the vibration energy transmission through the structure.

Sound insulation measurements have also been performed inside actual buildings. Beresford and Chen (2019) evaluated the effect of additions by comparing the sound insulation of CLT-based building systems to those made of timber joists and concrete. Bettarello *et al*. (2021), Hiramitsu *et al*. (2019), and Rodrigues *et al*. (2023) investigated the significance of using floating floors and suspended ceilings. Guigou Carter *et al*. (2023) investigated the acoustic performance of CLT floors combined with concrete screed for a three-story building, a typical solution to overcome inadequate sound insulation due to lack of mass.

The referred papers show significantly improved airborne and impact sound insulation using toppings/ceilings or linings compared to bare CLT panels. With a proper design, normative acoustic requirements for multifamily houses and other premises should be met. Airborne sound insulation, an R_{w} greater than 60 dB (Ljunggren 2022) (estimates from reported $D_{\mathrm{n}T,\mathrm{w}}$), (Rodrigues *et al*. 2023), and impact sound level, $L_{\mathrm{n,w}}$ well below 50 dB (Beresford and Chen 2019, Ljunggren and Simmons 2022), have been reported.

5.2. Fundamental vibroacoustic properties

Insight into the basic mechanical properties of CLT panels is essential for understanding and predicting the sound insulation of CLT-based building structures. Caniato *et al*. (2022) performed a comprehensive study where a 5-layer 200-mm CLT floor was fully characterized as excited with an acoustic source impact machine, rubber ball, and airborne noise. Besides sound insulation data, velocity maps were presented at 50–630 Hz in third-octave bands for each source and elasticity moduli at 20–5000 Hz. The data could be usable in analytical modeling and simulations. Santoni *et al*. (2017) focused on elasticity and stiffness. By experimentally obtaining flexural wave velocities of a CLT plate, they determined the elastic and shear moduli for different plate directions and propagation angles. Hu *et al*. (2020) contributed to the area with a paper about the fundamental parameters regarding airborne and impact noise control in CLT buildings, where the panels included various linings. A four-room mock-up was used to study the effect of the dynamic stiffness of added sound-insulating materials used in floor assemblies, which was significant.

5.3. Predicting sound insulation

The literature on modeling and predicting the sound insulation of CLT panels and CLT-based building systems is comprehensive. The mass m' law, according to which the frequency (f)-dependent sound reduction, $R = 20\log(m'f) - 47$, which to some success applies to solid isotropic structures, is unsuitable for CLT plates due to its orthogonal properties (Granzotto *et al*. 2022). Despite that, the most simplified model found in the review paper by Di Bella and Mitrovic (2020), where the following approximate expressions for weighted airborne and impact sound insulation are proposed, is a function of the bare panel's mass per unit area (m') only. The equations are valid within 35–130 kg/m^3:

$$R_w = 20.3\log(m') \quad (1)$$

$$L_{n,w} = 128–22\log(m') \quad (2)$$

Ljunggren (2019) presented an analytical model for bare panels, adjusted for some empirical findings. The model considers mass, Young's modulus, Poisson's ratio, and the loss factor to calculate the sound reduction in third-octave bands. Good accuracy for the weighted sound reduction index was reported for panel thicknesses of 65–320 mm with $R_w = 31$–45 dB. This simplified model relies primarily on the stiffness in the panel's main direction, whereas other models usually treat the panel as being orthotropic, i.e. with different stiffnesses for the two perpendicular in-plane directions (Krajči *et al*. 2012).

A significant consideration is whether the panel should be modeled as a homogenous structure or treat the layers separately. The latter can serve for higher accuracy, whereas the former can save computing power and time. Yang *et al*. (2021) studied these phenomena and proposed that modeling with individual layers is preferred to a homogenous panel to predict the vibroacoustic behavior correctly. A crucial moment in modeling the homogenous structure is determining an adequate equivalent elastic module representing the panel (Churchill *et al*. 2023).

The wave modes for the two modeling approaches (homogenous or layer by layer) exhibit different characteristics, especially at higher frequencies. Winter *et al*. (2017) concluded that CLT plates have lower stiffness perpendicular to the primary plane, which might introduce thickness resonances within the frequency range used for building acoustic measurements, i.e. up to 5 kHz. Thickness resonances are not considered by a plate modeled as one layer, but with an adequate number of layers of solid elements, the physical behavior becomes more accurate. A related study by Van Damme *et al*. (2015) claimed that the frequency dependence of the elastic parameters limits a fully homogenized model for CLT. However, Vallely and Schoenwald (2023) have proposed a homogenization method based on first-order shear deformation theory that obtains frequency-independent elastic material properties. The method was demonstrated to be vibroacoustically equivalent to layered models.

With a proper model established for a bare panel, the transfer matrix method (TMM) can include linings and toppings to calculate the sound insulation of complete wall or floor elements. The method is based on the following equation:

$$V(s_1) = [T]V(s_2) \tag{3}$$

The vector $V(s_1)$ defines the acoustic field on the source side, $V(s_2)$ contains descriptors related to each additional layer and variables defining the acoustic field on the receiving side, and $[T]$ contains data for the sound transmission through the layers (Santoni *et al*. 2019). Santoni *et al*. (2019), Santoni and Fausti (2021) and Caniato *et al*. (2019) provide examples of practical results using TMM.

Statistical energy analysis (SEA) and finite element (FE) modeling are two methods for calculations within the building acoustic field. A basic requirement for SEA is that the energy field, i.e. the vibration of the CLT panel, is diffuse (Kouyoumji *et al*. 2009). This diffusion is typically met for higher frequencies but not lower ones, as a transition from modal to diffuse behavior occurs at approximately 500 Hz (Morandi *et al*. 2020), leaving doubts about the accuracy. FE modeling has been a common method, although frequently restricted to lower frequencies due to the increased demand for the computational power for higher frequencies. With today's computer capacity, the problem is being overcome, and FE modeling is an option, even for the mid- and high-frequency ranges. Various aspects of the FE modeling of CLT panels have been reported by Yang *et al*. (2021) (the wave and FE models), Zhou *et al*. (2019), Morandi *et al*. (2022), Qian *et al*. (2019), Decraene *et al*. (2022) (hybrid, FE and SEA), Vallely and Schoenwald (2021) and Furtmüller and (2023).

