DOCTORAL THESIS

Moisture Safety of Cross-Laminated Timber Construction

Kristo Kalbe

TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY
TALLINN 2025

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DOCTORAL THESIS
44/2025

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PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
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This dissertation was accepted for the defence of the degree 26/05/2025

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Kristo Kalbe

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ISSN 2585-6898 (publication)
ISBN 978-9916-80-315-8 (publication)
ISSN 2585-6901 (PDF)
ISBN 978-9916-80-316-5 (PDF)
DOI https://doi.org/10.23658/taltech.44/2025
Printed by EVG Print

Kalbe, K. (2025). *Moisture Safety of Cross-Laminated Timber Construction* [TalTech Press]. https://doi.org/10.23658/taltech.44/2025

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
44/2025

Ristkihtliimpuit ehituse niiskusturvalisus

KRISTO KALBE

TALTECH KIRJASTUS

Abstract

Moisture Safety of Cross-Laminated Timber Construction

Moisture safety of cross-laminated timber (CLT) construction is an important and current topic. Previous studies have scarcely addressed water absorption through the end-grain surfaces of CLT. It is essential to understand when and how CLT panels become wet, including near the end-grain surfaces. A full-coverage weather protection structure is an effective method for ensuring moisture safety, but it is not always feasible. Therefore, it is necessary to investigate the efficacy of local moisture protection and alternative moisture safety strategies. This requires hygrothermal simulations, but modelling wetting and drying of CLT is complex due to the anisotropy of wood, which has often been overlooked in previous studies, due to e.g. limitations of simulation methods. This thesis addresses these gaps and offers solutions to improve the moisture safety of CLT.

To answer the research questions, three general methods were used: 1) field studies in eight buildings, including analysis of project and procurement documentation, on-site observations, moisture measurements, and weather data analysis; 2) laboratory experiments on the wetting and drying of CLT; and 3) computer simulations using a novel two-dimensional (2D) anisotropic heat and moisture transfer (HAM) simulation method.

The field study showed that wetting of CLT through end-grain surfaces occurred in all studied buildings, and often the moisture content (MC) remained above 25 % for several months until specific drying of the wet area was applied. Excessive MC frequently occurred even after single rain events. A rapid construction process is not always sufficient to ensure moisture safety. Protruding details, such as floor panels and bitumen strips under wall panels, facilitated water reaching the end-grain surfaces of CLT wall panels. Even with a well-planned moisture safety strategy and an experienced contractor, moisture safety could be compromised. Moisture safety solutions must be clearly defined during the design phase, as the quality of design appears to outweigh the contractor's experience in ensuring moisture safety. To support this, designs and proposals for local moisture protection solutions for CLT joints were developed.

A novel 2D anisotropic HAM simulation model was validated and corresponding material files for spruce were developed. The validation was done against three laboratory tests. Variability of measurement results required the use of multiple material files. Without adjusting the moisture storage function in the capillary pressure range of approximately -10^6 Pa to -10^5 Pa, it was not possible to simultaneously model rapid water absorption near the end-grain surfaces and slower moisture transfer further from end-grain. This new model enables a more precise evaluation of moisture risks in CLT.

A new two-step performance criterion for evaluating moisture safety of CLT in the event of wetting through the end-grain surfaces was developed: MC ≤ 16 % at 30 mm distance and MC ≤ 25 % at 10 mm distance from the end-grain surfaces. This performance criterion is valid only if wet areas are exposed or covered with vapour-permeable layers.

Simulations with 30 years of climate data showed that installing CLT in spring is beneficial for ensuring moisture safety. Local protection of end-grain surfaces or full-coverage weather protection is recommended, but long construction periods should be avoided even with complete protection. Moisture safety can be ensured with local moisture protection solutions. In the event of wetting through the end-grain surfaces, drying without external assistance is expected only in spring. The results of the moisture safety analysis were applied to predict the performance of moisture safety strategies in two of the buildings studied. The prediction method was broadly accurate.

Lühikokkuvõte

Ristkihtliimpuit ehituse niiskusturvalisus

Ristkihtliimpuit (CLT) ehituse niiskusturvalisus on oluline ja aktuaalne teema. Varasemates uuringutes on CLT lõikeservade kaudu vee imendumist vähe käsitletud. Vajalik on teada, millal ja kuidas CLT paneelid märjaks saavad, sealhulgas lõikeservade lähedal. Hoonet kattev täielik ilmastikukaitserajatis on hea vahend niiskusturvalisuse tagamiseks, kuid mitte alati teostatav. Seetõttu tuleb uurida ka kohaliku niiskuskaitse ja alternatiivsete niiskusturvalisuse strateegiate toimivust. Selleks on omakorda vajalikud niiskuslevi simulatsioonarvutused, kuid CLT lõikeservade märgumise ja kuivamise modelleerimine on keeruline puidu anisotroopsuse tõttu. Anisotroopsus on varasemates uuringutes sageli kõrvale jäetud, sh arvutusmetoodiliste piirangute tõttu. Käesolev töö täidab need lüngad ja pakub lahendusi CLT niiskusturvalisuse parandamiseks.

Uurimisküsimustele vastamiseks kasutati kolme üldist meetodit: 1) välitööd kaheksas hoones koos projekt- ja hankedokumentatsiooni analüüsi, kohapealsete vaatluste, niiskusmõõtmiste ja ilmaandmete analüüsiga; 2) laboratoorsed katsed CLT märgumise ja kuivamise kohta; ja 3) niiskuslevi simulatsioonarvutused rakendades uut kahemõõtmelist (2D) anisotroopset soojus- ja niiskuslevi arvestavat meetodit.

Välimõõtmised näitasid, et CLT märgumist läbi lõikeservade esines kõigis uuritud hoonetes ja sageli püsis märgunus kohtades puidu niiskussisaldus üle 25 % mitu kuud, kuni rakendati märgunud ala spetsiifilist kuivatamist. Lubatust kõrgem niiskussisaldus tekkis sagedasti ka pärast üksikuid vihmahooge. Ka kiire ehitusprotsess ei ole alati piisav niiskusturvalisuse tagamiseks. Väljaulatuvad detailid, nagu põrandapaneelid ja bituumenribad seinapaneelide all, soodustasid vee jõudmist CLT seinapaneelide lõikeserva alla. Isegi hästi planeeritud niiskusturvalisuse strateegia ja kogenud töövõtja korral võis niiskusturvalisus olla ebapiisavalt tagatud. Niiskusturvalisuse lahendused tuleb selgelt määratleda projekteerimisfaasis, kuna projekteerimise kvaliteet näib kaaluvat üles töövõtja kogemuse niiskusturvalisuse tagamisel. Selle toetamiseks töötati CLT liitekohtade jaoks välja ettepanekud paiksete niiskuskaitse lahenduste kohta.

Valideeriti uus 2D anisotroopset soojus- ja niiskuslevi arvestav simulatsioonimudel ning töötati välja vastavad materjalifailid kuusepuidu jaoks. Valideerimine teostati kolme erineva laborikatse põhjal. Mõõtmistulemuste varieeruvus nõudis mitme materjalifaili kasutamist. Ilma sorptsioonkõverat kohandamata (eriti poorirõhu vahemikus ligikaudu -10^6 Pa kuni -10^5 Pa) ei olnud samaaegselt võimalik modelleerida ulatuslikku vee imendumist lõikeservade lähedal ja niiskuse aeglasemat ümberjaotumist lõikeservast kaugemal. See uus mudel võimaldab senisest täpsemalt hinnata CLT niiskusriske.

Töötati välja uus kaheastmeline hindamiskriteerium CLT niiskusturvalisuse hindamiseks lõikeservade märgumise korral: niiskussisaldus ≤ 16 % 30 mm kaugusel ja niiskussisaldus ≤ 25 % 10 mm kaugusel lõikeservade pindadest. Toimivuskriteerium kehtib kui CLT jääb katmata või kaetakse kihtidega, millel on väike veeaurutakistus.

Simulatsioonid 30 aasta kliimaandmetega näitasid, et CLT paigaldamine kevadel soodustab niiskusturvalisuse tagamist. Lõikeservade kohalik kaitse või täielik ilmastikukaitse on soovitatav, ent tuleks vältida pikki ehitusperioode isegi täieliku kaitse korral. Niiskusturvalisuse tagamine on võimalik paiksete niiskuskaitse lahendustega. Lõikeserva kaudu märgumise korral on niiskuse abivahenditeta väljakuivamine oodatav üksnes kevadel. Niiskusturvalisuse analüüsi tulemusi rakendati niiskusturvalisuse strateegiate toimivuse ennustamiseks kahes uuritud hoones. Ennustusmeetod oli üldiselt täpne.

Contents

List of publications

The core findings and key arguments of the doctoral thesis have been published in two peer-reviewed journal articles and one peer-reviewed conference paper:

I **Kalbe, K.**, Kukk, V., & Kalamees, T. (2020). Identification and improvement of critical joints in CLT construction without weather protection. 12th Nordic Symposium on Building Physics (NSB 2020, Tallinn, Estonia), E3S Web of Conferences, 172, 10002. https://doi.org/10.1051/e3sconf/202017210002

II **Kalbe, K.**, Kalamees, T., Kukk, V., Ruus, A., & Annuk, A. (2022). Wetting circumstances, expected moisture content, and drying performance of CLT end-grain edges based on field measurements and laboratory analysis. Building and Environment, 221, 109245. https://doi.org/10.1016/J.BUILDENV.2022.109245

III **Kalbe, K.**, Pärn, R., Ruus, A., & Kalamees, T. (2024). Enhancing CLT Construction – Hygrothermal Modelling, Novel Performance Criterion, and Strategies for End-Grain Moisture Safety. Journal of Building Engineering, 111411. https://doi.org/10.1016/j.jobe.2024.111411

The thesis is further supported by two other peer-reviewed publications that provide complementary evidence and insights:

IV **Kalbe, K.**, & Kalamees, T. (2025). Evaluating Moisture Safety Strategies in CLT Buildings – Predictions vs Actual Outcomes. Case Studies in Construction Materials, https://doi.org/10.2139/ssrn.5073613 (submitted on 17th December 2024, revision submitted on 12th March 2025, under review)

V **Kalbe, K.**, Annuk, A., Ruus, A., & Kalamees, T. (2021). Experimental analysis of moisture uptake and dry-out in CLT end-grain exposed to free water. Journal of Physics: Conference Series, 2069(1), 012050. https://doi.org/10.1088/1742-6596/2069/1/012050

These publications are referred to in the thesis by their Roman numerals.

Author’s contribution to the publications

The author of the thesis is the principal author in all of the publications. Specific contribution to the articles in this thesis is as follows:

I The methodology was compiled by the author with valuable guidance from Targo Kalamees, who also contributed to the conceptualisation of the study. The author conducted the field measurements and identified vulnerable areas in the CLT panels, with support from Villu Kukk, who also assisted with data visualisation. The author was responsible for data analysis, developing the weather protection solution proposal, and preparing the technical drawings, all of which were discussed and validated with the co-authors. The article was co-written by the author and Villu Kukk. Targo Kalamees reviewed and edited the original draft.

II The author conceptualised the work and developed the methodology for the field observations, measurements, and laboratory analysis. The field observations and measurements were carried out by the author, with supplementary input from Villu Kukk. The laboratory investigation was carried out by Alvar Annuk, under the supervision of the author and Aime Ruus. Targo Kalamees contributed to the conceptualisation. The author wrote the original draft, which was later reviewed and edited by Targo Kalamees, Aime Ruus and Villu Kukk. In addition, the author handled data curation and visualisation for the article.

III The author conceptualised the work and developed the methodology for the laboratory analysis, simulation validation, creation of the novel performance criterion, and analysis of the moisture safety strategies. The laboratory investigation was carried out by Roland Pärn, under the supervision of the author and Aime Ruus. Targo Kalamees contributed to the development of the analysis of the moisture safety strategies. The author wrote the original draft, which was later reviewed and edited by Targo Kalamees. In addition, the author handled data curation and visualisation for the article.

IV The author conceptualised the work, developed the methodology and carried out the field investigation and case study analysis. The author wrote the original draft, which was later reviewed and edited by Targo Kalamees. In addition, the author handled data curation and visualisation for the article.

V The author conceptualised the work and developed the methodology. The laboratory investigation was carried out by the author and Alvar Annuk, with the help of Aime Ruus. The author wrote the original draft, which was later reviewed by Targo Kalamees. In addition, the author handled data curation and visualisation for the article.

Abbreviations

1D	One-dimensional
2D	Two-dimensional
CLT	Cross-laminated timber
CW	Cellulose wool
EMC	Equilibrium moisture content
EPS	Expanded polystyrene (insulation)
ETICS	External thermal insulation composite system
FSP	Fibre saturation point
FWP	Full-coverage weather protection
gnd.	Ground
HAM	Heat, air and moisture (modelling)
HSD	Horizontal surface drainage implementation
IBK	Institut für Bauklimatik (Technische Universität Dresden)
inst.	Installation
MBE	Mean bias error
$MC_{10\ mm}$	Moisture content measured at 10 mm from water contact surface
$MC_{30\ mm}$	Moisture content measured at 30 mm from water contact surface
MRY	Reference year for hygrothermal calculations
MW	Mineral wool
PE	Polyethylene
PIR	Polyisocyanurate (insulation)
RMSE	Root mean square error
RQ	Research question
TS	Test specimen
TSs	Test specimens
VB	Vapour barrier
Vent.	ventilated

Symbols and units

A_W	Water absorption coefficient, kg/($m^2s^{0.5}$)
M	Mould index by the Finnish mould growth model, —
MC	Moisture content, %
RH	Relative humidity, %
S_d	Water vapour diffusion equivalent air layer thickness, m
t	Temperature, °C
t_i	Indoor temperature, °C
$\Delta\nu$	Moisture excess of internal air, g/m^3

1 Introduction

1.1 Background and motivation

In *Cross-Laminated Timber: Pioneering Innovation in Massive Wood Construction*, Fleming (2021) traces the genealogy of Cross-Laminated Timber (CLT) and the development of early CLT panels in the 1990s from the initial Blockholz in Switzerland and Dickholz in Germany to Kreuzlagenholz (KLH) in Austria. Fleming suggests that among the previously mentioned three areas where CLT-like products first appeared, those developed in Austria at TU Graz and KLH-Massivholz GmbH most closely resemble modern CLT. Interestingly, in 2012, the first Estonian building to use CLT as a load-bearing element (Figure 1, left) was also constructed with panels from KLH-Massivholz GmbH (Reinberg et al., 2013). Having participated in the project, the author of this thesis has valued CLT as a construction material ever since and this appreciation also serves as the driving motivation for the thesis – to improve the moisture safety of CLT construction.

Figure 1. Left: Põlva, 2012 – Estonia's first CLT building under construction using panels from Austria. Right: Tallinn, 2024 – Estonia's largest wooden building, constructed with locally manufactured CLT from Arcwood, by Peetri Puit OÜ. Author's photos.

Beyond its lower environmental impact compared to concrete and masonry, CLT offers multiple advantages in construction, including faster assembly and a high strength-to-weight ratio. However, its inherent properties make it susceptible to moisture-related issues such as mould growth, decay, and reduced mechanical performance. In 2012, when the first CLT building in Estonia was built, moisture safety was still gaining attention. For example, a method for including moisture safety into the building process was standardised in Sweden as ByggaF in 2013, although the development of the method began in the mid-2000s. Despite existing knowledge and moisture management methods like ByggaF (2013), challenges remain. Olsson (2021) analysed CLT buildings constructed without weather protection and found mould growth in half of the measurement points, with around a third showing moderate to extensive mould growth.

Research regarding the moisture safety of CLT has mainly concentrated on the hygrothermal performance of the plane surfaces of CLT panels, such as the PhD research by Kukk, (2022). However, the author's experience suggests that moisture safety of CLT buildings during the construction period is most compromised near the end-grain surfaces and that is where the focus of research should be to enhance the quality of CLT construction. Yet, many studies regarding the moisture safety of CLT rely on one-dimensional (1D) hygrothermal simulation models or, when using the two-dimensional (2D) approach, often treat CLT as a homogeneous material, disregarding the anisotropic nature of wood. To accurately model moisture flow through the end-grain surfaces and the subsequent moisture dry-out and redistribution, a 2D approach must simultaneously incorporate multiple material properties corresponding to the characteristic wood grain directions within a single representative elementary volume.

Moisture safety is particularly important as larger and taller CLT buildings are being designed and built, amplifying the risks associated with moisture damage. An example of a larger CLT building is the Pelgulinna State Upper Secondary School in Tallinn, completed in 2023, where the total volume of CLT is 2,530 m^3 (Figure 1, right). The construction process of this school demonstrated advancements in moisture safety, particularly concerning CLT, to which this thesis has also contributed.

By identifying problem areas, analysing CLT wetting circumstances, developing and validating hygrothermal simulation models, establishing performance criteria, and proposing and testing moisture safety strategies, this thesis aims to improve CLT construction.

1.2 Objective and hypotheses

The primary objective of this thesis is to enhance the moisture safety of CLT buildings, with a specific focus on the end-grain areas of CLT panels. The thesis provides recommendations and strategies to improve moisture safety in CLT construction.

The explicit research questions (RQ) are as follows (Figure 2):

RQ1 Where should efforts be concentrated to achieve the greatest effect in improving the moisture safety of CLT construction?

RQ2 Are drawings of connection joints and general guidelines in design documentation enough to achieve moisture safety during the construction phase of CLT structures, or should technical drawings for the construction stage be developed for a moisture safety design, and what should they feature?

RQ3 In the event of failed moisture safety during construction, what are the moisture ingress patterns, exposure conditions, expected moisture content (MC), and dry-out characteristics of massive wood?

