Combining Wood Protection Options to Enhance Resistance against Decay and Improve Fire Safety of Engineered Wood Products like CLT

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Abstract. *Bio-based building products are considered key in our future socio-economic environment, since they are a very relevant nature-based solution (NbS) to climate change. The statement of President von der Leyen (European commission) to turn the construction sector into a carbon sink is critical in this respect: bio-based materials should be used on a larger and more targeted scale in the future. The long-term use of materials is therefore very important since we need to improve the lifespan of renewable materials to increase its carbon sink potential.*

Hence wood is increasingly considered as a main building material. Service life aspects are critical in relation to the EU Construction Products Regulation (CPR). Traditional treatments to protect against fungal decay and the impact of fire are not always performing adequately and often environmental impact has been an important consideration. The option to enhance wood properties using innovative technologies can be combined with better definition of the expectations and requirements. Besides focusing on combined innovative treatments of the wood matrix, also envelope treatments similar to the use of coatings can be envisaged. This all should lead to an increased use of timber and engineered wood products for green building. This paper mainly focusses on the increased use and high potential of CLT (Cross Laminated Timber) and options to use hardwoods and modified wood (like TMT) in relation to moisture dynamics to come to fit-for-purpose material properties even under more hazardous circumstances.

Keywords: *Cross Laminated Timber, Service life, Treatments, Decay resistance, Fire safety*

1 Introduction

Green building is to a large extent relying on bio-based building products, since they are a very relevant nature-based solution (NbS) to climate change (Seddon et al. 2021). The statement of President von der Leyen (European Commission) to turn the construction sector into a carbon sink is critical in this respect: bio-based materials should be used on a larger and more targeted scale in the future.

In particular **wood and wood-based building products** are considered critical in dealing with different aspects of the sustainable development goals as underlined by international, European and national political structures. Unlike carbon-demanding building materials such as concrete or steel, wood is the only resource that can be sustainably resourced (Churkina et al. 2020): harvested wood products (HWP) are regarded today as having clear potential for global CO_2 mitigation (Johnston and Radeloff 2019). Although biodegradability can be an asset as it is also part of the sustainable development goals (https://sdgs.un.org/), it is important to control this with regard to service life and related carbon sink potential.

In general, new approaches in using wood and wood-based materials, mainly focus on the use of glue-laminated products like more conventional glulam beams but, especially in respect of high-rise buildings, **Cross Laminated Timber (CLT)** is becoming increasingly important. CLT is selected as the most innovative wood product not only leading to great opportunities but also highlighting some of the more critical challenges. Controlling **moisture** dynamics in relation to mechanical performance (Schmidt et al. 2019), especially in the presence of biological hazards like wood decaying fungi is critical for future design of massive timber-based constructions. Next to the moisture and decay issues there remain also several restrictions in relation to **fire** hazard. Although massive timber like CLT is regarded to provide excellent fire safety (Barber 2018), some exposure systems are still largely prohibited for wood (Gasparri and Aitchison 2019). For example, wood is often still regarded as critical with regard to fire propagation especially when dealing with exterior walls and cladding in multi-storey buildings. Analysis of the environmental, economic, thermal and energy performances of green building technologies showed that those using natural materials have a lower environmental impact than both conventional and more industrialized materials (Caponetta et al. 2022).

2 Green building with CLT

2.1 Cross Laminated Timber

Cross Laminated Timber, or CLT, is a special type of manufactured lumber, also known as mass timber. It consists of layered lumber boards that are stacked, glued, and pressed into place (Figure 1). This manufactured wood product forms large wood panels that are used in floors, roofs, and walls and allows developers to create wood construction multi-floor buildings.

Figure 1. Cross Laminated Timber (CLT).

CLT is indeed a large-scale, prefabricated, solid engineered wood panel (Kurzinski et al

2022). Lightweight yet very strong, with superior acoustic, fire, seismic and thermal performance. It is also fast and easy to install, generating almost no waste onsite. CLT offers design flexibility and low environmental impacts. For these reasons, cross-laminated timber is proving to be a highly advantageous alternative to conventional materials like concrete, masonry or steel, especially in multifamily and commercial construction (Andersen et al. 2022, Liang et al. 2020).