5.4. ISO 12354 and flanking transmission

A significant difference between sound insulation measurements of single building elements in a laboratory compared to a complete building in the field is the flanking transmission between rooms in the latter case. The ISO standard 12354 parts 1 and 2 (2017) provide guidelines for calculating airborne and impact sound insulation of CLT and lightweight constructions between rooms inside a building, knowing the performance of the elements. Although focusing on flanking transmission, the sound insulation calculation includes formulas for improving linings/floor toppings. The method identifies the direct path and different flanking paths between rooms (Figure 7). The paths are treated independently, and the energy transmission through each path is summed up as a total sound transmission.

A crucial part of predicting flanking transmission is estimating the vibration index K_{ij} (Di Nocco *et al*. 2020), i.e. the vibrational power transmission over junctions. IOS 12354-1 provides two cases exclusively for CLT elements: T- and X-junctions. Figure 8 shows formulas for the transmission paths to estimate the respective vibration reduction index K_{ij}. The estimations have some shortcomings: the mass ratio of the two perpendicular plates is restricted to 0.5–2; different fasteners are not considered, and the effect of flexible interlayers is overlooked (for the CLT case). A flexible interlayer is a common technical solution affecting K_{ij} (Timpte *et al*. 2017).

Before launching the present ISO 12354-1 in 2017, Timpte *et al*. (2017) compiled measurements of a T-junction from six European universities/research institutes. On average, the result correlated well with the proposed procedure, but the spread in results was quite large. Di Nocco *et al*. (2020) studied three CLT constructions and compared the estimated vibration reduction indexes according to ISO 12354-1 and measurements. The estimated K_{ij} values differed considerably from the measured ones with different sound insulation. However, when the measured K_{ij} values were used as input to calculate the sound insulation, the results correlated better with the measured data.

Morandi *et al*. (2018) and Di Bella *et al*. (2019) performed laboratory measurements of T- and X-junctions (also L-junctions) of bare CLT plates to compare with the estimations according to ISO. The measured vibration reduction indexes differed significantly in the low- and high-frequency range compared to the ISO estimations. For the T-junction, the estimated K_{ij} values were substantially lower at frequencies below ≈500 Hz but with higher K_{ij} values above ≈1000 Hz (Morandi *et al*. 2018). Averaged over 200–1250 Hz, the measured K_{13}, K_{12},

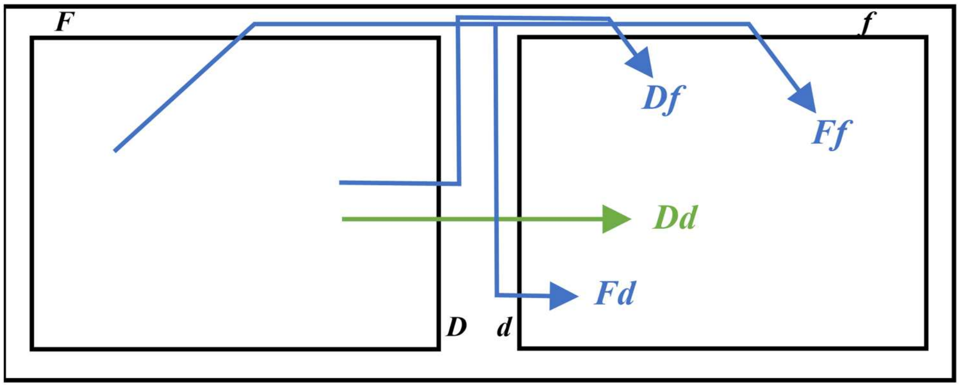

Figure 7. The sound transmission paths between rooms according to ISO 12354-1 (2017a, 2017b) regarding airborne sound insulation; the direct path (Dd) and flanking paths (Df, Fd, and Ff).

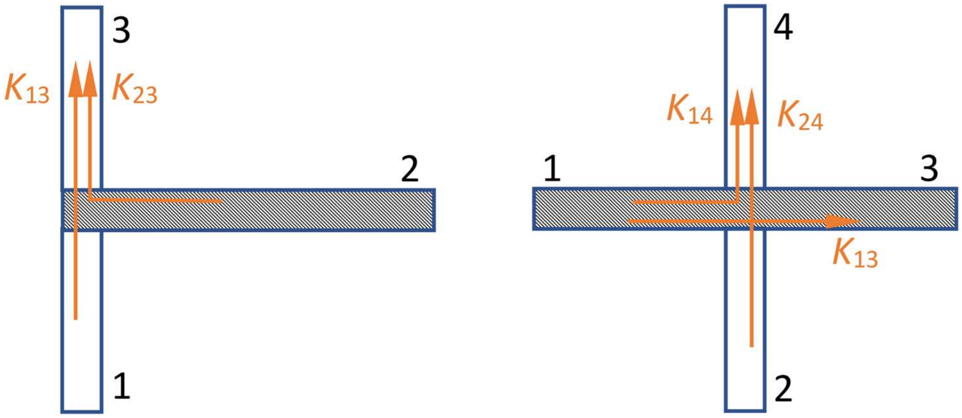

Figure 8. Transmission paths for estimating the vibration reduction index for a cross-laminated timber-based T-junction (left) and X-junction (right).

and K_{32} were estimated to be 5.5, 4.3, and 6.4 dB lower, respectively, than the corresponding estimation (Morandi *et al*. 2018). Further, it was claimed that the energy transmitted through a junction is strongly related to the metallic connectors, i.e. the angle brackets used for fastening.