RQ4 What is a suitable performance criterion for assessing moisture safety near CLT end-grain surfaces, given that liquid water absorption rapidly reaches commonly used MC limits, yet short-term wetting may not pose an immediate risk?

RQ5 While full-coverage weather protection offers high levels of moisture safety, what other strategies – considering building size, type, construction season, and local protection measures – can achieve optimised moisture safety?

RQ6 How effective are the optimised moisture safety strategies in practice, and to what extent do the realised outcomes match the predictions?

Drawing from the research questions, several hypotheses were proposed:

- During the construction period, the moisture safety of CLT panels is most compromised near the end-grain surfaces;
- In CLT, water absorption through end-grain surfaces causes a rapid yet localised rise in MC. A performance criterion should consider this;
- Early-stage analysis of moisture management strategies provides probabilistic insights that could improve decision-making for moisture management in CLT construction.

1.3 Research methodology and structure

The thesis is based on a peer-reviewed conference paper and on three journal articles. A graphical overview of the research structure is given in Figure 2.

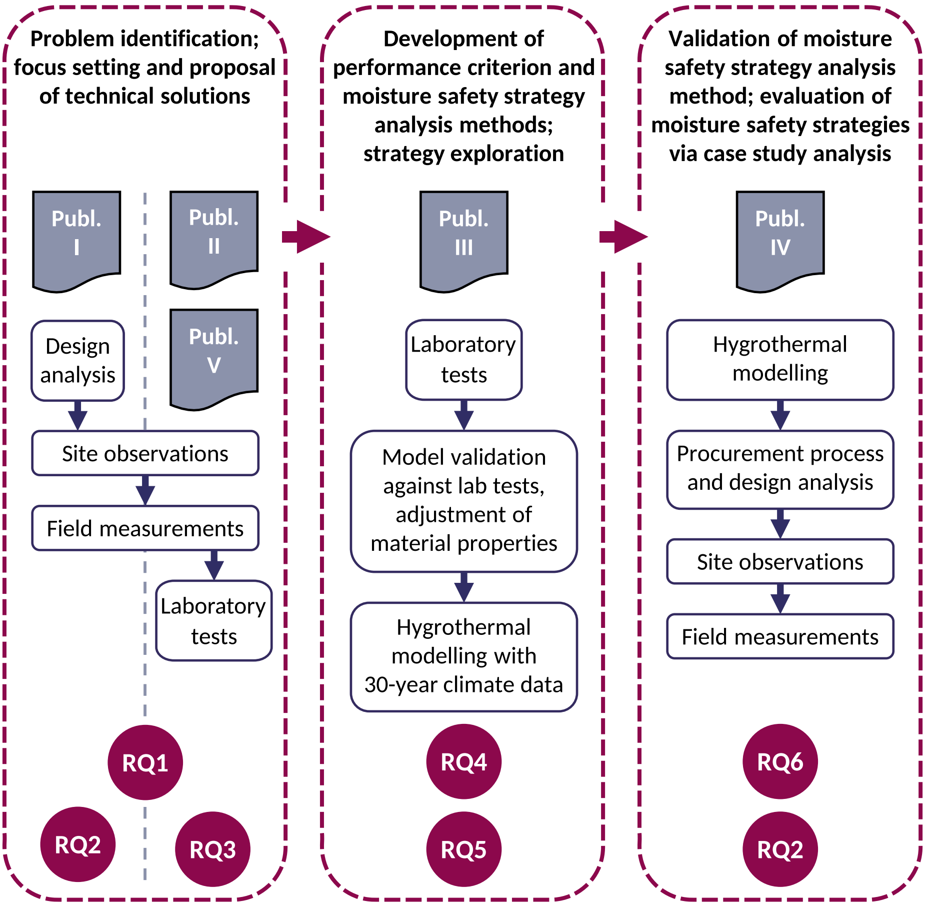


Figure 2. Research structure (RQ = research question).

To answer the research questions, the following main methods were employed:

- field studies – site observations, moisture measurements, precipitation data collection, and analysis of project design;
- laboratory studies – water absorption tests, wetting and drying cycling of CLT, electrical resistance-based and gravimetric MC measurements, measurement of basic material properties;
- hygrothermal modelling – accounting for anisotropic material properties in 2D moisture transfer, development of material files for anisotropic modelling, validation against measurements, mould index calculations, modelling with long-term climate data for moisture safety strategy analysis and for analysing correlation with climatic factors.

The first objective was to validate the initial hypothesis that during the construction period, the moisture safety of CLT panels is most compromised at the end-grain surfaces. The construction of the largest CLT building in Estonia at that time was closely followed and the results were published in **Publication I**. It was discovered that focus for further investigation must be on the bottom areas of CLT wall panels, and that execution method planning and design drawings for moisture safety measures should be added to architectural and structural drawings to ensure moisture safety. Draft technical drawings for proposed local protection measures were developed. As a result, **RQ1** and **RQ2** were answered mostly in **Publication I**. The method for obtaining information from construction sites was improved throughout the first field study and was later applied more extensively in following field studies covered in **Publications II** and **IV**.

Next, an in-depth investigation into the wetting circumstances was carried out using data gathered from six CLT buildings of various sizes and types. This provided additional insights to fully address **RQ1**, and as specific moisture ingress patterns, exposure conditions, expected MC, and dry-out characteristics of CLT were examined, **RQ3** was also answered. The findings were detailed in **Publication II**.

Laboratory tests and field study findings as detailed in **Publication II** and **Publication V** demonstrated that when liquid water was absorbed through the end-grain surfaces of CLT, the resulting elevated MC remained localised. While instances of moisture damage were observed, there were also cases where no damage was reported except increased MC, which itself was not yet damage. This led to the conclusion that commonly used MC limits in procurement processes may be overly stringent when dealing with end-grain water absorption, as even short-term wetting can cause elevated MC in localised areas. As a result, the development of a new moisture safety performance criterion for CLT, one that accounts for rapid water absorption along the grain, was identified as beneficial. The second hypothesis was confirmed.

To establish the new criterion, a reliable hygrothermal simulation model had to be constructed and validated. Simulating CLT end-grain wetting and dry-out posed several challenges, which were addressed in **Publication III**. This publication presented the validation of a 2D hygrothermal model that, at the time of writing, integrated an experimental anisotropic transport method and custom spruce material files to simulate vertical water uptake in CLT and the simultaneous drying processes. Although, the development of the 2D anisotropic simulation model was not explicitly an objective of this thesis, it became an integral part of the research.

With the sufficiently validated simulation model and a plausible performance criterion (which answered **RQ4** and confirmed the second hypothesis) based on the experience from the construction sites, it was now possible to do a comprehensive analysis of CLT wall panel end-grain moisture safety using climate data representing a period of 30 years and a total of 864 moisture safety strategy and process variables resulting in a total of 77,760 simulations. The results of this analysis were also included in **Publication III**, thereby offering an answer to **RQ5**.

The impact of applied and incidental moisture management strategies of two CLT buildings were evaluated and the model and analysis method from **Publication III** were applied in the case studies of **Publication IV**. The hygrothermal model was revalidated, and the moisture safety strategy analysis method was utilised to predict the moisture safety outcomes for the case study buildings. These predictions were then compared to the actual construction process and outcomes, answering **RQ6** and confirming the third hypothesis. To provide a more robust answer, **RQ2** was re-examined in the light of the data and insights obtained from the work presented in **Publication IV**.

1.4 Scientific novelty and practical application

This thesis and publications contribute to enhancing moisture safety in CLT construction and simulation science. New knowledge gained from this research includes:

- **Areas for targeted improvement of moisture safety.** The exterior wall-to-foundation connection and end-grain surfaces of CLT panels were found to be highly susceptible to moisture ingress. These areas often had limited drying potential. Expected moisture dry-out times were provided for varying exposure durations and conditions.

- **Recommendations for moisture safety design enhancement.** Specific guidance is needed on how to implement local moisture protection to ensure moisture safety. Design clarity and quality significantly influence the moisture safety of CLT construction.

- **Valuable empirical data.** Information from construction sites and laboratory tests on moisture ingress patterns, exposure conditions, and dry-out characteristics of CLT provided input data for hygrothermal modelling, risk assessment, and the development of moisture safety strategies. At the time of writing this thesis, the data has already been used to validate separate hygrothermal modelling approaches by independent research groups.

- **Validation of the 2D anisotropic hygrothermal simulation model.** It was demonstrated that accurately simulating water uptake through CLT end-grain surfaces, moisture redistribution within the panel, and subsequent dry-out to the surrounding environment required a hygrothermal simulation model that accounts for the anisotropy of timber material properties. The model was sufficiently validated. Additionally, it was indicated that selecting material files based solely on the water absorption coefficient was insufficient, and thorough validation was recommended. Laboratory tests revealed significant variations in water uptake intensity, indicating the need for multiple material definitions to reliably analyse the moisture safety of CLT when in contact with liquid water. Simulation results were also shown to be significantly influenced by the moisture storage function in the overhygroscopic range.

- **A refined moisture safety performance criterion** was developed to assess moisture safety near the end-grain areas of CLT panels. This criterion considered the rapid absorption of liquid water, which could quickly reach common MC limits. The performance criterion can be easily implemented in practice.
- **A moisture safety strategy risk assessment method** was developed using a large number of simulations based on 30 years of climate data and was tested on-site to evaluate its effectiveness.

The practical applications and recommendations for CLT building design and construction include:

- To ensure moisture safety, a tightly adhering protective material should be applied to the end-grain surfaces of CLT, or a full-coverage weather protection structure should be implemented. Installing CLT under a full-coverage weather protection structure provides high level of moisture safety.
- Local protection alone without full-coverage weather protection can suffice, but this approach entails higher risks and requires an adaptive moisture management strategy. A preliminary risk assessment is strongly advised when relying on local protection or considering the exclusion of protection measures. Local protection measures are not always reliable and can be damaged; regular moisture monitoring is necessary.
- Example drawings for local moisture protection of CLT panels during construction were developed.
- Estimation of moisture dry-out times for scenarios without assisted drying was provided. Unassisted dry-out is feasible only during relatively dry seasons (e.g., spring in Estonia). At other times, using additional drying equipment is warranted to ensure a timely moisture dry-out.
- Moisture dry-out periods should be incorporated into CLT moisture management, as even short installation durations entail a low success rate if no end-grain protection is implemented and moisture dry-out becomes necessary to avoid built-in moisture.
- Recommendations were provided for scheduling the start of CLT panel installation, along with suggested moisture safety strategies based on factors such as season, construction period duration, and other relevant conditions. Installing CLT panels during a dry period, such as spring, is highly advantageous, whereas autumn (in Estonia) poses the highest risk due to elevated ambient humidity and limited moisture dry-out potential, which persists in winter.
- Delaying the installation of full-coverage weather protection until after CLT is installed increases the risk of wetting incidents due to potential damage or incompleteness of local protection. Extended exposure to outside air, even under full-coverage weather protection, elevates CLT MC and increases the risk of damage.

2 State-of-the-art moisture safety of CLT

2.1 Moisture risk and CLT

The sensitivity of wood to moisture and the need to protect it from wetting are long-recognised concerns. For instance, Jürgenson (1939), an Estonian construction scientist brought out seven commandments for the protection of wood in his article *On Wood as a Building Material*. Protection against moisture was placed at the top of the list. It is well established that moisture is the most important factor for wood biodegradation (O. Schmidt, 2006). This also expands to cross laminated timber (CLT). For example, laboratory studies have shown that wet, contaminated CLT is vulnerable to decay (Cappellazzi et al., 2020; Singh et al., 2019). Research also indicates that decay may already start during the construction period. Austigard & Mattsson (2020) published fungal examination data from 11 massive timber buildings out of which 10 were CLT buildings. Five of the studied CLT buildings were under construction at the time of microbial sampling. Decay damage caused by brown-rot fungi was detected in two CLT buildings in the construction phase and in four CLT buildings in the use phase. In one of the decay cases detected during the construction phase, damage was found up to 2 cm into the CLT. Decay during the construction period is typically not expected because of unfavourable conditions, but Austigard & Mattsson (2020) argued that the outside temperature was higher than usual during the construction period of the studied buildings, which could have provided suitable conditions for microbial growth. In addition, they detected mould growth in four buildings in the construction phase and in two buildings in the use phase. The main causes listed for the microbial damage were water intrusion during the construction phase or constructional errors. Many fungi they detected were tolerant to low temperatures. This implies that moisture intrusion during the construction period is a high-risk factor for the durability of CLT, because other conditions for microbial growth might be present. A key takeaway from Austigard & Mattsson's (2020) work is to avoid covering wet CLT surfaces with layers that inhibit moisture dry-out, because it poses a high risk of microbial growth. In another study where the construction of CLT buildings where monitored, and CLT exposure to bulk water was detected, the author reported that half of the 200 samples collected for microbial analysis had mould growth and about a third had moderate or severe mould growth (Olsson, 2021). Most of the wood surface moisture measurement points had a MC of at least 19 %. Olsson (2021) deduced that when exposing CLT to free water (e.g., not using weather protection), it is very difficult to avoid microbial growth on the panels. However, CLT buildings are often erected without weather protection and errors during construction happen. Liisma et al. (2019) analysed construction of a CLT building without a temporary roof and showed that in an uncovered horizontal CLT element that was exposed to precipitation, the MC reached over 25 % after single intensive rain events. Despite established knowledge, moisture-related problems continue to occur. The CIB W040 study (Morishita-Steffen et al., 2021) found that one-third of the surveyed projects experienced moisture issues, despite the application of preventive measures in many cases. Respondents brought out that effective moisture safety requires dedicated time and resources during planning and construction. This indicates the importance of both targeted knowledge on moisture risks in CLT and the development of optimised moisture safety strategies, which are the central topics of this thesis.

2.2 Moisture safety of CLT panels regarding end-grain surfaces

Studies on CLT moisture safety have largely concentrated on the hygrothermal behaviour of plane surfaces and moisture transfer through the faces of wall and floor panels. For example, Kukk, Kaljula, et al. (2022) and Kukk, Kers, et al. (2022) conducted laboratory tests with CLT walls and applied hygrothermal modelling and stochastic analysis to define limiting values of MC for the interior and exterior surfaces of CLT wall panels. However, water uptake from the end-grain surfaces was not included in the tests. Some studies of CLT moisture safety have specifically excluded the effects of end-grain wetting by sealing these surfaces (Alsayegh, 2012; Kordziel et al., 2018; Lepage, 2012; McClung et al., 2014). Similarly, research on CLT wall assemblies has primarily concentrated on the hygro-thermal performance of their central areas (e.g. in studies by Kordziel et al. (2020), Lepage et al. (2017), Libralato et al. (2021), McClung et al. (2014), Öberg & Wiege (2018), Riviera (2021), Strang et al. (2021), Strang et al. (2023), Svensson Tengberg & Hagentoft (2021), Tripathi & Rice (2019), and L. Wang & Ge (2016)). Research in this area has improved knowledge of moisture safety of CLT and has contributed to the development of practical solutions. For example, Kukk (2022) introduced hygrothermal design criteria for CLT external walls. Additionally, moisture protection products, such as self-adhering membranes for floor panels have entered the market (MOLL bauökologische Produkte GmbH, 2024; SIGA Cover AG, 2024).

However, moisture safety analysis focusing on the end-grain wetting is lacking. A few studies have addressed this topic, primarily in the context of floor panels, where end-grain surfaces were exposed to water run-off, but the findings still focused mainly on the panel faces (Lepage et al., 2017; Öberg & Wiege, 2018; E. Schmidt et al., 2019). E. Schmidt et al. (2019) measured MC in various locations of wetted panels, with measurement points approximately 20 cm from the unsealed end-grain edge and 10 cm from the half-lap connection. The results near the half-lap connection indicated a notable moisture gain and retention, even after 130 cumulative days of drying. The authors pointed out that high MC (approaching or exceeding the fibre saturation point) can be observed in a small area near the end-grain surfaces of CLT panels and that repeated wetting of end-grain joints, combined with moisture-trapping conditions, could lead to moisture accumulation in the panel. In a recent study, Johns & Richman (2025) observed increased moisture content near the edges of CLT roof panels and attributed it to end-grain wetting. As an example, measurements from the centre wood layer, at a depth of 120 mm in 220 mm and 260 mm thick CLT roof panels, showed that MC exceeded 25 % in two of the three wet panels for which data was available. It took nearly one year for the MC to fall below 18 % in one panel, and over six months in the other. End-grain wetting could also pose a problem in panel-to-panel joints where the connection is perpendicular. A moisture monitoring study by E. Schmidt & Riggio (2019) showed that the MC in the lower locations of a CLT wall panel bottom connection generally reached higher values. Vertical plies had both a higher MC and a slower drying rate than horizontal plies, which indicates that the anisotropy of moisture transfer in wood must also be considered when assessing moisture safety at CLT end-grain surfaces.

Taken together, current research confirms that moisture safety at CLT end-grain surfaces is a matter of critical concern. The areas near end-grain surfaces demand greater attention in both analysis and design. Enhancing design practices, developing and testing protective solutions, and systematically analysing moisture safety strategies are necessary steps forward.

2.3 Challenges in HAM simulations of CLT end-grain wetting and drying

Hygrothermal (HAM) simulations can be useful to assess moisture uptake, distribution and dry-out in the CLT panels. However, modelling CLT end-grain joints poses some challenges. CLT comprises timber boards with perpendicular wood fibres in each layer, so that during liquid water absorption from the bottom end-grain surface of the CLT panel, there are a) layers where the water uptake occurs longitudinally and b) layers where it occurs either radially or tangentially (or commonly transversely). At the same time, there is moisture redistribution in and between the layers. Furthermore, moisture dry-out occurs on the side surfaces of the CLT towards the surrounding environment if the side faces remain unexposed to bulk water. This means that there is simultaneous moisture transport in various directions through wood layers with different fibre direction. Likewise, there is moisture transport in various directions in the same wood layer (e.g., water uptake along the grain in the outermost layer and simultaneously water vapour transport perpendicular to the grain from the surface of the same layer). Thus, the moisture transport model needs to vary the material properties depending on the moisture transport direction, i.e., the model must reflect anisotropic variation of the material properties.