Several guidelines and regulations are in place to underpin the use of CLT in Europe. Besides the general EU Construction Products Regulation Regulation (EU) No 305/2011 as a basis for design using CLT in relation to Eurocode 5 (EN 1995; Köhler et al. 1016) there is also the Commission Delegated Regulation (EU) 2017/2293 on the conditions for classification, without testing, of cross laminated timber products covered by the harmonised standard EN 16351 with regard to their reaction to fire.

In North America, specific CLT handbooks on the use of CLT for construction applications are available online (https://www.fs.usda.gov, https://web.fpinnovations.ca/clt/). Although many multi-storey building based on mass timber have been documented (Svatoš-Ražnjević et al. 2022) it remains critical that construction guidelines are provided to the building sector (Wahlstrøm 2020, Kurzinski et al. 2022). Over the last decade this has been the basis for dedicated research (Brandner et al. 2016, Buck et al. 2016), as the solutions to certain knowledge gaps can further increase the potential of mass timber (Campbell 2020). Key parameters like characteristic values were sorted out already more than a decade ago and were the basis for guideline handbooks, such as the one provided by Schickhofer and colleagues (2010), which was the basis for him being granted the Marcus Wallenberg Prize in 2019 (https://www.mwp.org/the-winners/).

2.2 Wood species

Traditionally softwood species are used to produce CLT, mainly spruce, although it can be manufactured from larch, fir, Douglas fir, pine or other timbers (Wang et al. 2018, Wang et al. 2018b, He et al. 2018, Puettmann et al. 2019, Ukyo et al. 2019). Lumber is visually graded or machine stress rated and is kiln dried to 12%. While C24-grade timber is often used, there has been an increase in the use of C16 timber. C16/C24 is the strength grade of the timber, which can be graded visually by a registered and qualified grader or by machine. The need for high grade timber seems not always critical (Cherry et al. 2019) and does allow for different reuse and recovery strategies (Rose et al. 2018).

Furthermore, CLT seems to be an excellent opportunity for relaunching the use of hardwoods in the building sector (Van Acker 2021) and even low-grade hardwood assortments can provide potential (Thomas and Buehlmann 2017). The publications of CLT based on hardwoods are numerous, some examples are beech (Franke 2016, Erhart et al. 2016), yellow poplar (da Rosa Azambuja et al. 2022), birch (Jeitler et al. 2016) and eucalypts (Liao et al. 2022). However, by far most interest goes to fast-growing hybrid poplar as single material (Kramer et al. 2014, Van Acker et al. 2020, Jiang et al. 2022, Rostampour Haftkhani and Hematabadi 2022, Shi et al. 2022), but also often in combination with other wood species (Hematabadi et al. 2021, Purba et al. 2022, Das et al. 2023) and in combination with other engineered wood products like LVL and OSB (Wang et al. 2017, Li and Ren 2022). This is however also valid for softwoods (Song et al. 2022) and the story of so-called composite cross-laminated timber (CCLT) even extends to the use of bamboo (Wei et al. 2019).

2.3 Production volumes & main producers

The DACH countries (Germany (D), Austria (A), Switzerland (CH)) have been the driving force in CLT development, not only as the originators of CLT products but also as the leading CLT producers. In 2021, the cross-laminated timber sectors in the DACH region, Italy and the Czech Republic totaled a production output around 1.1 million m³ and thus growing by 9% compared to 2020. In 2022, manufacturers expect a 17% increase which should bring total production to 1.28 million m³ (https://www.timber-online.net/blog/biggest-clt-producers.html).

Below a list is given of the top 5 EU CLT manufacturers in 2021:

- STORA ENSO (https://www.storaenso.com/en/products/mass-timber-construction/building-products/clt)
- KLH Massivholz (https://www.klh.at/en/)
- BINDERHOLZ (https://www.binderholz.com/en-us/products/clt-bbs/)
- MM HOLZ (https://www.mm-holz.com/en/products/clt-cross-laminated-timber)
- HASSLACHER (https://www.hasslacher.com/cross-laminated-timber)

Stora Enso’s new production site for cross-laminated timber (CLT) in Ždírec, the Czech Republic, was inaugurated in Autumn 2022. This new CLT site is one of the most modern in the world with an estimated annual production capacity of approximately 120 000 m³ after ramp-up.

Although similar mass timber products existed earlier, e.g. mid-last century in the US, CLT was actually manufactured from the 1990s in Europe and has spread after 2000 to other parts of the globe.