The reported uncertainties align with Simmons' study (2021), which shows that the uncertainty of the ISO's calculation method is larger when applied to CLT constructions than concrete constructions and that a more significant safety margin is needed for CLT buildings.

Fasteners and flexible interlayers are two crucial details affecting the flanking transmission in the complete building. Their effects have been studied practically and experimentally by systematic measurements performed in the field or dedicated mock-ups. A few such examples in recent years are Kraler and Brugnara (2022) and Toftemo and Løvstad (2023), reporting measurement results addressing the importance of using proper devices to join CLT elements.

6. Energy

The energy performance of CLT buildings is assessed through operational and embodied energy metrics. Operational energy focuses on the annual heating and cooling demands, whereas embodied energy encompasses a building's total energy consumption throughout its lifecycle. Since CLT buildings can readily meet diverse energy standards in heating-dominated regions, scientific literature predominantly covering their operational energy is scarce (Cabral and Blanchet 2021). Conversely, numerous publications investigate the embodied energy of buildings due to inconsistent metrics and methodologies, particularly with newer technologies, such as CLT. This section summarizes the literature on CLT buildings' operational and embodied energy performance.

6.1. Operational energy of CLT buildings

While the interest in CLT buildings is growing, CLT technology is new for many markets (Espinoza *et al*. 2016, Cabral and Blanchet 2021, Leskovar and Premrov 2021, Iuorio *et al*. 2023). Traditional construction materials, such as concrete and steel, have long dominated the industry with proven energy-efficient technologies. Research on CLT buildings frequently compares their operational energy efficiency to traditional buildings, considering local design norms, climate, and operational practices. These comparisons provide valuable insights into the energy performance of CLT buildings in specific contexts.

The comparisons are frequently performed using numerical simulations of the CLT envelope or entire CLT building, but the scope and assumptions for comparisons differ. To establish a baseline, it is common to align the thermal transmittance (*U*-value) of an insulated CLT envelope (exterior walls and floors) with a reference construction to ensure the average heat losses are the same (Kosny *et al.* 2014, Shin *et al.* 2023). However, that is not always the case, especially when the thermal resistance of CLT is greater than that of traditional materials.

A continuous layer of thermal insulation on the outer surface of CLT walls is the primary source of thermal resistance for well-insulated walls (Equation 4; Table 1). For less insulated walls, the CLT panel constitutes an essential part of the overall thermal resistance of the wall,

$$\frac{R_{\mathrm{CLT}}}{R_{\mathrm{CLT}}+R_{\mathrm{ins}}} \ll 1 \tag{4}$$

where R_{CLT} and R_{ins} are the resistances for the CLT panel and all insulation, respectively (m^2 K/W). The resistances are calculated as $R_{\mathrm{CLT}} = d_{\mathrm{CLT}}/\lambda_{\mathrm{CLT}}$, $R_{\mathrm{ins}} = d_{\mathrm{ins}}/\lambda_{\mathrm{ins}}$, where d[m] and λ[W/mK] denote the thickness and thermal conductivity, respectively.

Experiments by Ye *et al.* (2023) confirm similar findings for fir CLT panels of various thicknesses (45 mm, 75 mm, and 105 mm) and configurations (single or double panels), where the thermal transmittance was derived in a controlled climate and under stationary heat flux conditions (guarded hot box). Adding external insulation reduces thermal bridging compared to timber frame walls, see Figure 9. This reduction leads to a minimal 7% discrepancy between the measured and calculated U-values for insulated CLT panels, whereas timber frame walls show a larger discrepancy of approximately 32% (Švajlenka *et al.* 2020). Additionally, the type of insulation material used with CLT panels affects energy demands(Cabral and Blanchet 2021). For specific thermal bridge transmittance coefficients in CLT envelopes, see (Chang *et al.* 2019).

The thermal conductivity of a dry CLT panel ranges from 0.10 to 0.13 W/mK (Chang *et al.* 2019, Cabral and Blanchet 2021, Shan *et al.* 2022), with practical design values between 0.12 and 0.13 W/mK (Swedish wood 2017). This value is significantly lower than concrete (1–2 W/mK) and brick (approximately 1 W/mK), distinguishing CLT as an insulator. Therefore, studies comparing buildings with CLT envelopes to those with other envelopes of similar thickness (Khavari *et al.* 2016, Liu *et al.* 2016, Dong *et al.* 2019, Setter *et al.* 2019, Cabral and Blanchet 2021) or different designs affecting thermal transmittance (Guo *et al.* 2017, 2020b) reveal straightforwardly the differences in their operational energy. Despite methodological concerns, such studies focus on regions where existing buildings have poor energy performance. They examine energy-efficient CLT buildings to showcase potential energy and carbon savings, guiding national regulatory bodies in setting future strategies.

As a load-bearing component, the CLT panel's thickness is 60–300 mm (Swedish wood 2017), adding to the overall wall thickness. For example, a 391-mm thick CLT-based wall, with 142 mm taken by the CLT panel, requires approximately four

Table 1. The share of thermal resistance of a CLT panel alone, R_{CLT}, compared to the total thermal resistance of an insulated CLT panel, $R_{\mathrm{CLT}} + R_{\mathrm{Ins}}$, expressed as the ratio $R_{\mathrm{CLT}}/(R_{\mathrm{CLT}} + R_{\mathrm{Ins}})$ in percentage. For well-insulated panels (dark-shaded fields), the share is less than 10%. For less-insulated panels or thick panels (light-shaded fields), the share is greater than 30%. Other combinations are indicated as moderately insulated. In the example, the thermal conductivity of cross-laminated timber and insulation is 0.12 and 0.035 W/mK, respectively. The thicknesses of the CLT panel and the insulation are generic for illustrative purposes.