Most studies regarding hygrothermal simulations of CLT moisture safety implement one-dimensional (1D) models. In 1D calculations made for assessing CLT wall assemblies, e.g. in studies by Kordziel et al. (2018), Kordziel et al. (2020), Kukk, Kers, et al. (2022), Lepage et al. (2017), Libralato et al. (2021), McClung et al. (2014), Öberg & Wiege (2018), Riviera (2021), Sadłowska-Sałęga & Wąs (2020); Strang et al. (2021), Strang et al. (2023), Svensson Tengberg & Hagentoft (2021), Tripathi & Rice (2019), and L. Wang & Ge (2016), the entire panel is modelled as a single material block. This approach is suitable for assessing the moisture safety of panel centre areas, but cannot be used for moisture uptake and redistribution modelling from the end-grain surfaces. 1D models also do not consider the anisotropic properties of wood. In two-dimensional (2D) calculations (Kukk, Kaljula, et al., 2022), which can simulate moisture flow in multiple directions, the CLT block is still often modelled as one material dismissing the anisotropic nature of wood. There are fewer cases of differentiating the CLT layers as longitudinal or transverse with the respective material properties (Wang et al., 2023) and even fewer examples of simulating moisture transport in CLT by taking account of multiple characteristic directions of wood in a single representative elementary volume in a 2D model. Moreover, in case of contact with bulk water, there is moisture transport in both below and above the fibre saturation point, leading to a complex set of conditions that needs to be accurately considered in a hygrothermal model.

Brandstätter et al. (2023) implemented a purpose-built hygrothermal simulation model developed by Autengruber et al. (2020), which uses the finite element software *Abaqus* to solve the numerical problem. The model was adapted to incorporate moisture transport across all characteristic wood directions simultaneously. To validate their model, Brandstätter et al. (2023) used the laboratory results obtained from the research presented in this thesis. They achieved a good agreement between the simulations and measurements, but their model is not available for use for the general public (as of 2025).

This thesis validates the function of including anisotropic material properties into a 2D model within the commercially available hygrothermal simulation software IBK Delphin (Nicolai et al., 2007). Ensuring a reliable simulation model for analysing CLT end-grain moisture safety is essential.

2.4 Moisture content as a performance criterion

Mould index as well as MC limits are often used as the performance criteria of moisture safety analyses. In the case of end-grain surfaces, water contact can raise the MC in their vicinity very quickly (Kalbe et al., 2021), well above the maximum allowable limit of 15 % at assembly required by the European standard for CLT (EN 16351:2021) or the limits suggested by other researchers, e.g., 16 % proposed by Kukk, Kers, et al. (2022). MC of 16 % also corresponds to a relative humidity of approximately 80 % on the surface of wood (Glass & Zelinka, 2021) and this entails a mould risk if warm conditions last long enough (Johansson et al., 2012). Although it is safest to keep the MC of CLT below this limit, it is in practice difficult to do so without sophisticated weather protection (Olsson, 2021). Ensuring this MC level near end-grain surfaces during CLT construction, especially when exposed to the elements, is practically impossible, even though it may not pose an immediate risk owing to conditions that are unfavourable to mould growth or due to timely moisture dry-out. MC above the suggested limits but without negative consequences, creates contention at construction sites, hindering efficient construction processes. One possibility would be to implement a mould index calculation to predict whether the developed conditions lead to mould growth or not. However, performing mould index calculations during a moisture safety inspection round is not practical, given the rapid pace of modern construction. For a better practical and operative usability on a construction site, it would be beneficial to have a MC-based performance criterion which considers the rapid water absorption of the CLT end-grain surfaces and subsequent moisture dry-out, providing greater flexibility.

2.5 CLT moisture risk mitigation and moisture safety strategies

A reliable method for ensuring the moisture safety of CLT construction is the use of a full-coverage weather protection (FWP) structure, which prevents wetting entirely, excluding accidental leaks through the protection. For example, Bolmsvik et al. (2023) provided evidence supporting the advantages of employing FWP in CLT construction. However, there is reluctance on the market to implement this procedure because of concerns about increasing construction costs, and thus it is an ongoing practice to erect timber buildings without protecting them from precipitation. A cost-optimal solution would be implementing a specific construction methodology to increase the moisture safety of precipitation-exposed timber construction.

Time et al. (2023) presented a moisture safety strategy for CLT buildings comprising of 1) construction scheduling (the installation of the CLT was scheduled for July and August, which the authors referred to as a typically drier period in Trondheim, Norway), 2) localised protective measures, including end-grain surface protection (all interfaces between wood and concrete were protected), 3) immediate action upon rain events to protect the structure and drain free water, 4) regular moisture measurement, and 5) prevention of covering wet CLT panels (target MC < 15 %). The strategy presented by Time et al. (2023) yielded acceptable results by every investigated indicator and the authors concluded that FWP could be substituted by a comprehensive moisture management strategy.

In a Norwegian CLT school building, a temporary tent was considered, but due to cost considerations it was omitted, and a moisture measurement-based moisture safety strategy was opted for (Kellgren et al., 2023). It was presumed that through the constant monitoring, it would be possible to detect moisture ingress and prevent damage.

The sensors were placed on various locations to monitor specifically exposed areas, but it was unclear how close the sensors were to the end-grain surfaces of CLT panels. Nevertheless, several increases in MC were detected, which could have developed into more extensive moisture damage and were thus avoided, showing the usefulness of the selected strategy. A moisture measurement-based moisture safety strategy can also benefit from a more precise MC criterion, as discussed earlier.

A key component in determining moisture safety of CLT is also the season when the installation of CLT panels takes place or the construction of the CLT panels proceeds. The impact of seasonal variation on the moisture safety of timber structures has also been discussed by Pihelo & Kalamees (2020). The worthwhile question is whether seasonality has an effect in CLT construction. If there is an effect, then can the start of CLT installation during a favourable season be considered as an adequate moisture management method?

A common conjecture is that a short construction period could be a valid moisture safety strategy to avoid problems with excessive MC in CLT. However, this might not be the case considering end-grain surfaces. Öberg & Wiege (2018) analysed moisture influence on CLT building and concluded that short building time is essential, early planning to minimise building time is necessary, and some form of weather protection is required year-round. Furthermore, they noted that if expected rainfall exceeds 40 mm or construction lasts longer than a few weeks, a roof cover becomes essential.

E. Schmidt & Riggio (2019) documented the results of CLT moisture monitoring during construction and concluded that achieving a moisture-safe outcome requires preventive actions. These include design adjustments (e.g., avoiding details that trap moisture), fabrication enhancement (e.g., using localised coatings), and construction sequencing (e.g., limiting exposure and ensuring drying). These studies reinforce the critical need for a moisture safety strategy for each CLT building, whether it involves FWP, localised protection, or careful scheduling of installations.

Kodi et al. (2024) reported on moisture damage, specifically mould growth, resulting from inadequate moisture management during a renovation project in Estonia involving prefabricated timber panels. Alongside documenting the damages, the authors examined various moisture safety strategies that could have been implemented. They concluded that employing specific measures, such as maintaining a designated ventilation air change rate in the attic (where significant moisture ingress occurred during construction), could have prevented or mitigated the effects of the moisture ingress. This aligns with the broader consensus in the literature that emphasises the importance of moisture control throughout the building process, as highlighted by Mjörnell et al. (2011), who developed a method for including moisture safety in the building process. The method has different stages in the building process: planning, design, construction, and operation. Although the method contains several routines, templates and checklists for clients to formulate moisture safety requirements and to monitor and document the measures implemented by various actors, 10 years after the development of the moisture safety method, the results of the CIB W040 study (Morishita-Steffen et al., 2021) show that one-third of construction projects were affected by moisture problems, even though practitioners implemented several preventive measures at least some of the time. Wang (2020) has developed a guide for managing construction specifically in CLT buildings, taking a step further from the general guidelines of Mjörnell et al. (2011). The guide by Wang (2020) covers the basics of wood and moisture, detailing a range of moisture safety measures from simple to advanced and spanning local detailing to whole-building protection strategies. Additionally, it offers recommendations for moisture drying and remediation. Alsmarker (2022) also developed a guide for moisture-proofing CLT construction without the use of a full temporary shelter, providing practical solutions and general recommendations for managing moisture in such projects.

Nevertheless, an important question persists: although FWP ensures a high degree of moisture safety, what other strategies can deliver comparable results, considering variables such as a building size and type, construction season, and local protective measures? Additionally, how do these strategies perform under real-world conditions, and can their outcomes be predicted to support knowledge-based decisions for choosing a moisture safety strategy for CLT construction?

3 Methods

3.1 Field study, identification of risk areas and wetting circumstances

This thesis builds on the experience and data gathered during site visits and field measurements from eight CLT buildings in Estonia (Table 1, Figure 3). The site visits included inspecting CLT panels for moisture or damage, checking for free water, stains, shrinkage, or swelling. The delivered CLT panels and packaging were inspected, gaps and/or faults in the material were looked for. On the installed CLT panels, signs of moisture (or moisture damage) – such as the presence of free water on the surface of the structures, stained wood, shrinkage, or swelling – were searched for. In most cases, the construction process was observed until the commissioning of the building. For the buildings G and H, the efficacy and implementation of moisture safety strategies were also analysed, as the methods developed during this thesis for such assessments were ready for testing at the time construction was ongoing in those buildings.

Figure 3. Photos of the studied non-residential buildings during construction.

Table 1. Characterisation of the studied buildings

Studied building	A	B	C	D	E	F	G	H
Use type	Educational	Administrative	Healthcare	Detached houses			Educational	
Year completed	2020	2020	2020	2020	2020	2013	2023	2024
City, County	Tallinn, Harjumaa	Saue, Harjumaa	Kadrina, Lääne-Virumaa	Viimsi, Harjumaa	Saue, Harjumaa	Põlva, Põlvamaa	Tallinn, Harjumaa	Tallinn, Harjumaa
Floors above ground	3	2	1	2	1	2	4	2
Above ground floor area	1695 m^2	1320 m^2	555 m^2	165 m^2	238 m^2	195 m^2	8273 m^2	2427 m^2
Insulation system of CLT walls	MW* + vent. façade	PIR* + vent. façade	MW + vent. façade	PIR + vent. façade		CW* + vent. façade	MW + vent. façade & EPS* + ETICS	MW + vent. façade
Insulation system of CLT roofs	VB* + PIR	VB + EPS	VB + MW	CLT not used in roofs	VB + PIR	VB + EPS	VB + MW	VB + MW
Main CLT composition & thickness	7 ply** 240–260 mm	3 & 5 ply 120–200 mm	3 & 7 ply 120–220 mm	5 ply 100 mm		3 & 5 ply 100–140 mm	5 & 7 ply 110–300 mm	5 & 7 ply 140–300 mm
CLT wall panel surface protection	Yes	Yes	Yes	No	No	No	Yes	Yes
CLT floor panel surface protection	Yes	Yes	No	No	No	No	Yes	Yes
CLT end-grain surface protection	Partially	No	No	No	No	No	Yes	Partially
Moisture management	Comprehensive management***	Construction managed in the way of business-as-usual****					Comprehensive management***	Business-as-usual**** and partly comprehensive management

* MW = mineral wool; PIR = polyisocyanurate insulation panels; CW = cellulose wool; EPS = expanded polystyrene insulation panels; VB = vapour barrier.
** Ply = one timber layer (or lamella) in CLT.
*** Moisture safety plan, regular inspection rounds, water removal, mechanical drying, cleaning, replacement of materials where necessary.
**** No moisture management plan implemented, only casual moisture measurements and incidental water removal, in individual cases local mechanical drying.

Most of the load-bearing structure and partition walls of the studied buildings were made of CLT, except for in building A, where there were additional pre-cast concrete walls and an existing laboratory hall which was renovated (excluded from the study). In each building, the CLT panels were made out of Norway spruce lumber with the outer layers in the vertical direction (longitudinal wood grain in parallel to the height of the building). In the building A, the two outer layers of the CLT panel were both in the same direction, but in all the other buildings, the CLT layer composition was typical i.e., the adjacent layers were always perpendicular to each other. In all cases, the wood in the CLT was untreated, and the edges of the lumber boards were not glued together.

Timber MC was measured according to EN 13183-2:2002 with electrical resistance-based wood moisture meters Gann Hydromette LG 3, Gann Hydromette HT 65, Gann Hydromette CH 17, and Logica Holzmeister LG9 NG. The instruments' accuracy was ± 1 % for MC values < 30 % (± 0.8 % for the Logica Holzmeister LG9 NG for 12 % to 22 % MC). All MC measurements were taken with 60 mm long Teflon insulated pins which had 10 mm uninsulated peaks, making it possible to measure MC at different depths depending on how far the electrodes were rammed in. Measurements were taken from the surface layer (5–10 mm deep) and from the inner (middle) layers (20–50 mm deep, mostly in the 2nd layer, in rare cases in the 3rd layer). With regard to end-grain water absorption, the surface layer aligned with the longitudinal wood grain direction. In contrast, the inner layers (being perpendicular to the panel length) had the wood grain oriented transversely. MC measurements were taken at 30 mm vertical distance and occasionally at 10 mm vertical distance from the end-grain surface (Figure 4). Measuring near knots, cracks or other irregularities was avoided. Though, sometimes wetting had occurred at or near such features. In such cases, several measurements were taken. Since the objective was to identify potentially critical areas, the highest recorded value was prioritised and lower values were considered potentially unrepresentative as these might have been affected by subsurface cracks or other irregularities. Averaging the results might have led to underestimating localised MC peaks.

The general procedure for the MC measurements on the field was as follows:

- visual inspection of the entire building for wet areas,
- MC measurements in all the visually wet areas,
- MC measurements in nearby visually dry, but structurally similar areas.

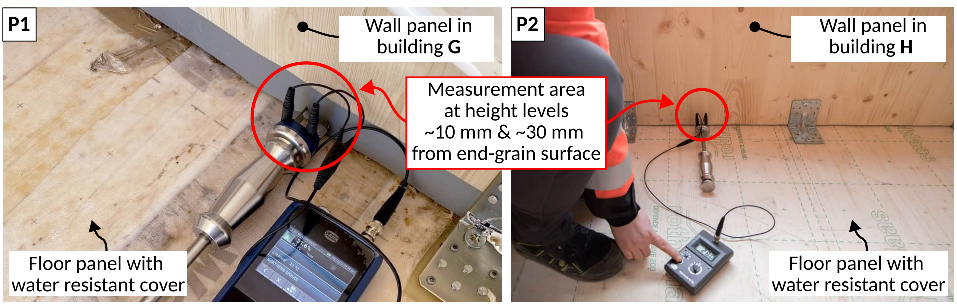


Figure 4. Measuring of CLT MC during the field study. The left photo (P1) is of the building G where the bottom end-grain area had a liquid-applied waterproofing cover (grey area), and the right photo (P2) is of the second floor of the building H where no end-grain moisture protection was used.

During each visit, the procedure was repeated. The MC measurements were never taken from the same probe holes but in close proximity in the same CLT panel. Visit and sampling frequency varied. In some buildings, MC measurements were taken during incidental visits, while in others, MC was measured during dedicated CLT moisture inspection rounds, which resulted in numerous samples per visit. The instruments were adjusted for usage with spruce wood and the temperature of the measured wood. A reference test adapter was used for frequent accuracy checks (rated at 21.0 % ± 0.5 % at 20 °C). For European conifers, a poorer accuracy is expected above 40 % MC, according to the product specifications of the measurement instruments. Some authors equate MC values above the fibre saturation point i.e. above ≈ 30 % to 30 %. However, in this thesis, the measured values were reported as they were. Readings above the fibre saturation point are less accurate (Dietsch et al., 2015), but they still indicate significantly wet wood. Data on MC exceeding the fibre saturation point could be important for dry-out analysis, as a value like 40 % suggests a greater water mass than a 30 % value would imply. When predicting dry-out, this information might be useful.

Air temperature and humidity were recorded with Hobo UX100-023 data loggers (accuracy: ± 0.21 °C, typically ± 2.5 % from 10 % to 90 % RH to ± 3.5 % max; below 10 % and above 90 % ± 5 %).

The site visits were accompanied by a thorough review of procurement and design documents, project drawings, and other relevant materials for the studied buildings. The aim was to analyse the technical drawings of identified vulnerable areas, assess potential improvements and determine whether general moisture safety guidelines were sufficient or if dedicated technical drawings were necessary to ensure the moisture safety of CLT. The field study served as a basis for proposing improvements to local moisture protection measures.

3.2 Precipitation data during the construction of the CLT buildings

The precipitation load on the CLT buildings during installation and subsequent construction, while the structures were exposed to precipitation, was analysed using data from nearby weather stations.

The installation time was defined as the period starting with the unloading of the CLT panels on site and ending with the installation of the last CLT detail (typically a roof/ceiling panel or a top floor wall panel). Of the post-installation construction works, the period when there were at least some parts of the CLT panels still exposed to precipitation was included. The buildings A and G were covered with an FWP structure; therefore, the end of the precipitation-exposed construction phase for these buildings was defined as the point when all parts of the studied building or building section were fully covered by the protection structure. For the other buildings, this phase was considered to end with the completion of insulation installation, when all CLT surfaces were covered by the insulation layer.

Precipitation data was gathered from the nearest weather stations to the buildings. The average distance between a meteorological station and the studied buildings in the coastal area was ≈ 4–10 km (buildings A, B, D, E, G, H). The two buildings (C, F) in the inland area were both ≈ 23 km from the respective nearest meteorological station. Due to the high spatial and temporal variability of precipitation, the recorded rainfall at the meteorological station likely differed from that on the construction site. Given the relatively flat topography of Estonia and the proximity of weather stations in the same climate zone, a similar frequency and general intensity of precipitation was assumed.