Per the 2020 edition of Forest Products Annual Market Review, global production capacity of CLT in 2020 is estimated at 2.8 million cubic meters (m³), of which 48% in Europe, 43% in North America, 6% in Oceania and 3% in Asia. Muszynski and co-authors have provided data on the global CLT Industry on a regular basis (Muszynski et al. 2020, Larasatie et al. 2021). Although large production units seem to become standard, it remains of interest that smaller production units can provide extra local capacity (Benedetti et al. 2022). Headquartered in Phoenix, Illinois, United States, Sterling is the world’s largest manufacturer of CLT. With manufacturing facilities in Phoenix, Illinois, and Lufkin, Texas they have an annual production capacity of 700 000 cubic meters, and serve both industrial and structural CLT markets throughout the U.S.

The CLT production in Asia is also becoming relatively important (Li et al. 2019, Hamdan et al. 2017). In China, the researchers and manufacturers began to develop and produce CLT materials and buildings since 2010. A number of research teams have carried out researches on the physical and mechanical properties and connection properties of CLT. Domestic fast-growing wood species such as poplar, eucalyptus and Japanese larch, and wood-based panels, such as construction OSB (COSB) boards, have been developed to produce CLT and hybrid CLT (HCLT) (Gong et al. 2016, Liao et al. 2017, Wang et al. 2018c). Up to 2022, there were 4 CLT factories located in Hebei, Shandong, Zhejiang and Jiangsu provinces. Among them, Jiangsu Global CLT Co., Ltd. was established in 2017, with an annual capacity of 60 000 m³

of CLT panels. In 2020, the first six-story pure timber structure building in China Shandong DENCHWOOD CLT Research and Development (R&D) Center project has been completed.
Within Europe stakeholders in both research and policy interacting with the producers can be found at different platforms and project frameworks: Cost Action CA20139 - Holistic design of taller timber buildings (HELEN) (https://cahelen.eu/), the New European Bauhaus (https://new-european-bauhaus.europa.eu/), https://www.timber-construction.eu/en, and EU-projects (https://www.build-in-wood.eu/ and https://basajaun-horizon.eu/).

3 Decay hazard and fire safety

3.1 Use classes

Related to decay hazard there is a global classification of applications related to different levels of moisture and decaying organisms (ISO 21887:2007) with document related to this i.e. in Europe (EN 335:2013). The classification criteria and test methods used to assess the performance of products covered by the CPR in terms of their decay resistance are indicated in the standard EN 350 (2016), while for reaction to fire such classification is covered by the European classification standard EN 13501-1 (2018), which divides building materials into seven main classes with regard to the material's fire behaviour: A1, A2, B, C, D, E and F where wood products can be classified from B to F. This classification is however only part of the story as fire safety assessment reveals other factor to be more important and hence often making CLT a preferred material to be specified.

The service life appraisal of CLT based buildings has indeed welcomed the positive trend based on fire safety but also revealed the limited focus on wood protection measures against wood decaying organisms (Taylor et al. 2016). Especially the fact that CLT as a structural component is hard to be repaired and replaced or remediated by curative treatments, makes a preventive protection treatment essential at least for those elements under use class 2 (Under cover and fully protected from the weather but where high environmental humidity can lead to occasional but not persistent wetting).

3.2 Moisture dynamics

Considering the use classes as defined in the standard mentioned above, the main applications of CLT focus on UC2 while any UC3 application might need extra attention. Hence controlling the moisture content and time of wetness (ToW) are critical. This means that any measure limiting condensation, infiltration and leakage can contribute considerably to the service life. When complementary measures are taken, including adequate maintenance and moisture content monitoring, there is often no risk for failure due to decay. Such monitoring can be an adequate tool to ensure that low durability wood species remain a viable option as standard wood species used for the production of CLT (Humar et al. 2020).

Although exposure to weather and in particular precipitation is not intended for most end uses of CLT, these UC3 conditions are often occurring during the construction of a building (Olsson 2020, 2021). Though CLT based buildings are showing a short time to be finalized it remains important to prevent excessive moisture levels to be reached and maintained (Kalbe et al. 2022) and this becomes even more relevant when considering combinations with moisture sensitive insulation materials (Kukk et al. 2022). Earlier research on moisture dynamics of plywood (Van den Bulcke et al. 2011; De Windt et al., 2018) using continuous moisture measurements (CMM) has recently been used to get more insight in these phenomena for CLT (Schmidt et al. 2019). This reveals interesting concepts of moisture control methodology underpinning the use of engineered wood products (Chinforush et al. 2019).