$\frac{R_{CLT}}{R_{CLT}+R_{Ins}}\cdot 100\%$		**CLT thickness [mm]**					
		50	**100**	**150**	**200**	**250**	**300**
Insulation thickness [mm]	**50**	**23**	**37**	**47**	**54**	**59**	**64**
	100	**15**	**23**	**30**	**37**	**42**	**47**
	150	**10**	**16**	**23**	**28**	**33**	**37**
	200	**7**	**13**	**18**	**23**	**27**	**30**
	250	**6**	**10**	**15**	**19**	**23**	**26**
	300	**5**	**9**	**13**	**16**	**20**	**23**

🟫*well-insulated panels* 🟨 *moderately insulated panels* ⬜ *less-insulated panels*

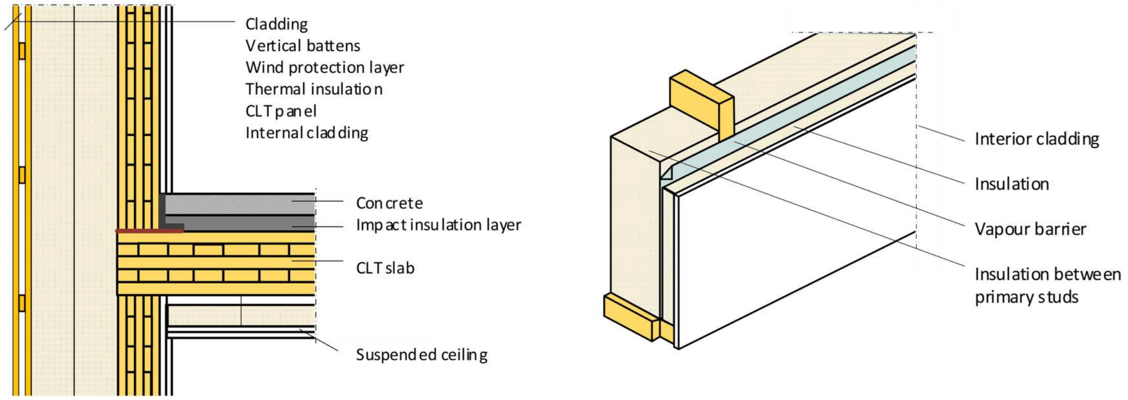

Figure 9. To the left: the principal sketch of the cross-laminated timber wall insulated on an exterior based on (Swedish wood 2017). To the right: the principal sketch of the timber-framed system based on (Swedish wood n.d.).

times more wood than North American timber frame walls with a similar thermal resistance ($R = 6.3$ m^2 K/W) (Kosny *et al*. 2014). However, the mass of the CLT panel enhances the thermal inertia of the building, which becomes evident when assessing the operational energy of CLT and timber-framed systems.

The opposite is valid when a reference building has a thermally heavier construction, e.g. concrete. The specific heat capacity of CLT is approximately 1600 J/kgK (Swedish wood 2017), nearly double that of concrete (880 J/kgK). Nevertheless, the volumetric heat capacity of CLT (0.56–0.8 J/m3, for typical densities of wood species ranging from 350 to 500 kg/m3 according to Swedish wood (2017)) is still lower than that of concrete (1.76–2.11 J/m3, assuming a density range 2000–2400 kg/m3), indicating that concrete exhibits larger thermal inertia. Jensen *et al*. (2020) measured the thermal inertia of a CLT panel for reduced overheating hours and deferred investments in air-conditioning systems, which is approximately half that of a comparable reinforced concrete (RC). Consequently, in heating-dominated regions, CLT buildings typically have lower heating energy demands but higher cooling demands and overheating risks than thermally heavier RC buildings (Hameury 2006, Dong *et al*. 2019, Kang *et al*. 2024). This risk increases with building height in dense urban areas (Guo *et al*. 2020a) as the shading from nearby objects decreases with the building height, resulting in longer overheating hours. Passive strategies, such as solar shading and night cooling, are crucial for preventing overheating in CLT buildings. Utilizing phase change materials is one approach to enhancing the thermal inertia (Kang *et al*. 2025).

In simulations, it is commonly assumed that CLT buildings are airtight or have superior airtightness compared to their counterparts, frequently linked to using solid CLT panels in construction (Guo *et al*. 2017, Setter *et al*. 2019, Cho *et al*. 2019a, Strang 2023). Until recently, airtightness measurements for existing CLT buildings were lacking, although data on individual CLT components' airtightness are available. Skogstad *et al*. (2011) found that airtightness depends on construction and moisture content, with edge-glued panels exhibiting enhanced airtightness (Figure 10). However, as CLT panels dry from delivery to operational conditions, their airtightness deteriorates (Skogstad *et al*. 2011, Kukk *et al*. 2021). Due to design tolerances, air leakage paths are expected at joints between CLT elements (Martin *et al*. 2019). These findings, supported by recent field measurements in a detached CTL-house in Korea (Kang *et al*. 2025), confirm that achieving airtightness in CLT buildings is not automatic; it demands careful planning, precise execution, and rigorous testing throughout the construction process. While infiltration and exfiltration through air leakages affect heat losses similarly, they have opposite effects on moisture durability in insulated CLT walls. The highest risk of moisture damage occurs during exfiltration of humid indoor air, whereas the lowest risk occurs during infiltration of colder outdoor air. Methods for achieving effective airtightness in CLT buildings are outlined in (Herms 2020).

In seismic regions, hybrid CLT buildings with RC floors and CLT walls ensure structural stability during earthquakes. This structural focus, highlighted by (Bruno *et al*. 2019), takes precedence over energy considerations. Retrofitting RC buildings with insulated CLT panels faces similar challenges (Contiguglia *et al*. 2021). Achieving the desired energy performance involves optimizing layouts, windows, shading, and heating, ventilation, and air-conditioning systems within structural constraints. Choices in hybrid CLT buildings affect energy and environmental performance. Following insights from Jensen *et al*. (2020), prioritizing dynamic thermal characteristics over steady thermal transmittance, as proposed by Bruno *et al*.