3.3 Laboratory experiments

3.3.1 Experiment 1: Moisture distribution development in CLT from end-grain wetting and drying, electrical resistance-based MC measurements

The experiment consisted of two phases: a water uptake test of 7 days (wetting phase) and then a moisture dry-out test of 14 days under four different climatic conditions (drying phase). This wetting-drying experiment was setup to reproduce a situation where the bottom surface of a CLT wall panel was exposed to bulk water, and then it was left to dry-out through its side faces.

The experiment was modelled after EN ISO 15148:2003, which outlines the procedure for determining the water absorption coefficient of building materials through partial immersion. The standard requires sealing all surfaces of the test specimen not in contact with water, however this protocol was modified. The objective of the experiment was not only to assess water uptake but also to investigate the drying behaviour of CLT. Therefore, a drying phase was incorporated into the procedure, and electrical resistance-based moisture measurements were introduced to study the moisture distribution development in CLT from end-grain wetting and drying. Accordingly, the test specimens (TSs) were designed to replicate a scenario, where a CLT panel is exposed to water ingress at the bottom end-grain surface (e.g., wall-to-foundation junction), and the side surfaces remain uncovered by insulation or other layers, thereby allowing moisture to dry-out through the sides.

Twelve spruce CLT TSs (average dry density 415 kg/m^3 ± 18 kg/m^3), measuring 400 mm × 400 mm × 100 mm, were cut from a five-layer CLT panel where each layer was 20 mm thick. The end-grain surfaces of the TSs were coated with a liquid plastic coating (IKO MS Detail), except for the bottom surface which was subjected to water contact (Figure 5, P1 and P2). The TSs were conditioned in sheltered autumn outdoor climate conditions for two weeks before wetting (t ≈ 2 °C ± 2.7 °C, RH ≈ 92 % ± 5 %, measured using a Hobo UX100-023 data logger). This resulted in an initial MC of 10 % to 12 % and up to 20 % on the outermost surface of the TSs.

During the wetting phase, the untreated bottom end-grain surfaces of the TSs were in continuous water contact for one week. The TSs were in containers partially filled with water, and the water level was consistently maintained at approximately 1–2 mm above the base of the specimens by regularly adding small quantities of water (Figure 5, P2). Blunt pins were positioned beneath the TSs to maximise water contact area.

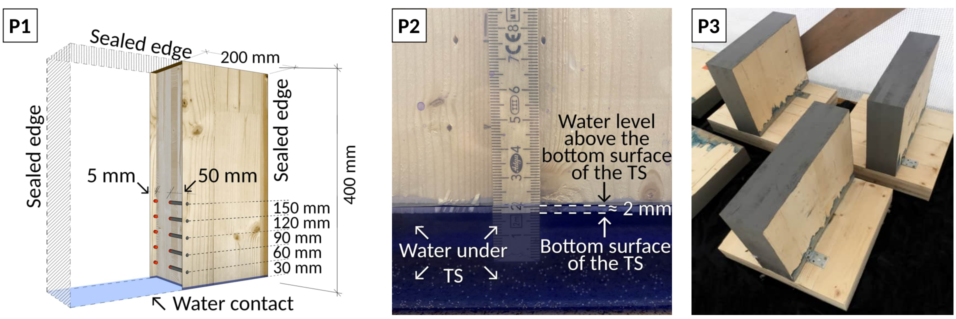


Figure 5. A diagram of the test specimen (TS) with moisture measurement points shown (P1), a TS submersed ≈ 2 mm into water (P2) and TSs in the outdoor shelter during the dry-out phase (P3).

The dry-out phase of the experiment was conducted under both controlled indoor conditions and sheltered outdoor conditions. The indoor conditions were observed to be favourable for drying, with a water vapor pressure difference of ≈ 1800 Pa between the surrounding air and the wet surfaces of the CLT TSs. Conversely, outdoor conditions offered only marginal drying potential, with a water vapor pressure difference of ≈ 50 Pa. The twelve TSs were divided into four groups in the dry-out phase:

- indoor climate and moisture trapping conditions under the end-grain surface,
- indoor climate and uninhibited dry-out,
- outdoor climate and moisture trapping conditions under the end-grain surface,
- outdoor climate and uninhibited dry-out.

To simulate moisture trapping conditions, the TSs were secured to another CLT plate using angled metal fasteners and screws, placing the wet surface in direct contact with the second plate, thereby mimicking a typical CLT wall-to-floor connection (Figure 5, P3). Ambient conditions (Figure 6) were recorded with HOBO UX100-023 data loggers.

All TSs were weighed regularly (every 2 h for the first 6 h and every 24 h afterwards) with a Kern DS 30K0.1L platform scale with an expanded uncertainty of 0.8 g for loads up to 10,000 g. Electrical resistance-based MC measurements were taken with the Logica Holzmeister LG9 NG moisture meter following EN 13183-2:2002 guidelines. MC was measured at two depths from the side faces (5 mm and 50 mm) and at five heights (30 mm, 60 mm, 90 mm, 120 mm, and 150 mm) from the water level (Figure 5, P1). Measurements at the depth of 5 mm and 50 mm are respectively representative of the MC in the surface layer and the middle (3rd) layer of the CLT (made of 5 layers). The wood grain direction was consistent in both layers, with the bottom end-grain surface exposed to free water. The longitudinal layers were considered to be most critical in terms of wetting risk, and measurement efforts were concentrated there. To prevent cross-influence between readings at different depths within the same location, measurements were not taken from the transverse layer. The electrode pins for surface and middle layer measurements were inserted from the opposite sides of the TSs, perpendicular to the measured layer's wood grain. The results revealed minimal variation in MC development at the height of 120 mm and 150 mm, both at the depths of 5 mm and 50 mm. Consequently, only the results from the heights of 30 mm, 60 mm, and 90 mm were utilised for validating the simulation model and preparing subsequent experiments.

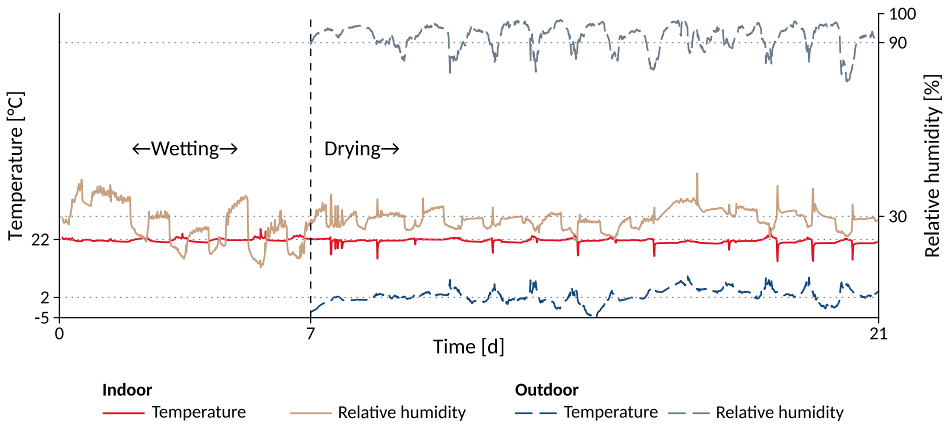


Figure 6. Ambient conditions during the wetting-drying experiment (measured 0.5 m from the TSs).

Blue ink (Parker Quink) was added to water to better visualise moisture transport in the CLT. Parker Quink has been deemed suitable for staining fungal structures in mycological studies (Rodríguez Yon et al., 2015) and was thus considered appropriate for the water uptake study as well. After completing all moisture measurements, the TSs were cut into half, and the reach of the blue staining was analysed. A composite image was generated, which involved stacking the images from all TSs in the darken blending mode. This method allowed integration of the darkest areas across all images, resulting in an image with the more stained regions emphasised.

3.3.2 Experiment 2: Water absorption of timber in different grain directions

In this experiment, 20 timber boards (measuring 400 mm × 100 mm × 20 mm) were extracted from the same batch of CLT panels as in the first experiment. The experiment procedure followed EN ISO 15148:2003, with the only deviation being the addition of electrical resistance-based moisture content measurements. Each board was covered with liquid plastic coating on each side, except the surface contact with water. To compare anisotropic water uptake behaviour, half of the boards were prepared to absorb moisture along the longitudinal grain direction, and the other half along the transverse direction. Although directional moisture absorption in wood is well understood (Glass & Zelinka, 2021), the experiment was required to determine whether, and which, of Delphin built-in material files could be reliably used for compilation of the anisotropic material files (as detailed in Section 3.4.2) and for validation in Experiments 1 and 3, which involve more complex hygrothermal processes.

Mass change of the specimens was measured at intervals of 1 hour, 2 hours, 5 hours, 8 hours, 24 hours, and 48 hours from the initiation of water contact. The experiment was conducted under isothermal conditions (t ≈ 22 °C ± 1 °C, RH ≈ 29 % ± 5 %, recorded using a Hobo UX100-023 data logger). Water absorption coefficients were determined according to EN ISO 15148:2003 via gravimetric measurements. The electrical resistance-based MC measurements (with Logica Holzmeister LG9 NG moisture meter) were taken at regular distances of 10 mm from the water-contact surface, moving upward from the surface that was in contact with water.

3.3.3 Experiment 3: Moisture distribution development in CLT from end-grain wetting, gravimetric MC measurements

The gravimetric MC method (EN 13183-1:2002) was used in this experiment to enable analysis of moisture distribution within different CLT layers near the end-grain surface, where the MC rises rapidly beyond the range of electrical resistance-based MC measurement devices. The experiment involved CLT from the same batch as in the previous experiments, but the TSs were smaller, as the previous experiments showed that the areas most affected by moisture uptake were located up to about 60 mm from the water contact edge. Nineteen TSs were prepared by cutting them from a five-layer CLT. The tested surface of the TSs was 100 mm by 140 mm and the height of the TSs was 70 mm (Figure 7, P1). Before the experiment, the TSs had been stored in indoor conditions for approximately four years under conditions of ≈ 22 °C ± 1 °C (occasionally up to ≈ 27 °C during HVAC downtime) and RH of ≈ 29 % ± 7 %. Prior to wetting, flexible vapour barrier tape (Tectis Sitko Flex) was applied to the end-grain surfaces on the sides of the TSs to prevent moisture transfer through them. The bottom end-grain surface and side faces of the TSs were intentionally left untreated, similarly to Experiment 1 (as described in Section 3.3.1).

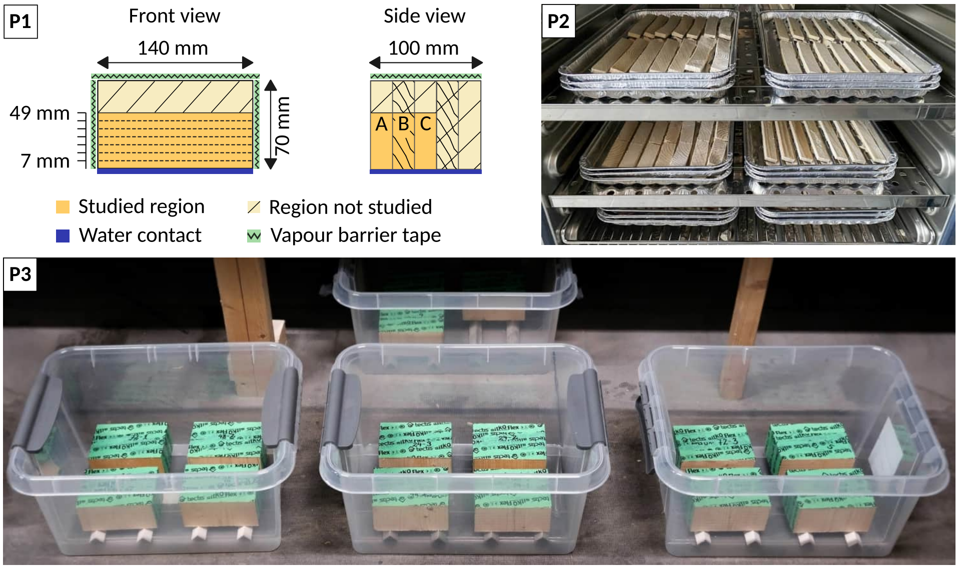


Figure 7. CLT TS dimensions and cutting scheme for the gravimetric MC measurements (P1); specimen ribbons in the drying oven (P2) and TSs in containers for water contact (P3). In P1, A is the outer (surface) longitudinal layer, B is the transverse layer, and C is the inner longitudinal layer.

EN 13183-1:2002 provides guidelines solely for MC measurements and does not prescribe a specific testing protocol prior to sampling. EN ISO 15148:2003 outlines procedures for determining the water absorption coefficient but does not account for moisture dry-out. As such and similarly to Experiment 1, this experiment also required a custom protocol. The experiment consisted of two phases: an initial water uptake test for up to 72 hours (wetting phase) followed by a moisture drying-out test for up to 336 hours. During the wetting phase, the TSs were kept in containers with water levels continuously controlled and maintained at about 1 mm to 2 mm above the test surface of the TSs (Figure 7, P3). Unlike in Experiment 1, it was not possible to use the same TSs throughout the whole experiment due to the destructive nature of the gravimetric method. Thus, MC was measured from separate TSs for each water contact duration.

Weighing the TSs was performed before and after the wetting phase, and following water contact for 4 hours, 8 hours, 24 hours, and 48 hours (three TSs for each duration). Immediately after the wetting phase, the TSs were cut into seven sections with a target thickness of 7 mm using a bandsaw at slow speed with a 0.5 mm-thick blade. This interval was chosen because 5 mm steps made the samples too small, making it difficult to cut uniformly sized specimens, whereas thicker specimens would have had a negative impact on the measurement resolution. Subsequently, these sections were fractured by hand into ribbons, with each ribbon corresponding to a specific layer and timber board within the CLT structure. The thickness of the ribbons was measured with a MarCal 16 EWR digital calliper (error limit 0.03 mm, (Mahr GmbH, 2019)). The ribbons were weighed, then transferred to a Memmert UFB-500 convection oven (Figure 7, P2) and were kept at 70 °C until the difference in mass between two successive weighings, taken two hours apart, was less than 0.1 %. Mass measurements were taken with a Kern PLJ 1200-3A precision balance with a weighing capacity of 1200 g, accuracy of 0.001 g, and precision of ± 0.003 g (KERN & SOHN GmbH, 2021).

In addition, four TSs were kept in water contact for 72 hours and were then transferred to drying in a moisture-trapping setting in conditions with moderate dry-out potential. The moisture trapping conditions were created by tightly securing the TSs to a dry planed timber beam using cable wraps, imitating a CLT wall-to-floor connection. The ambient conditions (t ≈ 6 °C ± 1 °C, RH ≈ 65 % ± 5 %) produced a water vapour pressure difference of approximately 520 Pa between the surrounding air and the wet surfaces of the TSs. This was chosen as a middle ground compared to the two climate conditions in Experiment 1 (Figure 6, in Section 3.3.1). Half of the TSs underwent one week of drying, while the other half underwent three weeks of drying (Table 2). The dried TSs were again cut and fractured into ribbons which were then transferred to the drying oven.

Table 2. Test plan for Experiment 3. Wetting and drying phase durations.

Number of TSs	Water contact duration (h)	Drying duration (h)	Comment
3	4	—	
3	8		
3	24		
3	48		
3	72		
2	72	168	Moisture trapping conditions during drying
2	72	504	

3.4 Hygrothermal modelling

The analysis of CLT end-grain moisture performance was conducted using the dynamic hygrothermal modelling software IBK Delphin 6.1.6 (Bauklimatik Dresden Software GmbH, 2024; Grunewald, 1996) which is suitable for applications in building sciences. Delphin has been validated several times (*Bauklimatik Dresden Software GmbH | DELPHIN - Documentation*, 2024). A technical report from the software developers summarises its validation results using HAMSTAD Benchmarks 1–5, DIN EN ISO 10211 cases 1 and 2, DIN EN 15026, and the absorption-drying test. Delphin was validated for heat, moisture, and air transport in both 1D and 2D situations, with all versions meeting the test case requirements (Sontag et al., 2013). Other authors, independent of the program developers, have validated Delphin models, including Kalbe, Piikov, et al. (2020) who validated a 2D simulation for insulated sandwich panels which were exposed to high humidity and varying climate conditions. Wang et al. (2023) validated a CLT hygrothermal simulation model generated in Delphin and highlighted the significance of differentiating liquid transport properties between the transverse and longitudinal directions. Starting from Delphin version 6, it is possible to consider the anisotropy of materials such as timber, where moisture transfer depends on the wood grain direction. However, there are no definitions of anisotropic spruce or pine material in the Delphin database as of 2025, and custom files must be composed for the anisotropic transport model to work. While the functionality of anisotropic modelling in Delphin has been shown before (Vogelsang & Nicolai, 2014), it is still experimental and needs further validation. Since timber properties can vary even across the same CLT panel, careful consideration is needed when selecting the material properties. Thus, the model and the material properties were validated using the results of the three experiments described above.

3.4.1 Model basics and simulated geometry

Separate model geometries were developed for validating the model with each experiment and for the final analysis (Figure 8). The simulation files were configured to closely align with the experimental conditions. Scheduled water contact was used on the surfaces immersed in water. Water vapour transfer and heat exchange were simulated on the surfaces that were in contact with the ambient air, and the corresponding measured temperature and relative humidity data were used as the boundary condition climate data. No moisture or heat transfer was assumed on the top surface in the models. Relevant outputs (MC, RH, temperature) were defined and set exactly in the locations where measurements were taken or samples were cut during the experiments.