3.3 Protection by design

Since exposure to rain during construction is a main concern (Olsson 2021) at least temporary protection is to be recommended and this should preferably be a complete weather protection. Schmidt and Riggio (2019) suggest preventative approaches implementable in the design (e.g., avoiding moisture trapping details), during fabrication (e.g., localized coating), and construction (e.g., sequencing installation to minimize exposure and allow drying).

Temporary exposure to the outdoor climate not only leads to warping but also brings the material under time of wetness conditions at risk for decay due to construction encapsulation of the exposed CLT. The impact of standing water on horizontal surfaces can be avoided by using temporary roof or tent structures (Herms 2020), but also through the use of (adhesive) membranes or liquid-applied membrane coating (Kalbe et al. 2020). Although mainly focusing on protection during construction several similar measures can apply as part of a general protection by design strategy for moisture management (Riggio et al. 2020).

As the hygrothermal performance of a CLT wall assembly is an important parameter in designing (Wang and Ge 2016), the concept of protective measure to ensure no excessive moisture ingress can take place remains critical for the long-term performance.

3.4 Fire safety

CLT performs better than most wood products, mainly based on a high level of fire resistance due to its cross-sectional thickness and air tight construction (Klippel et al. 2016, Östman et al. 2018). This results in a reduction in the fire’s ability to spread and increase fire safety (Barber 2018). Furthermore, the thermal mass allows for no conduction between one side of the panel to the other. Fire resistance can be further enhanced by applying a fire-resistant lining material such as plasterboard to the flooring or walls. CLT panels burn at a slow and predictable rate. The slow char keeps significant structural capacity for extended durations when exposed to fire and allow for safe evacuation of the occupants of a building. A whole range of fire properties and performance parameters are to be assessed in relation to fire safety (Östman et al. 2023) leading to the potential of CLT as building product with positive fire safety attributes.

4 Enhancing performance

4.1 Treatability

The wood species used for the production of CLT are often difficult to treat: spruce, Douglas fir, etc. Treatability or impregnability is important when penetration of chemicals in the wood matrix is key for extending the service life or enhancing performance in general. The methodology to evaluate wood species can be based on general data (EN 350:2016) or assessed according specific procedures (CEN/TR 14734:2004).

The flow through the wood substrate can be checked with micro CT enabling to verify the penetration but also the flow and repartition in different tissues of active components in relation to the wood treatment (Burridge et al. 2021). The different wood species options enabling better treatment of CLT are anyhow related to impregnability for many processes (Tarmian et al 2020). New insights in penetration of cell wall are often related to nanotechnology approaches (Civardi et al. 2016, Dai et al. 2022).

4.2 Wood preservation

As indicated in Table 1 by Van Acker and co-authors (2020) the option to increase service life of CLT products is limited by its dimensions. Since CLT is based on timber as key component, glue line additives are not suitable while impregnation related treatments are not feasible for the final product and should relate only to individual beams prior to assembly.

Table 1. Options to increase service life of Engineered Wood Products (EWP).

Component	EWP	Durable wood	Vacuum pressure[1]	Glue-line additive	Surface spray[2]	Thermal modification	Chemical modification	Resin[3]	Coatings
Strand	OSB	-	-	±	+	+	+	+	-
	LSL	-	-	±	±	-	-	+	-
Veneer	Plywood	+	+	+	+	+	±	+	+
	LVL	±	±	+	±	±	±	+	+
Timber	CLT	+	+	-	+	+	±	±	+
	GLT	+	+	-	±	±	±	±	+

Legend: +: existing option, ±: feasible option, -: less probable option
[1]: deep impregnation with biocides; [2]: surface biocide application with potential diffusion, e.g. borates, [3]: analogue to glue used for production or a hydrophobing agent; Abbreviations: EWP = engineered wood product; OSB = oriented strand board; LSL = laminated strand lumber; LVL = laminated veneer lumber; CLT = cross laminated timber; GLT = glue laminated timber or glulam.

Given the size of CLT panels, conventional pressure treatment is not feasible (Sterling and Morris 2017). A surface-applied penetrating treatment results in superficially treated zones. Borate treated lamina glued together without re-planing after treatment had poorer adhesion than untreated controls.