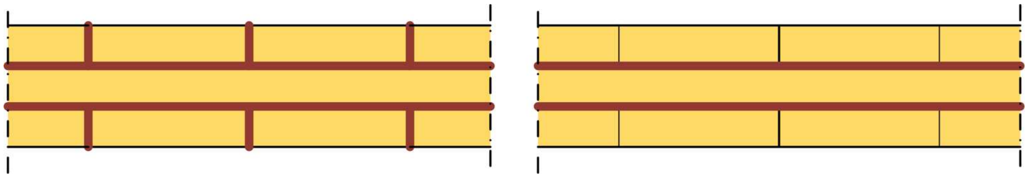

Figure 10. Cross-laminated timber panels with (left) and without (right) edge-glued boards.

(2019), aims to minimize cooling loads. Widening thermostat dead bands optimizes thermal mass use, whereas nighttime ventilation reduces cooling needs by releasing built-up heat.

Most CLT buildings have been constructed in regions with dominant heating needs. However, due to CLT's sustainability benefits, they are now being built in warm, humid climates where cooling needs are predominant (Cho *et al*. 2019a, 2019b, Strang 2023). Significant disparities in the thermal and moisture demands during cooling periods and variations in energy standards across countries mean a successful CLT design in one region must be reconfigured to suit different climatic loads (Strang 2023). Well-exposed CLT elements in indoor environment can stabilize the indoor RH, positively impacting operational energy use (Lü *et al*. 2020, Salonvaara *et al*. 2022). This feature deserves more attention when analyzing the benefits and differences between CLT and other building types, within both the same climate region and across different climate regions.

Another critical aspect related to energy use that requires more attention is the emissions from CLT elements. Emissions of volatile organic compounds (VOCs) from new materials are typically most intense during the first year of building use, necessitating increased ventilation and directly impacting the building's overall energy consumption (Domhagen *et al*. 2023). Given the direct exposure of CLT elements in indoor environments, the choice of adhesives and bonding methods significantly influences the release of VOCs, as demonstrated in a study by Yauk *et al*. (2020). Among the tested CLT samples, those bonded with soy-based adhesive, PU adhesive, or using dowels without adhesive exhibited low formaldehyde emissions indoors. However, an eight-month-old sample bonded with MF adhesive exceeded the permissible formaldehyde levels in the USA. Elevated levels of VOCs have also been measured in a CLT-house (Kang *et al*. 2025), underscoring the need for further research on this issue.

6.2. Embodied energy of CLT buildings

Embodied energy has been a crucial metric in LCA. When examining the embodied energy for CLT buildings, a prevalent method is to compare it with conventional alternatives, such as RC structures, similar to the approach used in analyzing operational energy. However, methodological challenges related to LCA, including temporal differences in stages considered, spatial differences in material boundaries, physical disparities in data coefficients and performance metrics (Arvidsson and Svanström 2016, Chen *et al*. 2020) vary widely, contributing to abundant research in this area. Hence, only selected studies and findings will be presented rather than attempting an all-encompassing overview.

The prior statement about using RC buildings as a reference is backed by an analysis of 62 peer-reviewed articles on LCAs, most focusing on CLT buildings, conducted by Duan *et al*. (2022). Furthermore, the most assessed category indicators across these articles were global warming potential (GWP) and embodied energy. Their findings revealed that, on average, the embodied energy in mass timber buildings, including CLT ones, was 23% higher than that of their RC counterparts. Conversely, the average embodied greenhouse gas (GHG) emissions of RC buildings were approximately 43% higher than those of CLT alternatives.

Using alternative indicators yields different outcomes. Mass timber buildings, including CLT ones, show lower GWP and consume less lifecycle primary energy than RC and steel structures. For instance, Tettey *et al*. (2019) found that CLT and wood frame buildings had 20%–37% and 9%–17% lower total lifecycle primary energy consumption, respectively, than concrete buildings when using combined heat and power plants for heating. These results apply to a typical multi-residential building in Sweden. Duan *et al*. (2022) proposed that in China's cold regions, RC office buildings might have lower primary energy demands and GHG emissions during operation than thermally equivalent CLT buildings due to RC's larger thermal mass. However, over a 50-year lifecycle, CLT buildings show lower GHG emissions during production and construction, resulting in a reduced lifecycle energy footprint. Similar conclusions are reported by Shin *et al*. (2023). However, in regions where CLT panels are not readily available and cooling demand dominates over the heating demand, CLT-based building design may result in increased GHG emissions compared to RC buildings (Kang *et al*. 2024).

Häfliger *et al*. (2017) and Anand and Amor (2017) observed that while traditional building LCAs focused on operational energy and emissions, low-energy buildings have shifted the focus to embodied energy and emissions. However, this shift is not universal. Depending on the case, operational energy may still be the main environmental impact factor, even in energy-efficient buildings (Felicioni *et al*. 2023). When optimized together, embodied and operational energies can be equal contributors (Pal *et al*. 2017). The results also depend on how RC and CLT buildings are defined—whether both the structural system and building envelopes are made from these materials (Pal *et al*. 2017) or only the above-grade structural systems (Felicioni *et al*. 2023), but also on energy sources that embodied and operational energy calculations are based on.

Another detail that can substantially influence embodied energy results involves below-grade building parts—basements and foundations, typically made of concrete or steel, although CLT solutions for small houses are emerging (Daneshvar *et al*. 2022). These parts are usually excluded from LCA calculations (Helal *et al*. 2023) because they are consistent across compared building alternatives, merely offsetting the results. Interestingly, they are often included in analyses of buildings in regions with high moisture (Kang *et al*. 2024) and seismic risks (Nakano *et al*. 2020, Valluzzi *et al*. 2021, Dragonetti *et al*. 2025, Junda and Málaga-Chuquitaype 2025). To avoid biased conclusions regarding environmental benefits of CLT-buildings, the contribution of below-grade systems should be declared in all analysis.