Moisture trapping conditions were simulated by increasing the water vapour diffusion equivalent air layer thickness to 125 m on the bottom end-grain surface of the CLT wall panel, in order to simulate the CLT wall-to-floor connection imitated in the experiments. Liquid water transfer towards such a CLT floor panel was neglected, as the auxiliary CLT panels in the experiments had a very low MC (< 10 %) and thus the liquid conductivity of the dry panels was low. Excluding liquid water transfer towards the CLT floor panel also made sense in the analysis of end-grain protection strategies, because in today's practice CLT floor panels are frequently installed with waterproofing membranes which effectively block liquid water flow, but have a relatively low vapour resistance e.g., Pro Clima Adhero 1000/3000 with an S_d = 0.3–0.8 m (MOLL bauökologische Produkte GmbH, 2024), or Siga Wetguard 200 SA with an S_d = 2.5–4.5 m (SIGA Cover AG, 2024).

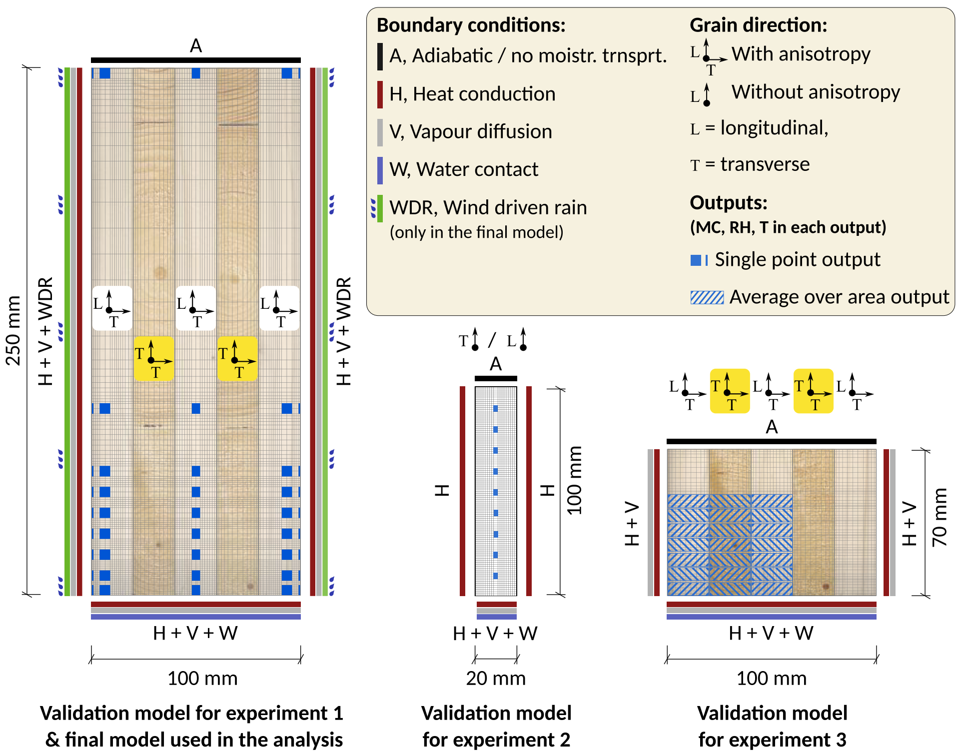


Figure 8. Modelled CLT geometry for each experiment and for the final analysis. The grain direction, boundary conditions, discretisation grid and output locations are shown. Descriptions of the Experiments 1, 2, and 3 are provided in Sections 3.3.1, 3.3.2, and 3.3.3 respectively.

The model used for comparison with the results from the first experiment for moisture distribution development in CLT due to end-grain wetting (electrical resistance-based MC measurements) served as the basis for the final model utilised in the end-grain moisture safety analysis (leftmost diagram in Figure 8). In this model, the bottom surface was configured to experience water contact in accordance with a schedule derived from the simulated actual yearly climate data. The schedule was modified to reflect the simulated moisture management practices (more on this in Section 3.6). Additionally, wind-driven rain was considered on the side surfaces of this model (west and east winds were taken into account, as they lead to the highest wind-driven rain loads in Estonia).

3.4.2 Selection and development of material definitions

Careful consideration is necessary when selecting the material properties. In the Delphin HAM software database, the material files are distinguished by unique identification (ID) number, and there are five material files available for spruce for the longitudinal direction (ID459, ID697, ID711, ID807, ID844) and seven files for the transverse direction (ID235, ID460, ID626, ID695, ID696, ID717, ID713). In the database, the file ID697 is replaced with ID807, and ID235 is replaced with ID460, but nevertheless they were included in the initial testing and pre-selection.

Delphin built-in material files were evaluated based on water absorption measurements with separated timber boards (Experiment 2, Section 3.3.2). The results, as discussed in Section 4.4.1, showed that material files ID711 and ID807 correlated well with longitudinal moisture transfer, and ID695 and ID713 showed reasonable agreement in the transverse direction (Figure 35 in Section 4.4.1).

In the Delphin database (version 6.1.6), there are no material files for spruce that account for anisotropy as of 2025. However, for the simulation model to consider different moisture flow directions within one representative elementary volume, the corresponding properties must be defined within a single material file. Thus, files of anisotropic spruce materials had to be compiled.

While the moisture transport properties of timber vary with the direction of moisture flow relative to the grain, the moisture storage function and the associated storage base parameters should be isotropic and thus independent of flow direction. Further research is needed to confirm this assumption. Nonetheless, this posed a challenge for the compilation of the files of anisotropic materials, as only one pair from the subset of suitable isotropic material files had the same moisture storage function and moisture storage base parameters – the materials ID711 and ID713. Combining other material files would have made it necessary to alter the storage parameters and moisture storage function, which would have introduced a further level of uncertainty. Therefore, it was possible to compile only one material file with anisotropic spruce material properties from the built-in material files (ID711 and ID713) from Delphin database (Table 3).

The analysis of Delphin built-in material files omitted material anisotropy and transient climate conditions to avoid introducing unnecessary complexity and uncertainty. Accordingly, the laboratory test used to select the material files (Experiment 2, as described in Section 3.3.2) was designed for one-dimensional water uptake. Validation of the anisotropic material transport model and material files, was thus based on data from Experiment 1 (described in Section 3.3.1) and from Experiment 3 (described in Section 3.3.3) as those experiments included anisotropic moisture transfer in transient conditions. The respective validation results are presented in Section 4.4.3.

Table 3. Moisture transport and storage base parameters of the reference material files ID711 and ID713 in Delphin database.

	Longitudinal (ID711)	Transverse (ID713)	Unit
Bulk density of dry material	393.703		kg/m^3
Specific heat capacity of dry material	1843		J/(kg·K)
Open porosity	0.737531		m^3/m^3
Effective saturation content (long process)	0.72809		m^3/m^3
Capillary saturation content (short process)	0.655		m^3/m^3
Hygroscopic sorption value at 80 % RH	0.0598372		m^3/m^3
Thermal conductivity	0.151167	0.105583	W/(m·K)
Water absorption coefficient	0.012024	0.00526733	$kg/(m^2 \cdot s^{0.5})$
Water vapour diffusion resistance factor	4.57501	487.724	—
Liquid water conductivity at effective saturation	2.00481×10^{-10} Altered files = 1×10^{-11}	9.22366×10^{-10} Altered files = 1×10^{-11}	s

It was presumed that some alteration of the material properties was necessary to achieve a good fit with the experimental data. First, the water absorption coefficients were modified based on the results of the second experiment, but this did not yield a better agreement in preliminary testing (specifically, it did not improve agreement with the data on MC development over time). Instead, it was found that altering the liquid conductivity and moisture storage had a greater impact.

Wang et al. (2023) have also emphasised that the moisture storage function at the capillary range and the saturation water content of the CLT have a substantial impact on the accuracy of the hygrothermal model. In their analysis of simulated CLT water uptake, Brandstätter et al. (2023) showed that the mass transfer coefficient of free water is the main contributor to the intensity of moisture uptake and that the effect of glue lines is smaller than the role of the investigated mass transfer coefficients. They demonstrated that the MC curve trends for the initial configuration and the configuration incorporating reduced permeability and diffusion due to the glue were broadly similar. The effect was minor at the surface but more pronounced in the middle layer. Therefore, the focus of optimisation in the current thesis was set at the liquid water conductivity function and the effect of the glue line was considered negligible.

The goal of the material properties' optimisation was to have three files for the anisotropic spruce material – one that produced the best fit for the measurement data as a whole, i.e., a close correlation with the mean of the measurement results, another that yielded results in agreement with measurements with the lowest values, and finally a material file which generated an outcome corresponding to the highest measured values. This approach was chosen due to the wide variation observed in the measurement results of the first experiment, as presented in the results section for Experiment 1 (Section 4.3.1). A similar method was used by Brandstätter et al. (2023).

The optimisation of the material properties was done iteratively until a satisfactory fit was found. Care was taken to remain within the range of values defined for material functions in the built-in Delphin material database. For an optimised fit, it was necessary to increase the liquid water conductivity for volumetric MC lower than 0.4 m^3/m^3 but decrease it for higher MC. Figure 9 presents the liquid conductivity, vapour permeability and moisture retention functions of the final selected and optimised material files.

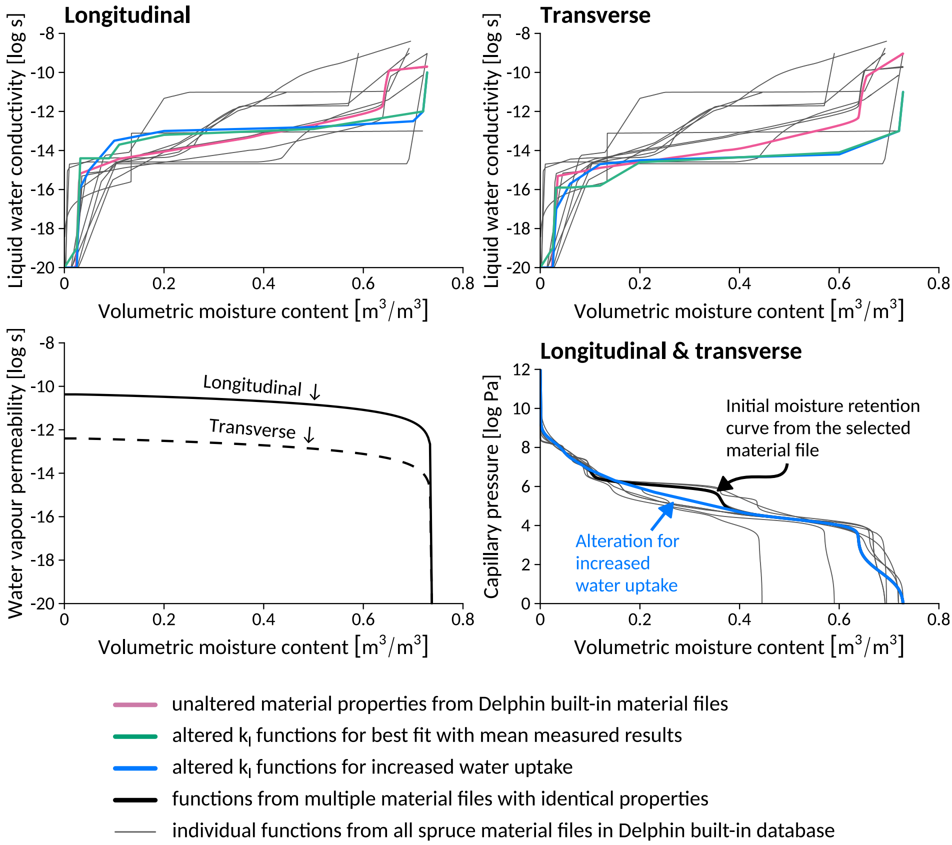


Figure 9. Material functions from the selected and optimised material files. The anisotropic material file referred to as "unaltered", was based on files ID711 and ID713 from the hygrothermal simulation tool Delphin database.

Root mean square error (RMSE, Equation 1) and mean bias error (MBE, Equation 2) were calculated to provide a quantitative indication of the fit of the simulation results with the measured data. A lower RMSE indicated a closer agreement of the simulation results with the experimental data, suggesting a better fit. However, RMSE penalised large errors. Therefore, MBE was also included, which gave equal weight to all errors and indicated whether the simulation tended to consistently over-, or underestimate compared to the measurements. Experiment 1 (as described in Section 3.3.1) served as the primary basis for validating the hygrothermal simulation model and the RMSE and MBE were both calculated on the basis of the measured data from Experiment 1. The indicators were determined as follows (Equation 1 and 2):

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(s_t - m_t)^2}{n}} \qquad (1)$$

$$MBE = \frac{\sum_{t=1}^{n}(s_t - m_t)}{n} \qquad (2)$$

Here, *n* is the number of measurements, s_t represents the simulated data, while m_t refers to the measured data at time point *t*. The measured data m_t comprises averaged measurement results from the TSs exposed to the given climate conditions.

3.5 Development of the MC-based two-step performance criterion

The underlying performance criterion used in this work was mould growth initiation, calculated according to the improved Finnish mould growth model (originally referred to as the VTT mould model) (*Tampere Universities Community*, 2024; Viitanen & Ojanen, 2007). The output of the model is an index (M) on a seven-grade scale: 0 – no growth (clear surface), 1 – growth seen with a microscope (growth is beginning), 2 – clear growth seen with a microscope (mould colonies have formed), 3 – growth seen with the naked eye, 4 – clear growth seen with the naked eye (> 10 % coverage detectable visually), 5 – rich growth seen with the naked eye (> 50 % coverage detectable visually), 6 – very rich growth (~ 100 % coverage). For input, the model considers exposure time, temperature, relative humidity (RH) and drying periods. The Finnish mould growth model has proved to be reliable and accurate in predicting mould growth when using wood surface RH as an input (Lie et al., 2019), particularly when contaminators are present (Kuka et al., 2022), which is common on a construction site. However, the calculation of M requires input data in the form of a time series. For better practical and operative usability on a construction site, a two-step MC performance criterion has been proposed.

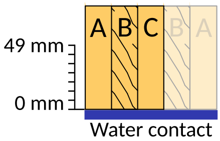
The concept of the two-step MC limit is that higher MC may be acceptable in close vicinity to the end-grain surface, provided MC is markedly lower further from the end-grain surface and that the excess moisture can dry out or redistribute before mould growth begins. The novel two-step performance criterion has been designed to provide greater flexibility and serve as a foundation for an adaptable strategy that can accommodate various circumstances arising during the construction process.

For the development of the two-step MC performance criterion, measured MC distribution values were used as the initial conditions in the hygrothermal simulation model. Gravimetric MC data from Experiment 3 was selected for this purpose (see Section 3.3.3 for the experimental method and Section 4.3.3 for the experiment results).

To identify the limiting MC values, a series of mould index calculations were done in the hygrothermal model. The simulation generated temperature and RH time series from the surface of the CLT panel as an output throughout the simulation period. The obtained results were subsequently utilised as input parameters in the Finnish mould growth model. The initial MC values that did not result in conditions yielding an M > 1 were deemed safe for use. These MC values were then chosen as practical MC limits when managing end-grain wetting of CLT.

It may be argued whether M < 1 is an appropriate criterion, but the position of the author is that if the interior surface of the CLT panel can be exposed to the indoor air, it is reasonable to avoid the condition M > 1. Viitanen et al. (2015) has also referred to M > 1 as a “green traffic light” situation, i.e., a suitable limit to minimise the risk resulting from mould growth on surfaces which are in contact with the indoor air. Other researchers concur that mould should not be allowed, even if it can be removed because it is difficult to check all joints and hidden areas (Öberg & Wiege, 2018). Svensson Tengberg & Hagentoft (2021) and Kukk, Kaljula, et al. (2022) have also opted for the M < 1 limit.

Four sets of initial MC values, corresponding to different wetting durations, were used in the hygrothermal model. The MC values, derived from the results of Experiment 3 (Section 4.3.3), are presented in Figure 10 as the initial input data for the simulation. Experimental data were deemed to provide more accurate information on MC distribution than hypothetical values.



Height [mm]	4 h A	4 h B	4 h C	8 h A	8 h B	8 h C	24 h A	24 h B	24 h C	48 h A	48 h B	48 h C
42–49	8	8	8	9	9	9	10	9	11	15	13	13
35–42	8	8	8	10	9	9	11	9	11	16	13	14
28–35	9	8	8	10	9	10	12	10	13	18	14	16
21–28	10	8	9	11	9	12	15	11	15	22	15	20
14–21	12	8	10	14	10	14	19	11	19	31	18	28
7–14	19	9	14	23	10	21	28	12	26	51	19	48
0–7	67	19	62	68	22	78	96	24	85	131	33	120

Moisture content [%]

Figure 10. Initial MC used in the hygrothermal simulation model for determining the performance criterion. MC values here are the mean of measured values from Experiment 3 (Section 4.3.3). Height values show the boundaries (cut planes) of the measured layers.

Although the measured MC distribution values used in the simulations encompassed the entire CLT test specimen, only two areas were chosen as reference points for the performance criterion (hence the two-step MC performance criterion). The first area was between 7 mm and 14 mm (midpoint ≈ 10 mm), and the second area was between 28 mm and 35 mm (midpoint ≈ 31 mm) from the water contact surface. For simplicity, the height values are hereinafter referred to as 10 mm and 30 mm, respectively. These height values can also be readily utilised for on-site MC measurements.