Out of the many options of wood protection (Van Acker et al. 2023) only a selected range can be used to treat CLT related to the durability (Udele et al. 2021, Ayanleye et al. 2022). Standard assessment of penetration and retention however is different to just solid timber when considering the layup parameters of CLT (Ayanleye et al. 2023). Anyhow standard modern wood preservatives can provide extra service life (Lim et al. 2020).

Non-pressure treatments (Miyauchi et al. 2021) and the use of exterior coatings (Bobadilha et al. 2020) are becoming relevant options while mainly borate treatments have been checked on their potential (Lloyd et al. 2019, Taylor et al. 2023, Bagheri et al. 2022).

4.3 Wood modification

Over the last decades a wide range of innovative wood modifications were developed (Mai and

Militz 2023). Often it is not the intention to just increase mechanical properties or biological durability. The impact on moisture dynamics and related improved dimensional stability are considered key property objectives also to improve weathering especially related to the performance of exterior coatings. These properties are not considered critical for most end uses of CLT. Furthermore, chemical wood modification processes face the same technical issues as impregnation with wood preservatives. As such most research on wood modification of CLT deals with thermal modification methods (Han et al. 2017, Mohebby and Broushakian 2022). Unfortunately, the altered mechanical properties related to wood modification might hinder the use for load bearing applications (Wang et al. 2022, Zelinka et al. 2022).

4.4 Combined products for multiple laminated functionality

CLT based on different wood species leading to adequate or increased mechanical performance (He et al. 2020, Ma et al. 2021, Yusoh et al. 2022) and adhesion properties (Brunetti et al. 2020), as well as other properties can be tailored based on combinations of different layers. In fact, many options to produce engineered wood products like CLT have been assessed for their potential to be manufactured to perform optimal in the context of green building (Sun et al. 2020).

Besides options for seismic performance (Sandoli et al. 2021) and sound insulation (Ljunggren 2023), a lot of attention goes to the incorporation of thermal insulation in CLT (Shan et al. 2022) and their impact on Life Cycle Analysis (LCA) (Santos et al. 2021). The layered structure of CLT allows including additional functionalities. CLT is not just a wood panel but can perform as an integrated construction system (De Araujo et al. 2023). Modular construction potential can be combined with seismic performance (Bhandari et al. 2023, Li and Tsavdaridis 2023). Also, thermally modified wood layers can add functionality (Jeleč et al. 2018).

In some buildings the CLT is covered with gypsum plasterboard for fire protection (Barber 2018), and the combination with built-in or add-on components to CLT can improve the overall performance with multiple laminated functionality (Xu et al 2022).

4.5 Combined wood protection options

The commercial competition between different treatments to enhance properties is however also a weakness for the sector (Van Acker 2019). A major opportunity could be in combining different treatments and methodologies, also related to fire safety, to come to fit-for-purpose engineered products based on a wide range of wood species and qualities. Unfortunately, the amount of available woody biomass will remain both a challenge as well as a long-term threat to ensure sustainability for green building. Based on the SWOT structure proposed by Viaggi (2013) it is clear that there are various strengths, weaknesses, opportunities and threats related to the life cycle stages of wood-based products for green building, as indicated in Figure 2: resources, production, use and disposal (Van Acker et al. 2023).

	Resources	*Production*	*Use*	*Disposal*
Strengths	Renewable, sustainable	Many options	Substitution man-made	Embodied energy
	Bio-based	Less energy required	Low energy housing	Biodegradability
Weaknesses	Max on availability	Internal competition	Biodegradation	Environmental impact
	Forestry economics	Logistics transport	Low fire resistance	Recovery sorting
Opportunities	Fast growing trees	Value added products	Extended CO_2 seq.	Circularity
	Engineered Wood Prod.	Local rural production	Fire safety	Cascade use
Threats	Bioenergy	Low on high quality	Impact biocides	Historical treatments
	Biorefineries	Low industrial lobbying	Inefficiency	Impact CO_2 seq.