To manage the complexity of LCA calculations, it is common to exclude detailed technical design aspects of CLT buildings and their alternatives, such as metal connectors, frames, and claddings. However, comparing structural materials requires assessing the full system (Sanchotene *et al*. 2024), as these details are often crucial for the function, durability and reusability of the system. The consequence of ignoring technical details on embodied energy use can be found in (Moncaster *et al*.

2018) for cementitious claddings on CLT floor slabs and separation walls, and in (Nakano *et al*. 2020) for connectors between CLT elements. These details also significantly impact the moisture, acoustic, and fire performance of CLT buildings.

Recent insights indicate that embodied carbon is a more effective sustainability metric than embodied energy because it considers the energy source, distinguishing between renewable and nonrenewable sources. Although CLT is popular for mass timber construction, other alternatives seen through embodied carbon might have comparable environmental impact or better economic feasibility (Balasbaneh and Sher 2021, Robati and Oldfield 2022, Kang *et al*. 2024). Thereby, the focus shifts to non-renewable energy sources in embodied energy analysis. However, Arvidsson and Svanström (2016) argue that using primary energy—including all renewable and nonrenewable sources, for both production and materials, along with associated losses—provides a more comprehensive basis for LCA studies. This approach effectively addresses concerns about limited energy reserves.

Focusing excessively on energy intensities and embodied energy can detract from other crucial functional requirements, such as structural stability (Zeitz *et al*. 2019). In areas with significant mechanical stress, such as garages, the environmental advantages of CLT over concrete or steel alternatives might diminish because larger CLT volumes are required to achieve comparable structural stability (Zeitz *et al*. 2019). Similarly, when comparing structural frame and floor designs, CLT, concrete, and steel might be similar alternatives (Hart *et al*. 2021). Furthermore, circular economy principles complicate the environmental assessment of CLT buildings. While CLT buildings offer benefits like flexibility for renovation, reuse, and adaptation (Myint *et al*. 2025, Vasuks *et al*. 2025), the material is prone to physical changes and biological contamination as addressed earlier. This affects all the addressed building physics areas, leading to uncertain designs. Additionally, CLT requires special care during storage and transport, introducing uncertainties in the value chain.

Predicting deterioration issues of buildings and their consequences require other assessment methods, where timeline and probability of events need to be included. Anand and Amor (2017) propose dynamic LCA to track changes in emissions over time, although uncertainties remain regarding how to integrate these emissions with a time-defined inventory without complicating the LCA model. Nevertheless, probabilistic methods are emerging to cope with uncertainties in input data for LCA calculations regarding e.g. wood consumption patterns, land use impacts, and forest growth (Lan *et al*. 2019, Robati and Oldfield 2022), or lifetime of building components and end-of-life scenarios (Robati and Oldfield 2022). Ignoring deterioration of CLT buildings due to earthquakes significantly underestimates emissions, which can be up to 2.6 times lower than in a deteriorating building as shown by (Junda and Málaga-Chuquitaype 2025). These and similar studies provide a nuanced picture of the environmental benefits of CLT buildings.

Khadim *et al*. (2025) conclude that while biobased materials like CLT and wood can enhance the circular economy, they do not automatically translate into improved sustainability. They propose combining the Whole Building Circularity Indicator (WBCI), which captures essential circularity aspects such as material circulation and component disassembly, with cradle-to-cradle LCA to gain insights into the environmental impacts of manufacturing, recycling, and transportation processes. More research is needed to address and consolidate uncertainties and complexities of LCA methods, including specific results such as embodied energy. Future developments will likely focus on a system perspective and overall results, with existing isolated studies serving as benchmarks.

7. Discussion

Interest in CLT has grown rapidly since its introduction to the market in the 1990s. This paper provides an overview of four building physics areas of significant importance for CLT development toward a competitive product for construction frames. Hereafter, some key observations within each area discussed individually followed by a joint discussion, comparing two or more individual aspects.

7.1. Key observations within each area separately

7.1.1. Moisture

Moisture is a crucial parameter for CLT structures and liquid water absorption through end-grain surfaces and joints has generally been pointed out as critical (Schmidt *et al*. 2019, Kalbe *et al*. 2022, Olsson *et al*. 2023). Simultaneously, difficulties with modeling liquid water uptake and moisture transport at high humidity levels have been addressed in several studies (McClung *et al*. 2014, Kordziel *et al*. 2020, Wang *et al*. 2023). These difficulties pose challenges for predicting the wetting and drying of CLT elements and other applications, such as modeling moisture transport in outdoor wood structures for service life prediction (van Niekerk *et al*. 2021). Thus, modeling water uptake and drying of rain-exposed CLT adds to the need for an accurate model of liquid water absorption by end grain. Additionally, (Kordziel *et al*. 2020) highlights the lack of data in common hygrothermal simulation software for liquid water transport coefficients. They found that for wood, unlike other materials, such as masonry, water vapor diffusion contributed significantly to the total transport of water, in parallel with liquid water transport, which must be considered in modeling.

The inherent moisture and durability-related properties for large CLT panels are the same as those of the corresponding wood species in smaller dimensions. However, since CLT has a layered structure, some properties are affected by the anisotropic structure and adhesive layers. Such properties are diffusion and liquid water transport coefficients, which differ considerably in the three structural directions, and transport can be affected by the adhesive layer in the direction perpendicular to the plane of a CLT element (Chiniforush *et al*. 2019, Kordziel *et al*. 2020). Other moisture-related properties, such as sorption isotherms, are unrelated to the structural direction and, thus, similar to the corresponding wood species. Likewise, if untreated, the durability is similar as for the corresponding non-CLT wood species (Udele *et al*. 2021), which can be seen in the degradation experiments performed by Singh *et al*. (2019) and Sinha *et al*.(2020). Although CLT at present is manufactured primarily from softwoods, several studies have highlighted a broader use of hardwood species (Yusoh *et al.* 2023, Jiang *et al.* 2024), e.g. birch (Obernosterer *et al.* 2023) and beech (Altaher Omer Ahmed *et al.* 2023). While softwoods are usually found in durability class 4 (SSI Swedish Standards Institute 1994), hardwoods can have very different moisture and durability properties. For example, birch and beech belong to durability class 5 (not durable), and their use would require even more care to protect CLT from elevated moisture contents.