The general geometry and boundary conditions of the hygrothermal model used for developing the performance criterion are detailed in Section 3.4 and illustrated in the leftmost diagram of Figure 8, located in the same section. Additionally, a 200 mm thick insulation layer with thermal conductivity λ = 0.028 W/(m·K) and water vapour diffusion resistance factor μ = 100 was added to the exterior side of the CLT geometry to decrease the moisture dry-out capability of the simulated CLT structure. This produced a vapour diffusion resistance equivalent to that of 20 m of stagnant air on the CLT external surface, providing a higher risk scenario where moisture dry-out towards the outdoor environment was limited. Four variations of the model were made for the interior side of the geometry by combining two additional indoor surface vapour diffusion resistance values (S_d = 0.3 m and 1 m) with a low and high indoor air humidity load. An equivalent air layer thickness of 0.3 m corresponds to two gypsum boards with a total thickness of about 25 mm, which is a common solution in CLT construction. Kukk, Kers, et al. (2022) have also used S_d = 0.3 m as an equivalent to the resistance of a water vapour permeable interior layer in CLT hygrothermal calculations. One meter of stagnant air represents a situation where additional layers (e.g., timber finishing boards, paints, etc.) might be added to the gypsum boards, making the interior layer less water vapour permeable and thus increasing the risk of moisture build-up. However, both variants of the additional vapour diffusion resistance on the interior side of the CLT panel can be considered vapour permeable and not moisture-trapping. Thus, the developed two-step MC criterion only applies for situations where at least the interior surface of the CLT panel is relatively open for moisture dry-out. For the bottom end-grain surface, moisture trapping conditions were modelled as described in Section 3.4.

All things considered, the model described a situation where a CLT wall would have been covered with insulation and relatively vapour open interior finishing layers, while the MC in the bottom part was still elevated from past wetting incidents, and the bottom surface was in moisture-trapping conditions. As detailed in the results section for the field study (4.1.2) and laboratory investigation (4.3) moisture-trapping conditions occur often near CLT end-grain surfaces, and MC in these areas could remain high even after lengthy periods without additional water contact.

Estonian Moisture Reference Year (MRY) for mould growth analysis (Kalamees & Vinha, 2004) was used as the climatic dataset in the simulations for the performance criterion development. The simulations started in July and lasted for two months. This is a reference period that produces the highest mould risk during the MRY and corresponds to the time frame for completing interior finishes. For the indoor environment, a temperature shift of −5 °C from the standard indoor temperature setpoint (21 °C) was applied in order to describe the indoor environment during the construction period more realistically and provide a less intense moisture dry-out. Moisture excess during the construction period can vary depending on the moisture intensity of the interior finishing works (e.g., concrete pouring and plastering can be moisture-intensive). The simulations were performed with both low and high humidity loads. Table 4 summarises the hygrothermal boundary conditions used in the model. The calculations were made with the three material files described in section 3.4.2.

Table 4. Ambient air temperature (t), relative humidity (RH) and indoor moisture excess (Δv) in the hygrothermal simulation model for the performance criterion analysis.

	Outdoor	Indoor construction site – low humidity load	Indoor construction site – high humidity load
t	15.6 °C ± 4.4 °C	17.8 °C ± 1.0 °C	
RH	78 % ± 17.3 %	70 % ± 10 %	88 % ± 10 %
Δv	–	0.7 g/m^3 ± 1.5 g/m^3	3.3 g/m^3 ± 1.7 g/m^3

3.6 Analysis of moisture safety strategies considering end-grain wetting

Long-term hygrothermal simulations were conducted to analyse which moisture safety strategies and process factors most influence the success of CLT construction regarding the moisture safety of the end-grain surfaces of CLT wall panels. Climate data representing a period of 30 years was used as opposed to a test reference year (MRY). While the MRY is appropriate for the analysis of mould growth risk, its precipitation data is too arbitrary and cannot be used to assess for example which season presents a higher or lower risk stemming from rain exposure.

The focus was on key construction process variables affecting CLT end-grain wetting and dry-out. The variables may be categorised into three groups (as detailed in Table 5):

1) variables influenced by the building size and type (expected CLT installation duration and post-installation period when the CLT panels were still exposed to the elements),

2) variables controlled by CLT producers as well as by the design team (i.e., localised moisture protection methods such as CLT wall face protection and CLT end-grain surface protection), and

3) variables mainly controlled by the general contractors (implementation of FWP, efforts to reduce water load on horizontal surfaces, and, to some extent, also the length of the post-installation period before addition of the next layers).

Additionally, the CLT installation start season impacts the outcome, and although it might be possible to choose (or plan ahead) the start season at the time of design, it is often subject to external factors, especially in public procurement situations. Thus, this variable is mostly considered to be a factor that introduces randomness, which is not under the direct control of any particular actor. Each variable value was combined with all the other variable values and thus a total of 864 individual combinations were compiled. Each individual combination was simulated with each year from the 30-year climate data period and with each of the three material files described in the section 3.4.2. This produced a total of 77,760 individual simulations. Variability of the material files and years contributed to the randomness, providing a basis for the probability calculations. The variables are listed in Table 5 and form the basis of the analytical approach and are collectively referred to as the moisture safety strategy analysis framework.

The choice of variables was supported by findings from the field study (Section 4.1.2) and laboratory investigation (4.3). For example, the duration of precipitation exposure – both during installation and after its completion until the addition of subsequent structural layers – determined whether critical end-grain wetting occurred. Liisma et al. (2019) found that CLT protected with preliminary PE foils during construction exhibited lower MC, indicating the importance of vertical protection foils for CLT wall panels. The potential benefits of end-grain protection are discussed in the results section of the field study (4.1.2). Additionally, Time et al. (2023) proposed a moisture safety strategy that included localised protection measures such as end-grain surface treatment. They also emphasised that scheduling CLT installation during drier months and promptly addressing rain events could be beneficial, supporting the inclusion of seasonality in the analysis. The impact of seasonal variation on the moisture safety of timber structures has also been discussed by Pihelo & Kalamees (2020). Tengberg & Bolmsvik (2021) demonstrated that FWP structures effectively enhanced moisture safety.

Table 5. Variables of the analysed CLT moisture protection process safety measures.

<table>
<tr><th>Process factor type</th><th>Process factor</th><th colspan="12">Variable value</th></tr>
<tr><td rowspan="2">Building type and size</td><td>Expected CLT installation duration</td><td colspan="4">1 week</td><td colspan="4">4 weeks</td><td colspan="4">16 weeks</td></tr>
<tr><td>Expected duration from CLT installation until the addition of the next structure layers</td><td colspan="4">1 week</td><td colspan="4">4 weeks</td><td colspan="4">16 weeks</td></tr>
<tr><td rowspan="2">Moisture safety design</td><td>CLT wall face protection (applied prior to installation)</td><td colspan="6">Yes (ideal rain protection)</td><td colspan="6">No side face protection</td></tr>
<tr><td>CLT end-grain surface protection (applied prior to installation)</td><td colspan="6">Yes (ideal waterproofing)</td><td colspan="6">No end-grain protection</td></tr>
<tr><td rowspan="3">Construction management</td><td>Full-coverage weather protection (FWP) implementation</td><td colspan="4">FWP before installation</td><td colspan="4">FWP after installation</td><td colspan="4">FWP not implemented</td></tr>
<tr><td>Horizontal surface water drainage (HSD) implementation</td><td colspan="6">Rainwater drainage and prevention of puddle formation after rain</td><td colspan="6">Absence of activities enhancing drainage</td></tr>
<tr><td>Predicted start season of the CLT installation</td><td colspan="3">Spring</td><td colspan="3">Summer</td><td colspan="3">Autumn</td><td colspan="3">Winter</td></tr>
</table>

The combination setup for the hygrothermal modelling began by setting the simulation time periods, defined as the sum of the installation duration and the post-installation period. The simulation was scheduled to end at the moment when the CLT panels would begin to be covered with additional layers.

If no localised moisture protection methods or FWP were used, the CLT structure in the model (as described in Section 3.4 and illustrated in the leftmost diagram of Figure 8 in the same section) was left exposed to wind-driven rain on the side faces and water contact on the bottom end-grain surface throughout the entire simulation period.

If CLT side face protection was applied, the wind-driven rain was excluded from the model. This meant that the side face protection was simulated as being ideal without any water leaks. Any additional vapour resistance was neglected. The observations of the field study (Section 4.1.2) indicated that typically the protection foil was cut open from the bottom of CLT panels at the time of installation and the space between the foil and the CLT panel became ventilated. Moreover, if the protection foil was considered as ideal and no ventilation was assumed, the additional vapour resistance would hinder the influence of outside air which would skew the result towards drier conditions due to the low initial MC of the CLT. Furthermore, the application of the protection foil could vary, and the foil could have imperfections and damages which produced both water leaks and holes for ventilation, as described in the field study (Section 4.1.2). Inclusion of these effects would have expanded the number of studied parameters and would have made the analysis unnecessarily complicated and more time-consuming. Thus, it was decided to exclude the effect of (arbitrary) additional vapour resistance of the protection foil and no changes were made to the vapour transfer component on the side faces regardless of the presence of the protection foil.

If CLT end-grain protection was applied, water contact via the bottom end-grain surface of the CLT wall panel was excluded from the model. This meant that the end-grain protection was simulated as ideal without any water leaks. Marginal vapour transfer was assumed, considering outdoor climate and a vapour resistance value of S_d = 125 m for the floor panel, regardless of the presence of CLT end-grain protection.

Both of these local protection methods were assumed to have been employed in the CLT factory, i.e., they were implemented in the hygrothermal model from the beginning of the simulation. In case of utilising both the side face protection foil and end-grain protection, both the wind-driven rain on the side faces and water contact via the bottom end-grain surface were excluded. This resulted in a model without liquid water ingress into the CLT, leaving only the effect of air humidity. FWP was simulated in the same manner as in the case where both local protection methods were employed. However, for the case of FWP erected after CLT installation, the wind-driven rain and the bottom edge water contact were still included until after the end of the installation period.

The implementation of horizontal surface water drainage can be seen as another measure that can form a part of methodical moisture safety management by the construction site team. This aspect was included in the analysis in order to compare it with the impact of the more absolute protection measures described earlier. This provided information on whether limiting water contact could be an efficient measure in conjunction with a short installation period.

For the case with enhanced rainwater drainage and prevention of puddle formation (i.e., active moisture management by horizontal surface drainage), the start of the water contact was delayed in the model until the cumulative precipitation reached 2 mm.

It was assumed that skilled and well-equipped construction workers could cover the construction in time in case of light rain, but moderate rainfall (≥ 2 mm (Ahrens, 2009; Met Office, 2011)) might produce leaks that might overwhelm even a well-prepared team. The end of water contact in this case was defined as the last hour of the recorded precipitation period, regardless of the rain amount. The assumption was that the construction team could promptly dry the structure and nearby surfaces after a rain event. For simplification purposes, no account was taken of the time or weekday when making this assumption.

If horizontal surface drainage management was not applied, the water contact start was taken to be the moment when the cumulative rain amount reached 0.5 mm, which corresponds to a moderate drizzle (Met Office, 2011). Cumulative precipitation below 0.5 mm was defined as a light drizzle which produces negligible runoff and does not result in the accumulation of water under the CLT wall panel. The end of water contact was defined as the last hour of the recorded precipitation period if the cumulative precipitation amounted to less than 2 mm. For precipitation amounts larger than 2 mm, it was assumed that a water puddle could form around the structure, extending the water contact duration. Thus, the end of the water contact for the unmanaged variant was specified to be delayed by 6 hours based on the data from Experiment 1 (4.3.1) which showed that water uptake rate of a CLT wall panel through the bottom end-grain surfaces was the highest for up to ≈ 6 hours after the start of water uptake (Figure 31, left in Section 4.3.1). Preliminary modelling also showed negligible effect of a longer time lag.

The 30-year climate data (1991–2020) from Tallinn, Estonia, recorded by the Estonian Weather Service at the Tallinn-Harku meteorological station, N 59°23´53´´, E 24°36´10´´ (*Estonian Weather Service*, 2024), was chosen for the analysis. Rather than relying on a single constructed test reference year, the analysis was based on the full 30-year series of climate data. Each simulation scenario was run 30 times (once for each individual year in the dataset). This enabled a more comprehensive assessment of performance under varying climatic conditions.

Tallinn is characterised by rainy summers and cold, snowy winters (Köppen climate classification Dfb). It is located in the northern part of the temperate climate zone. The utilised climate data included the outdoor air temperature, relative humidity, hourly rain amounts, wind velocity and direction. Solar radiation data was excluded due to the potential for shading on construction sites (e.g., due to nearby buildings or construction elements), which could increase moisture risks. The exclusion of solar radiation data resulted in a more conservative, safety-oriented assessment.

The start of the simulation for each season was chosen based on which four consecutive weeks had the highest statistical cumulative precipitation amount and, at the same time, included the single week in the given season with the highest statistical precipitation amount. The simulation start weeks were thus week 20 for spring, week 32 for summer, week 40 for autumn, and week 52 for winter (Figure 11).

The simulation covered durations from 2 to 32 weeks, based on combinations of the expected CLT installation time (1–16 weeks) and the period until the addition of subsequent structural layers (another 1–16 weeks). Thus, the simulated periods ranged from two weeks per season to covering up to three seasons (e.g., starting in winter and ending in summer for the 32-week duration).

An outcome was considered successful if it met the requirements of the new performance criterion, as defined in Section 4.5 (Equations 3 and 4).

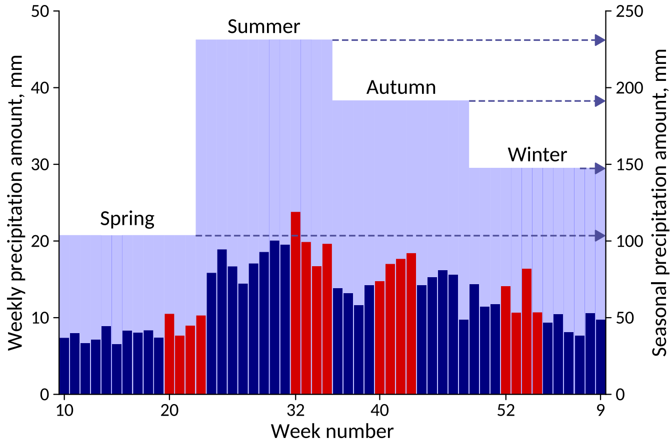


Figure 11. Weekly and seasonal rain amounts in Tallinn, Estonia, for the years 1991–2020. Red columns mark the chosen weeks for each season in the analysis. The first week of each chosen period served as the simulation starting point for the corresponding season.

3.7 Analysis of the efficacy of moisture safety strategies in practice

The efficacy of moisture safety strategies in practice was assessed through a field study of the buildings G and H. The method used to identify moisture issues and evaluate the effectiveness of protective measures followed the same approach described in Sections 3.1 and 3.2. By the time these buildings were under construction, prior experience allowed for a more targeted and efficient investigation, as key risk areas and early indicators of moisture issues had already been identified during previous investigations.

A detailed analysis of customer specifications, procurement requirements, and design documents for the buildings G and H was also included. The findings are presented in Section 4.9 separately from the field study results from other buildings.

Evaluation of the moisture safety strategies in the buildings G and H formed the final part of the work. This evaluation was based on the earlier analysis of moisture safety strategies (detailed in Section 3.6), using the subset of results in which variables for the moisture safety strategies most closely matched the actual planned and incidental measures implemented in the two buildings. This allowed a specific "track" of a moisture safety strategy to be mapped over the framework of studied variables (Table 5 in Section 3.6). For each track, 90 moisture safety outcomes were available based on simulations using 30 years of climate data (Section 3.6) and three different material files (Section 3.4.2). From these 90 results, the mean MC in the CLT wall panels near the end-grain area was calculated, along with an estimated probability of a moisture-safe outcome, expressed on a scale from 0/10 to 10/10 – where, for example, a rating of 0/10 indicated no guaranteed moisture safe outcome, while 6/10 suggested a moisture safe outcome in approximately six out of ten cases (i.e., meeting the performance criteria, as defined by Equations 3 and 4).

For clarity and ease of interpreting the results, the formation of the strategy track is described in greater detail in the corresponding results section (Section 4.9).

4 Results and discussion

4.1 Wetting circumstances and vulnerable areas

4.1.1 Cumulative precipitation amounts and site environment measurements

The panels for the studied buildings were delivered either in a dry freight trailer, where they were mounted vertically on a stand and were entirely protected from the outside environment (Figure 12, left), or on a flatbed trailer, where the panels were lying on their sides and were protected from the elements only by packaging foil (Figure 12, right). In the latter variant, the CLT panels and packaging foils were susceptible to potential physical damage during transport. Nevertheless, no excessive MC was reported after transport with either option.

Figure 12. CLT panel transport in a dry freight trailer (left) and on a flatbed trailer (right).

If CLT was not delivered just in time and on-site storage was required, the risk of wetting arose. Typical packaging did not prevent the wetting of the panels during interim storage (Figure 13). Imperfections in the foil allowed water to enter the package where it remained unnoticed until specifically inspected (e.g., Figure 13, right). Also, damage (e.g., incisions, ripping, tearing) in the packaging foil became entering points for precipitation for panels already installed. Site observations indicated that opaque foils inhibited the detection of wetting, whereas translucent protection foils facilitated faster response to occurred problems.

Figure 13. Interim storage of CLT on-site (left) which proved to be inadequate and allowed water to enter the package, as shown by water being poured out of the package (right).

After installation, CLT panels were often left exposed to precipitation (whether covered with packaging foils which might have been compromised or without any weather protection). Eventually the CLT panels became protected against wetting either by the addition of subsequent structural layers or by the installation of a full-coverage weather protection (FWP) system (e.g., as seen in Figure 3, A2). The accumulated precipitation during the periods of CLT exposure – from the arrival of the first panels on site (usually at installation start) to final coverage – is presented in Table 6 and Figure 14.

Table 6. Summary of the precipitation loads the studied buildings were exposed to.