Figure 2: SWOT analysis related to wood protection for green building

Some recent research on functional incorporation of fire protection (Guo et al. 2019, Fu et al. 2017) has an impact on the fixation and potential compatibility with wood preservation. Historically, both wood preservation and fire retardancy treatments are often based on inorganics. Nanostructured organic–inorganic wood hybrids may, however, offer new possibilities both scientifically and in terms of industrial potential (Berglund and Burgert 2018). An important research goal is therefore to be able to control the nanoscale distribution of inorganic matter in wood tissue, and to understand mechanisms for nanoparticle effects on wood properties. Looking for both functionalities (fire retardancy and decay resistance) in one treatment is not new (Terzi et al. 2011), but some promising results with combined technologies have been presented recently (Zhou et al. 2023). However, the implementation of this approach (Marney and Russell 2008) still requires additional innovation.

5 Conclusions

CLT has become a commodity construction product for green building and hence options are explored to cover alongside standard product use also enhanced performance based on material properties and a range of technology tools. Enhanced performance is often related to fire safety and extending service life under conditions with more risk of longer time of wetness, use classes 2 and even 3 according to EN 335 (2013). Modern decision support systems can be based on a range of parameters. Specific for the functionalities ‘fire safety’ and ‘service life’ several technology pathways are feasible leading in future to multi criteria decision making (MCDM) tools for CLT applications (Figure 3) based on more general methodology (Taherdoost & Madanchian 2023).

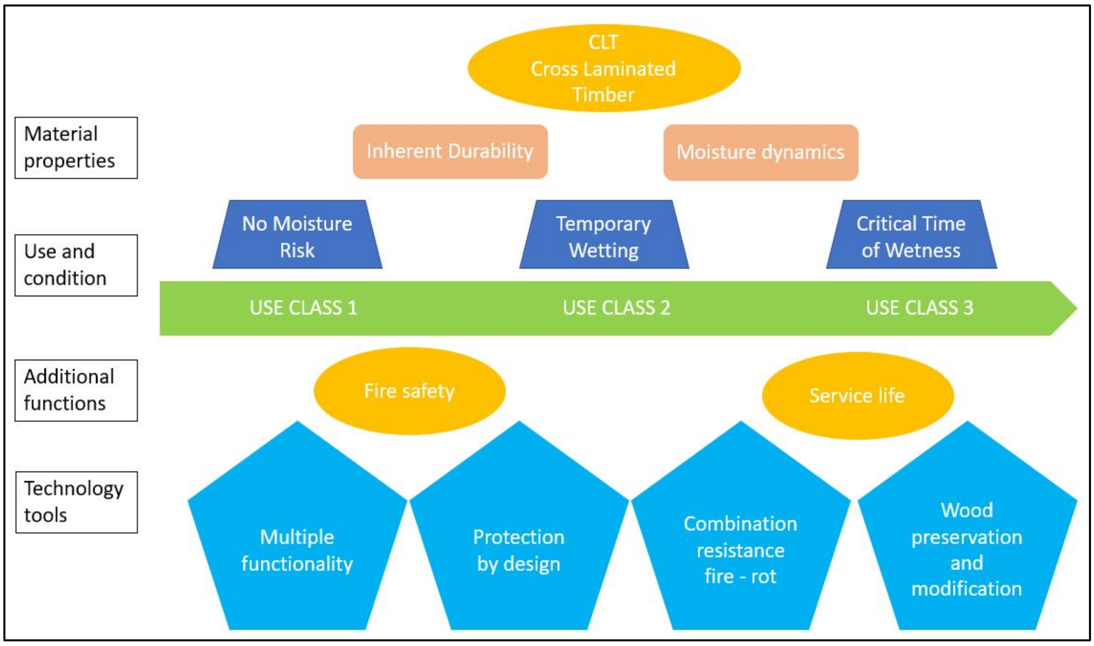

Figure 3: Parameters for multi criteria decision making on wood protection of CLT

A first one is based on built-in or add-on components that lead to enhanced performance like the use of plasterboard to increase fire safety. A second technology tool is protection by design that related to service life mainly focusses on avoiding higher moisture content by including barriers to prevent rain impact during construction and leakage and condensation issues during use. When moving towards use class 3, exterior applications, it becomes more relevant to increase the inherent or natural durability against decaying organisms by adding specific treatments in the range of wood preservation and wood modification. Nevertheless, also impacting on the moisture dynamics can be part of the solution, e.g. by means of coatings. Finally, there is the option to combine both fire and decay resistance with often the critical parameter of fixation of active ingredients. This clearly is a technology tool still to be explored beyond current state of the art, but could bring an extra boost to the use of CLT.

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