Crack formation (Kukk *et al.* 2021) and delamination (Kalbe *et al.* 2022) can occur in CLT elements during drying if the initial moisture contents are high and growth of mold as well as wood degrading fungi has been detected (Austigard and Mattsson 2020, Ott and Aondio 2020). These types of damage not only compromise the building's functionality, such as air tightness and indoor air quality, but also limit the potential of reusing CLT elements if the building is to be disassembled. Preventing moisture-related damage is therefore crucial not only to maintain the building's performance, but also to enable reuse, promote circularity, and reduce the environmental impact of the built environment.

7.1.2. Fire

The fire performance of CLT has been studied in numerous publications. Several areas have been highlighted as requiring more research, including self-extinguishment (Barber *et al.* 2016), the contribution of CLT to the overall HRR (Ronquillo *et al.* 2021), the behavior of fire stops (Ronquillo *et al.* 2021), the influence of different wood treatments on delamination (Mahnert and Bertelsen 2023), and the fire behavior in compartments with large areas (>75%) of exposed timber (Mitchell *et al.* 2022). Several authors (Ronquillo *et al.* 2021, Mitchell *et al.* 2022) have stressed the lack of knowledge and data on how fire behaves in large open-plan compartments (floor areas >100 m^2), and recent studies (Kotsovinos *et al.* 2023, Bøe *et al.* 2023a, 2023b) have addressed this matter. Another area requiring attention is developing models for heat transfer in engineered timber (Wiesner *et al.* 2021).

An effective way to improve fire performance of CLT is encapsulation with protective materials. A single layer of fire-rated gypsum board delays charring by 30 minutes and two layers extend it beyond 40 minutes. The required gypsum thickness depends on fire severity and the area of use of the CLT panel, ceilings need more protection than floors. However, although claddings delay charring, they cannot fully prevent smoldering or charring under extreme conditions.

A large dataset from experimental fire tests is available, and most correlate. However, the findings of individual studies are highly dependent on the specific experimental setups used, and care should be taken in directly using results from an experimental test without a critical review and evaluation of whether the circumstances during the test apply to the situation at hand. Recently, reviews and meta-analyses (Brandon and Östman 2016, Ronquillo *et al.* 2021, Mitchell *et al.* 2022) have contributed to creating a conceptual understanding of various processes related to the fire behavior of CLT. Even though several aspects are crucial for the fire safety design of CLT constructions, it is necessary to adopt a holistic approach to ensure the design is resilient (Bartlett *et al.* 2015b).

7.1.3. Acoustics

According to the performed review, proper modeling of vibroacoustic behavior is a fundamental factor in developing CLT building systems. Although a CLT panel represents a homogenous building element, predicting sound insulation is considerably complex and cannot, in that respect, be compared to similar procedures used for concrete elements (Granzotto *et al.* 2022). The primary reasons are the orthotropic properties of the CLT panel and its structure of separate layers (Van Damme *et al.* 2015).

Predicting the sound insulation of a building system is a three-step process. First, the sound insulation of the CLT panel must be determined. Then, the effect of linings/toppings/ceilings must be considered. Last, the assembly of adjacent wall/floor elements must be considered. This step, likely the most demanding one, includes determining the vibration reduction indexes between elements, where the type of fastening is crucial. Accurately modeling typical junctions with pointwise angle brackets and elastic layers is a delicate process, where a lot of work remains until accurate methods are found. Furthermore, documenting data from field and laboratory measurements is crucial and should be encouraged to validate the development work toward refined sound insulation prediction models.

7.1.4. Energy

When assessing the operational energy of CLT buildings, it is crucial to consider both heating and cooling demands due to their limited thermal mass (Jensen *et al.* 2020), which can lead to overheating during sunny periods (Dong *et al.* 2019). Passive measures such as solar shading and night ventilation can help maintain a comfortable indoor environment and reduce cooling needs. Increasing thermal mass by means of phase-change materials (Kang *et al.* 2025) or through hybrid constructions with concrete intermediate floors and CLT elements are particularly beneficial. All these aspects can be readily addressed with detailed building energy simulation tools such as e.g. IDA ICE, EnergyPlus and TRNSYS.

Comparing the operational energy of CLT and reference buildings reveals methodological inconsistencies. CLT exterior walls are sometimes assumed to have superior thermal resistance compared to reference walls, favoring CLT in heating energy analysis. However, the opposite is true for cooling energy. Therefore, the comparison's goal should be clearly stated to avoid biased conclusions.

Emerging measurements reveal that achieving airtightness in CLT buildings requires careful planning and execution to avoid significant energy losses. Established CLT-building technologies alone do not guarantee airtightness and need to be combined with other airtightness measures. This aspect is often overlooked in energy analyses. Therefore, more research is needed on the airtightness of CLT buildings and how it varies over time.

Metrics and methodologies for evaluating the sustainability and circularity of CLT buildings are evolving. Assessing embodied carbon is a stronger metric than embodied energy alone, as it accounts for energy sources. An excessively detailed focus on the environmental impacts of individual materials, components, or systems within a building can detract from their relative significance compared to other crucial factors, such as structural stability, as highlighted by Zeitz *et al*. (2019), diminishing the effectiveness of environmental assessment methodologies. Furthermore, Younis and Dodoo (2022) highlighted notable uncertainties in assessing the lifecycle carbon footprint of CLT buildings, primarily stemming from oversimplifications in the assessment process. Circular economy studies also face challenges, as CLT properties and assemblies change over time, and the material's susceptibility to moisture damage complicates transport and storage—issues often overlooked in existing research, requiring further study.