Building		A	B	C	D	E	F	G	H1	H2
Above gnd. floor area [m²]		1695	1320	555	165	238	195	8273	1328	1099
Accumulated precipitation [mm]	**During CLT install.**	200	43	106	6	2	29	65	67	28
	From CLT install. until fully covered	75	292	77	8	33	200	2	29	28
	TOTAL	**275**	**335**	**183**	**14**	**35**	**229**	**67**	**96**	**56**

The installation of CLT panels in the building A lasted for about 10 weeks and during this period there were frequent rain events (Figure 14, A). Many CLT details were continually exposed to precipitation after the initial installation until a full coverage weather protection system was erected (Figure 3, A2).

In the building B, the three-week CLT installation period coincided with a period of low rain amount (Figure 14, building B). However, many of the wetting incidents were documented during this three-week period. Moreover, the few days of heavy rain which occurred during the first half of the installation process (Figure 14, B, 2nd week of installation) might have contributed to many of the wetting incidents which resulted in an elevated MC. The construction site of the building B was not fully covered with an FWP system, as was the case for the buildings A and G. Some CLT remained exposed to precipitation until the exterior envelope was entirely covered with insulation (polyisocyanurate boards with aluminium foil). There were frequent and heavy precipitation events during the 18 weeks after the CLT installation (Figure 14, B, approximately weeks 4–20) and several connection joints repeatedly got wet before the façade was finished (Figure 15, P1).

The installation of the CLT panels in the building C lasted for five weeks, and during this period, there were several rainy days (Figure 14, building C). Similarly to the building B, the construction of the building C continued without FWP, however the exposure period was shorter, as was the accumulated precipitation amount.

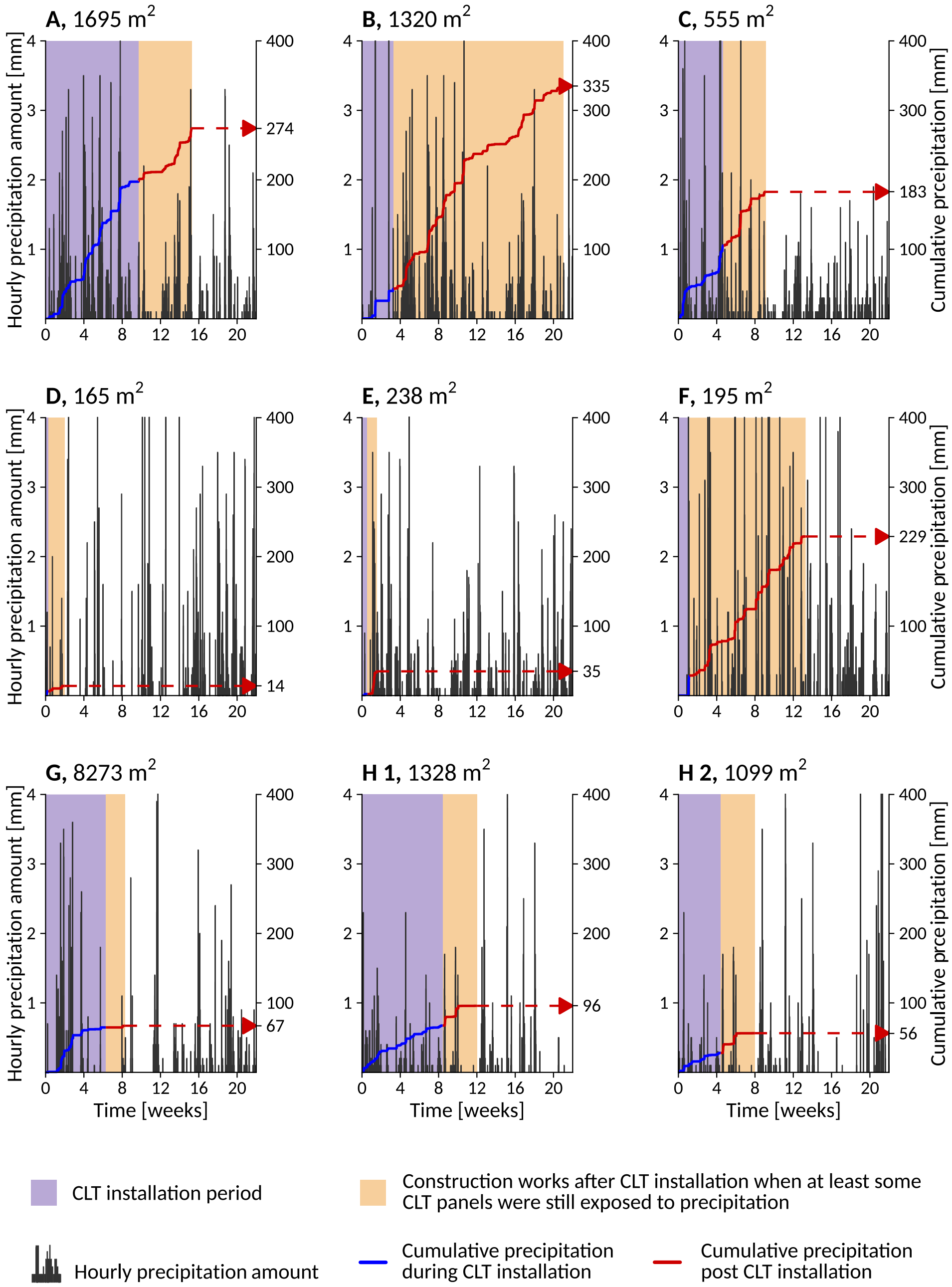


Figure 14. Precipitation amounts during the construction of the observed buildings. A, B, C, G, and H are non-residential buildings and D, E, and F are detached houses. The black columns represent hourly precipitation amounts (values shown on the left y-axis), while the blue and red lines illustrate the cumulative precipitation throughout the CLT installation process and subsequent period when the panels were still exposed to precipitation (values shown on the right y-axis).

Figure 15. Photos taken during the field study. P1: Moisture measurements at the exterior wall to foundation connection in the building B about nine weeks after the installation of CLT. P2: Installation of the FWP structure at the construction site of the building G. P3: High MC in the bottom area of a wall panel on the 2nd floor of the building H.

While the building G was the largest of the studied buildings, the weather conditions during its construction were more favourable, and the chosen moisture safety strategy included the implementation of an FWP system as soon as possible after the installation of CLT panels (Figure 15, P2). This resulted in an installation duration of approximately five weeks per building section and an approximately two-to-three-week period after the installation when the CLT panels were still exposed to precipitation (until covered with the temporary weather protection structure). Thanks to this, the total accumulated precipitation amount that the building G received was comparable to much smaller buildings.

In the building H, the installation of the first-floor CLT panels lasted for eight weeks, while it took four weeks for the second-floor panels. Due to different end-grain protection methods for the panels on the two floors, installation duration and precipitation were analysed separately. After the installation, the CLT on both floors of the building H remained exposed for approximately a month until it was covered with insulation. The accumulated precipitation amount for the second-floor panels in the building H was the lowest among the non-residential buildings, but nevertheless excessive MC was reported (Figure 15, P3).

The CLT installation periods were significantly shorter in the detached houses and consequently the precipitation amounts were smaller (Figure 14, buildings D, E, F). The low precipitation amounts correlated with the low severity of wetting in these buildings. In the building F, there was an extended period after the CLT installation when the construction progressed slowly, and unlike other detached houses, the CLT was in part exposed to precipitation for a relatively long time.

In the building G, the temperature and relative humidity were monitored on the site after the FWP structure was erected. The data showed that conditions under the temporary structure were similar to outdoor air conditions, with moisture excess remaining near zero until the openings were sealed and heating started. There was a rising trend for equilibrium moisture content (EMC) of timber in the indoor area of the construction site. The calculated EMC (from the measured temperature and relative humidity data) often exceeded 20 % and occasionally reached nearly 25 %. However, once heating started, the EMC decreased rapidly, which indicated a good potential for moisture dry-out. Throughout the measurement period, the 24-hour moving average temperature never exceeded 15 °C, even after heating was initiated.

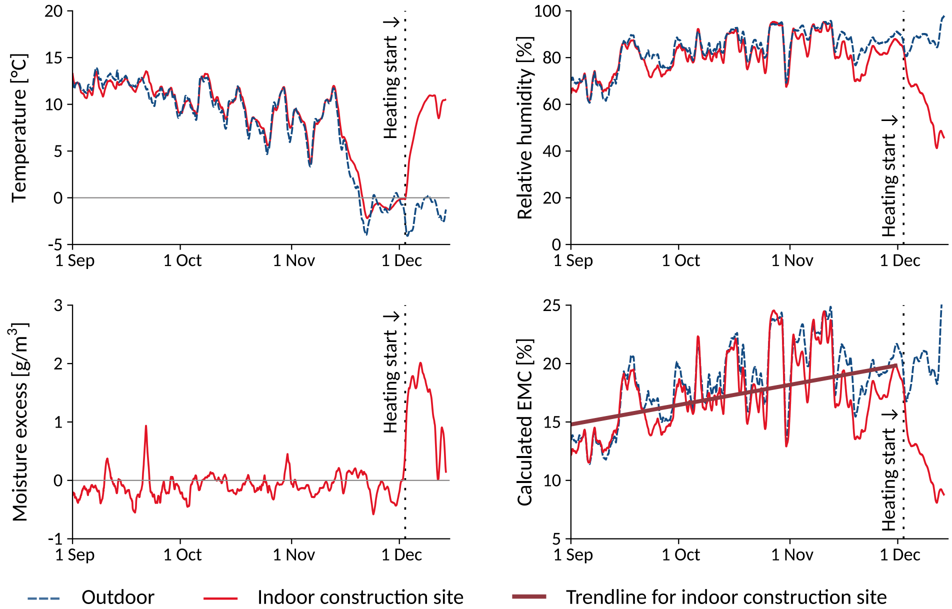


Figure 16. Ambient air conditions on the site of building G. 24-hour moving averages of temperature (t, top left) and relative humidity (RH, top right) in the indoor area and in an outdoor shaded area. Moisture excess (bottom left) and equilibrium moisture content (EMC, bottom right) for timber were calculated from the recorded t and RH values.

4.1.2 Vulnerable areas and wetting circumstances of CLT panels and joints

The site observations from all eight buildings indicated six areas which were further investigated for moisture safety issues. These were:

- exterior wall to foundation connection (Figure 17, P1),
- floor panel to intermediate wall connection (Figure 17, P2),
- floor panel to external wall connection (Figure 17, P3),
- floor panel to window connection (Figure 17, P5),
- roof to exterior wall connection, and
- roof to skylight shaft connection (Figure 17, P6).

The CLT wall panel bottom area in the wall to foundation and wall to floor connection (Figure 17, P1–P3) proved to be the most critical area. Most precipitation which landed on areas higher up flowed down the wall to this joint. These areas were also most susceptible to splashing water. A notable example of excessive wetting occurred in the building A, where rainwater flowed down on the wall panel exterior side (behind an opaque protection foil which had gaps and damage in it) and then under the end-grain surface of the panel (Figure 18). The floor panel protruded enough to facilitate water flow under the wall panel. The bottom part of the wall panel remained wet (MC > 25 %) for over 6 months and prohibited the advancement of construction.

The same general principle of wetting also occurred in the foundation connection. Bitumen foil strips under the wall panels (Figure 19) acted as the protruding surface, which diverted the vertical water flow horizontally under the end-grain surfaces of the CLT wall panels. It became evident that the bonding between the bottom end-grain surface of the CLT panels and the bitumen foil was not ideal. Thin gaps and channels facilitated water flow under the panel.

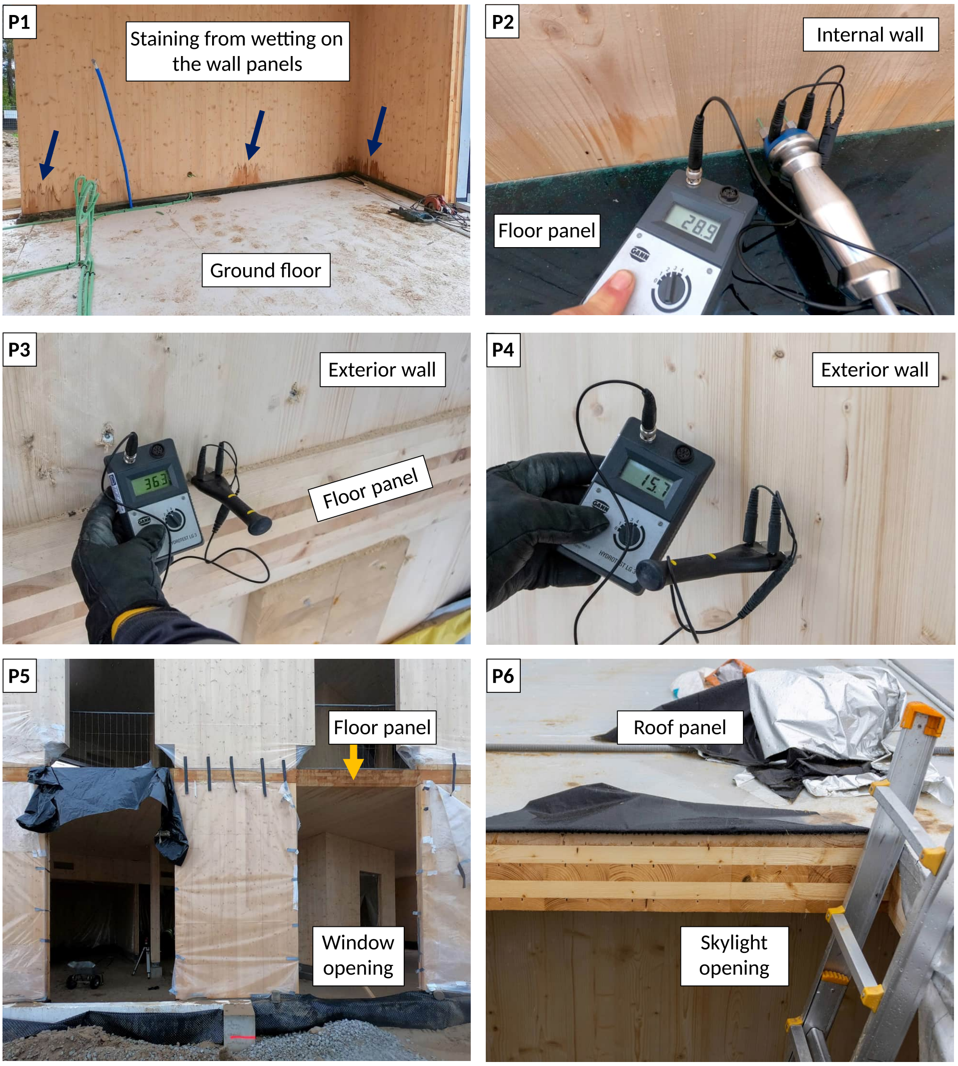


Figure 17. Photos of areas vulnerable to wetting in CLT construction. P1 depicts the wall-to-foundation connection, while P2 & P4 show the wall-to-floor panel connection. P4 illustrates that the same wall panel as in P3 remained dry further away from the floor panel connection. P5 shows window openings, and P6 shows a skylight opening.

Moisture measurements showed that when the bottom of the CLT wall panel was exposed to free water (as illustrated in Figure 18 and Figure 19), the MC in the inner layers of the CLT increased over 30 % and remained at that level for months (Figure 20). This occurred regardless of protection foils installed over wall panels (as in Figure 17, P5) or bitumen foil strips installed under the wall panels (Figure 17, P1 & Figure 19).

In the building A, the wet area exhibited negligible moisture dry-out over the course of five (winter) months (Figure 20, building A) after which the general contractor started intensive local drying. However, such wetting and subsequent drying resulted in large cracks in the CLT surface where the drying equipment was installed.

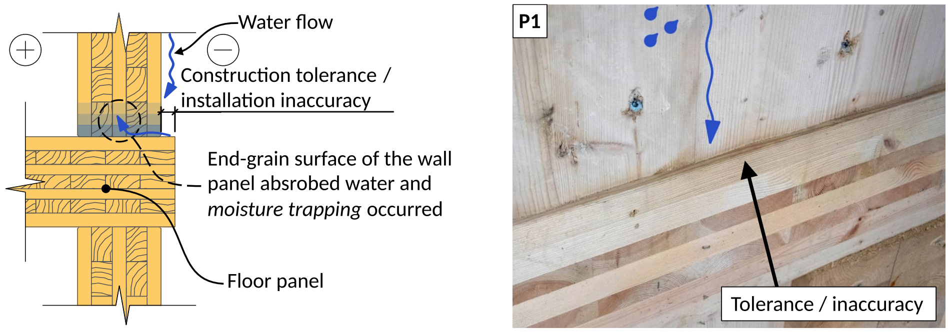


Figure 18. CLT floor and wall panel connection joint, where the protruding floor panel (P1) facilitated water ingress to the wall panel. Photo P1 is of the building A.

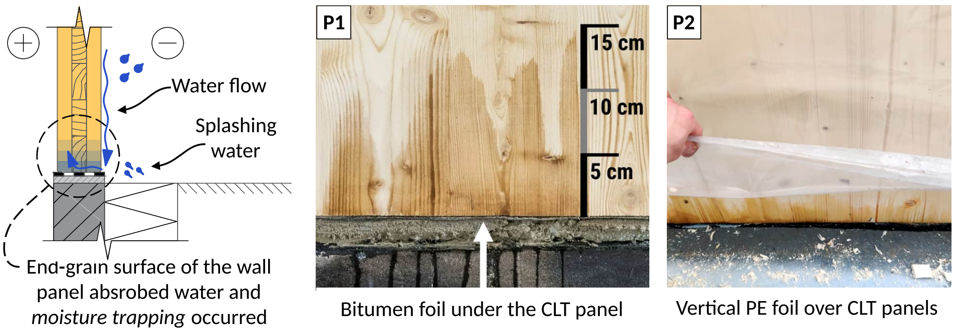


Figure 19. CLT wall panel and foundation connection joint. The bottom edges of wall panels absorbed moisture despite the bitumen strips under the CLT panels (P1 & P2). Photo P1 = building B, photo P2 = building C.