The development of dynamic and probabilistic calculation methods for LCA analysis is a logical step forward to deal with variabilities and uncertainties in LCA calculations, including operational and embodied energy, particularly for CLT buildings due to their recognized potential for environmental benefits. Integrating these approaches without complicating LCA assessments remains a challenge. A pragmatic approach is essential, but simplifications regarding the detailed technical design of CLT buildings and their alternatives must be done with care. Detailed technical design often reflects best practice, which is inherently probabilistic as it represents accumulated knowledge over time and space.

7.2. Key observations across different areas

This review identifies several synergies among the different technical aspects of structures. For instance, in the areas of fire safety and acoustics, the mass of CLT panels contributes significantly to both fire resistance and sound insulation. Thicker panels enhance fire performance by reducing heat transfer and forming a protective charring layer, while simultaneously improving acoustic properties by reducing sound transmission. Additionally, proper sealing of joints in CLT panels is crucial for maintaining both fire containment, acoustic integrity and airtightness.

Furthermore, insulated and airtight CLT buildings offer improved energy efficiency, which is particularly valuable in colder climates. However, the low thermal inertia of CLT presents challenges, such as a higher risk of overheating during warmer seasons. This low thermal inertia also suggests that fire temperatures in CLT buildings can be more intense than in concrete structures, potentially resulting in harsher fire conditions.

Elevated VOC levels in CLT buildings may necessitate increased ventilation, leading to higher operational energy use, especially during the first year of occupancy. While uncovered building materials allow for rapid ventilation-driven removal of shallow VOCs, this approach has limited effectiveness for deeply stored VOCs or covered materials (Domhagen *et al*. 2024). More research is needed on VOCs emission types and dynamics from CLT panels in both early stages and after extreme events. Moreover, uncovered CLT panels will make a possible fire more critical, and the sound insulation might need to be accomplished by other means. Therefore, covering CLT panels may be beneficial from the perspectives of energy efficiency, fire safety, and acoustics.

High initial moisture content in CLT can cause volumetric changes and cracking as the material dries, potentially compromising both airtightness and structural integrity. These issues, in turn, can affect fire, acoustic, and energy performance of the building. Therefore, airtightness measurements are central in existing CLT buildings to understand the distribution of air leakage paths, assessing how their airtightness changes with time and developing appropriate mitigation strategies.

Poor moisture management can negatively impact CLT buildings. The direction of built-in moisture removal from CLT elements in different parts of the building envelope must be carefully considered when selecting vapor barriers and insulation materials to prevent moisture accumulation, condensation, and microbiological growth on CLT surfaces. Different solutions apply to different climate regions. The flammability of insulation materials and barriers are noteworthy mentioning, especially in exposed areas like ventilated cavities. Junctions are particularly vulnerable due to risks for moisture entrapment within and around small elements like screws, brackets, and similar. These details affect also the quality of sound and vibration protection. Existing simulation tools in the related fields have limited capacity to address the quality and durability of CLT junctions. This highlights the need for further research and integrated strategies for moisture and acoustic safe CLT building design.

Other conflicts can also arise between the different technical aspects. For example, a sprinkler system designed to enhance fire protection may cause moisture issues due to water leakage. Similarly, treatments like thermal modification of wood, while beneficial regarding moisture, can increase the flammability of wood. Due to synergies, but especially the potential conflicts, it is important to have a holistic approach when designing CLT buildings to ensure that all technical aspects are satisfactorily considered.

8. Conclusions

This review explored four key technical aspects of CLT buildings —moisture, fire, acoustics, and energy—which are integrated in building physics design but often studied independently in scientific literature. By synthesizing findings from related research fields, the following joint aspects were identified, highlighting the remaining challenges in the design of CLT buildings.

Airtightness is critical in CLT buildings, affecting all four areas, but often overlooked. Current simulation tools struggle to accurately model in-built air leakage paths, their change over time, and new leakages due to humidity-induced volumetric changes or mechanically displacements of CLT elements. Thus, field and laboratory measurements remain essential, and further studies are encouraged.

Junctions between CLT elements present challenges in modeling sound and vibration transfer, as well as water absorption and distribution, particularly at end-grain surfaces. Multiple sound and water leakage paths, water entrapment risks, and combined transport mechanisms complicate these processes. The presence of screws, brackets, and isolators, along with volumetric changes due to humidity, further complicate design aspects. More research is needed on the design and robustness of CLT junctions, especially after extreme events like flooding and fire extinguishment. This research is crucial for both extending the service lifetime of CLT buildings and enabling the potential reuse of CLT elements in circular economy value chains.

Operational energy studies should focus more on overheating risks and cooling demand. The limited thermal mass of CLT elements can negatively impact fire extinction in buildings where these elements are exposed. There is a significant knowledge gap regarding thermal and fire behavior in large open-plan compartments, and the limited experimental studies make it difficult to draw general conclusions. Identifying synergies between thermal performance and fire behavior is essential, and developing complementary assessment methods is necessary.

CLT elements introduce various volatile organic compounds (VOCs) into indoor environments, originating from both the raw wood and treatments like bonding and thermal processes. Since enhanced ventilation has limited impact on reducing VOC emissions from exposed building materials, more research is needed on the short-term and long-term emissions from CLT elements, both in early stages and after extreme events like fire and flooding. This is particularly important for their potential reuse in circular economy applications. Covering CLT panels may be beneficial for energy efficiency by avoiding the need for enhanced ventilation, as well as for fire safety and acoustics.

Environmental impact assessments of buildings, including CLT buildings, are complex and challenging due to evolving metrics and methodologies. They often overlook technical aspects during the operation phase, such as those identified in this review, which are crucial for extending the service life of CLT buildings and enabling the reuse of CLT elements in circular economy value chains. Methodological innovations are needed to enhance the flexibility of these assessments across entire value chains.

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