In the building B, portable air heaters and dryers were put to work, and the rooms were heated up to +15 °C as soon as the windows were installed. However, even after two and a half months under these conditions MC (measured from the indoor side) was still over 20 % in many points and reached up to 27 % locally (Figure 20, building B). Safe MC levels were achieved only after the building heating system was turned on and the interior temperature reached +20 °C.

In the building G, construction began approximately two years after the completion of the non-residential buildings A, B, and C, and the publication of the first two publications of this thesis (where improvements were proposed). Thus, the moisture safety strategy for the building G included liquid-applied end-grain protection on CLT wall panels across all floors. This measure largely prevented end-grain wetting. However, damage to the protection coating in some areas led to raised MC (Figure 20, building G). The erection of an FWP structure after CLT panel installation allowed for moisture dry-out and prevented further moisture ingress until the CLT was covered.

In the case of the first floor in the building H, there were neither visual indications of end-grain moisture ingress or swelling of timber boards nor did the measurements indicate elevated MC (Figure 20, building H 1). The fabric-based self-adhesive waterproofing membrane (Riwega VSK Micro, S_d > 2 m) over the bottom of the first-floor CLT panels performed well. No damage was identified in the fabric-based waterproofing membrane as opposed to the liquid applied membrane coating used in the building G. The ≈ 100 mm of rain (Figure 14, H 1) was effectively diverted.

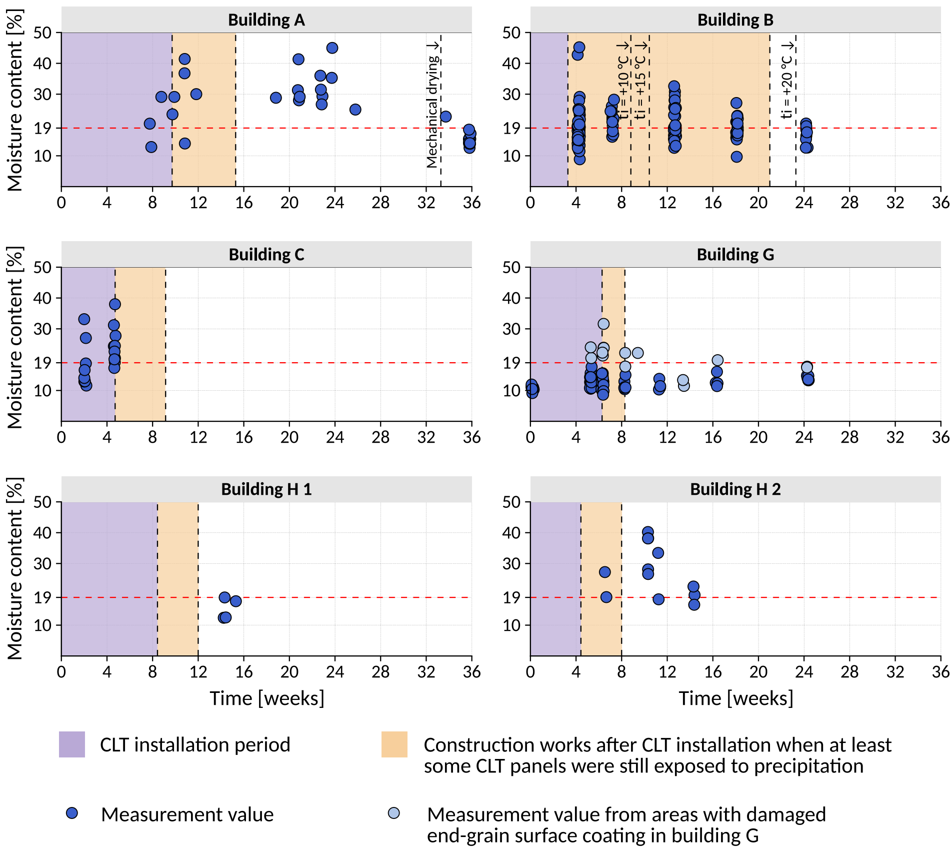


Figure 20. Measured MC in the CLT wall panels at the wall-to-floor or wall-to-foundation connection area in five of the studied buildings. For the building G, values are provided for both cases: with and without functioning end-grain protection. For building H, the measurement values are separated by floors (H1 = first floor, H2 = second floor); t_i = indoor temperature.

The second-floor wall panels in the building H did not have any end-grain protection. The moisture measurements confirmed elevated MC (Figure 20, building H 2), similar to what was reported in the buildings A, B, and C. Several measurement values on the second floor in the building H were higher than the values collected from areas in the building G where end-grain protection damage was suspected.

The buildings D and E were smaller detached houses where the installation of the CLT panels was a matter of days, and the insulation layer was installed shortly after. Stain marks from wetting were detected at the CLT wall panel bottom connection in the buildings D and E, but MC over 20 % was not detected about a month after the start of the insulation installation. The CLT erection and following insulation layer installation took place during a short period with relatively low precipitation amounts (Figure 14, D & E), which could have contributed to a lower initial wetting.

In addition to water ingress to the wall panel bottom end-grain surface at the intermediate ceiling connection, the wetting of the ceiling/floor panel itself was detected in several buildings (Figure 21). Loose vertical foils did not provide sufficient protection against wetting. Casual measurements showed that compared to the wetting of the wall panel bottom surface, the side surface of the floor panel end dried out faster.

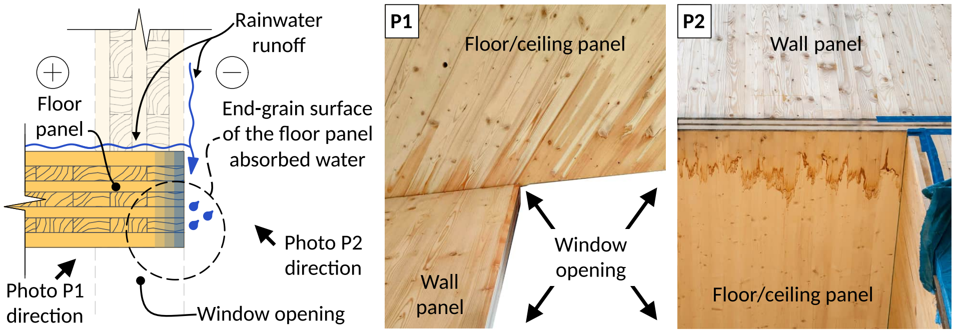


Figure 21. CLT intermediate ceiling (floor) connection with a window opening, where frequent wetting occurred (P1 = building B, P2 = building F).

Similarly, to the intermediate ceiling (floor) panel, the side end-grain surfaces of the roof panels were exposed to precipitation in several studied buildings and temporary protection foils were not sufficient. Rainwater runoff was flowing over the end-grain surfaces of the roof panels (Figure 22, P2). In the building A, the roof panels were installed at a slope which concentrated water flow to a single side of the building increasing the water load at that side, which resulted in a high MC (Figure 23). Unfortunately, this was discovered after the parapet wall was built which hindered moisture dry-out and MC remained elevated for long enough to facilitate mould growth (Pilt, 2020). The parapet was disassembled, and local electrical heaters were used under a temporary cover to improve moisture dry-out. After this, the edges of the CLT roof panel formed cracks and delamination occurred (Figure 22, P1). Additional screws were installed to preserve the structural integrity of the wall to roof connection.

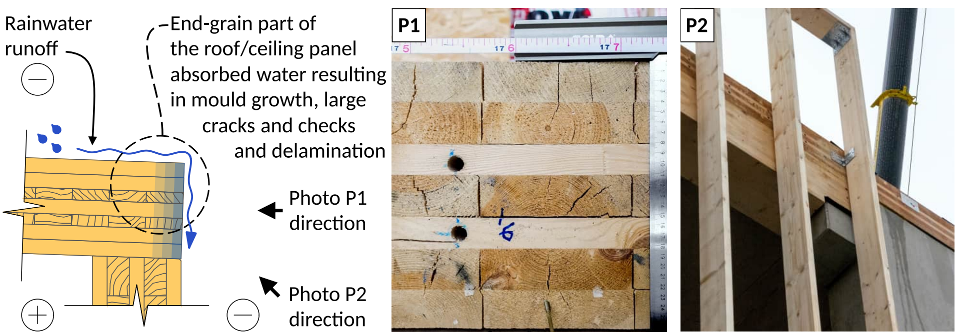


Figure 22. CLT roof panel connection, where large cracks (P1), delamination, and mould growth occurred after frequent wetting (P2) and moisture dry-out. Photos of the building A

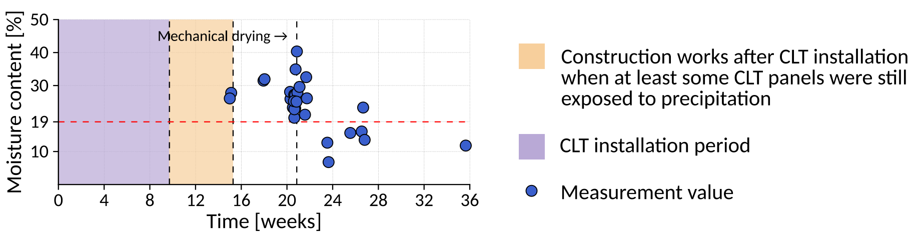


Figure 23. Measured MC in the CLT roof panel ends in the building A.

The window and skylight opening perimeters were also prone to wetting if not covered properly and both were prone to delamination if excessive moisture ingress happened. Such occurrences were documented in buildings the A and B (Figure 24 P1 and P2). The suppliers of the CLT panels were different and originated from different countries. The delamination was not considered to be the case of producer peculiarity.

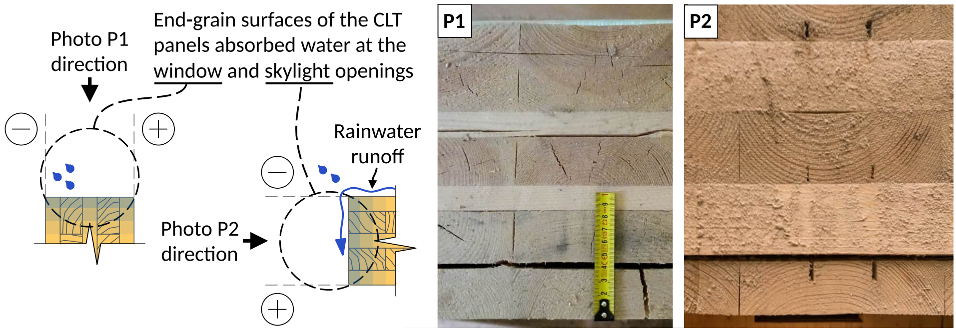


Figure 24. Wall to window and roof to skylight connections, which experienced repeated wetting and where cracks and delamination occurred (P1, P2) after moisture dry-out (P1 = building A, P2 = building B).

All studied buildings showed some form of end-grain wetting (Table 7). The larger buildings exhibited all types of CLT end-grain wetting identified in this study. In contrast, the detached houses D and E experienced fewer incidents, likely due to shorter construction periods. A correlation exists between wetting severity and cumulative precipitation (Table 7), yet many severe wetting incidents also occurred over single rain events. For instance, Figure 14 shows intense rainfall at building B during the first week of CLT installation, followed by a dry period; nevertheless, very high MC was recorded in week 5 (Figure 20, building B).

Table 7. Summary of the on-site findings. Colours: wetting incident detected visually (W = wet, red) or not (D = dry, green). If not applicable or data not available (N/A), then grey.

Building **Connection joint**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H1**	**H2**
Bottom surface of CLT wall panel	W	W	W	W	W	W	W	D	W
Side surface of floor panel	W	W	N/A	D	N/A	W	D	N/A	W
Side surface of roof panel	W	W	W	N/A	N/A	W	D	N/A	N/A
Window or skylight perimeter	W	W	W	D	D	W	W	W	W
Accumulated precipitation [mm]	275	335	183	14	35	229	67	96	56

In the building G, the floor panel connection joint was also highly problematic. At this joint, there was a groove, rather than a half-lap connection, and the groove acted as a bowl where water accumulated. A plywood strip was secured into the groove, which then also got wet and prohibited moisture dry-out. Unfortunately, the waterproofing membrane was not installed within the groove on the CLT floor panels, which were otherwise covered already in the CLT factory. Protection was only added over the connection when the plywood strips were fitted, allowing water ingress beforehand. This caused elevated MC in the CLT and the plywood strips (Figure 25).

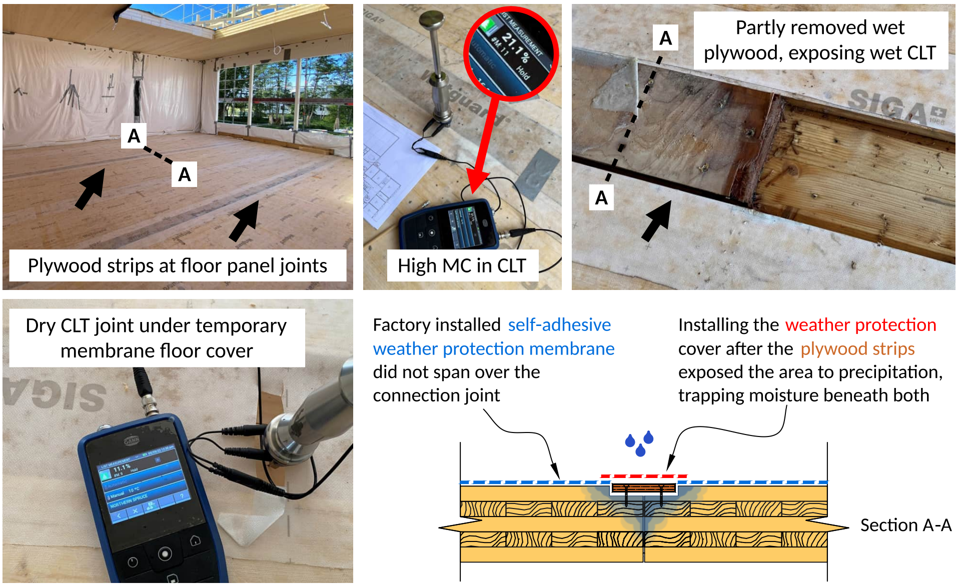


Figure 25. Problematic floor panel connection joint in building G. Water ingress to CLT floor joints raised CLT MC above 20 %. Initially, a plywood strip was installed before the weather protection membrane, but in a revised method, the membrane was installed first, ensuring dry construction.

From the on-site observations and measurements, it was determined that to achieve the greatest effect in improving the moisture safety of CLT construction, efforts should be concentrated on the improvement of moisture safety near the end-grain surfaces of CLT panels.

4.2 Design vs technical drawings and improvement proposition of local moisture protection measures for CLT moisture safety

A moisture safety plan and regular moisture inspection rounds were present only in the buildings A and G. The buildings B to F were constructed without specific moisture safety plan or technical drawings – only the constructor expertise was relied upon to ensure moisture safety. No moisture safety strategy pre-analysis was done to any of the studied buildings.

The building A was the first CLT building in Estonia to include a moisture safety plan. However, the plan remained generalised and without specific technical drawings.

For the building G, the institutional client (Riigi Kinnisvara AS, the state real estate development and management company) mandated the use of previously established technical requirements for non-residential buildings, which included moisture safety requirements (Riigi Kinnisvara AS, 2021). The project documentation of the building G advised to install CLT under an FWP structure or alternatively treat the bottom end-grain surfaces with a moisture-proof sealer; wrap panels in thermal film; and apply water resistant self-adhesive protective films to floor panels.

As the designers of the building G specified the use of an FWP structure, they did not provide drawings for additional weather protection solutions. Moisture safety was scarcely covered in the architectural section of the project documentation. The moisture safety topic also remained brief and general in the structural design section, which concentrated only on the load-bearing capacity of the building and overlooked moisture loads during construction.

Site observations suggested that design quality played a greater role than contractor expertise in ensuring moisture safety (this deduction is further detailed in Section 4.9). General moisture safety guidelines and typical connection joint drawings alone seemed to be insufficient. It was hypothesised that incorporating specific technical drawings of moisture protection measures into design documentation could improve moisture safety in CLT construction. The results from the site observations, analysis of the procurement documentation and project design indicated that specific guidance was needed on how to implement local protection. Stating the need for protection alone was inadequate – just as stating that timber must be dry falls short without a measurable threshold. Although there was limited evidence on the precise format of design drawings, it was clear that incorporating moisture safety into building design enhanced quality assurance. Nevertheless, example drawings were developed and, along with recommendations for improving moisture safety of CLT construction, were published in 2020 in Publication I. Two examples of these are given on Figure 26 and Figure 27, with additional drawings available in Publication I. At that time, the recommendations were as follows:

- A waterproof membrane coating should be applied in the factory to the end-grain surfaces of CLT, specifically for bottom end-grain surfaces of wall panels.
- Using a clear foil to protect the sides of the CLT panels from precipitation helps in detecting accidental water flow behind the foil. To function as weather protection after CLT installation, the foil must be resistant to winds and tearing. The foils should be fixed to the plinth immediately after installation with a water-resistant tape to prevent splashing water getting under the foil.
- To ensure an air- and vapour-tight connection, a sealing tape is necessary at CLT panel connections on the building envelope. If the sealing is also moisture-resistant and installed immediately after installation, it further prevents water infiltration into the connection joints.
- Horizontal CLT panels require factory-installed weather protection membranes that must not emit harmful substances in indoor use. All joints and feedthroughs must be sealed against water penetration immediately after CLT installation.
- Excess water should not drip over the edges of the floor and roof panels.

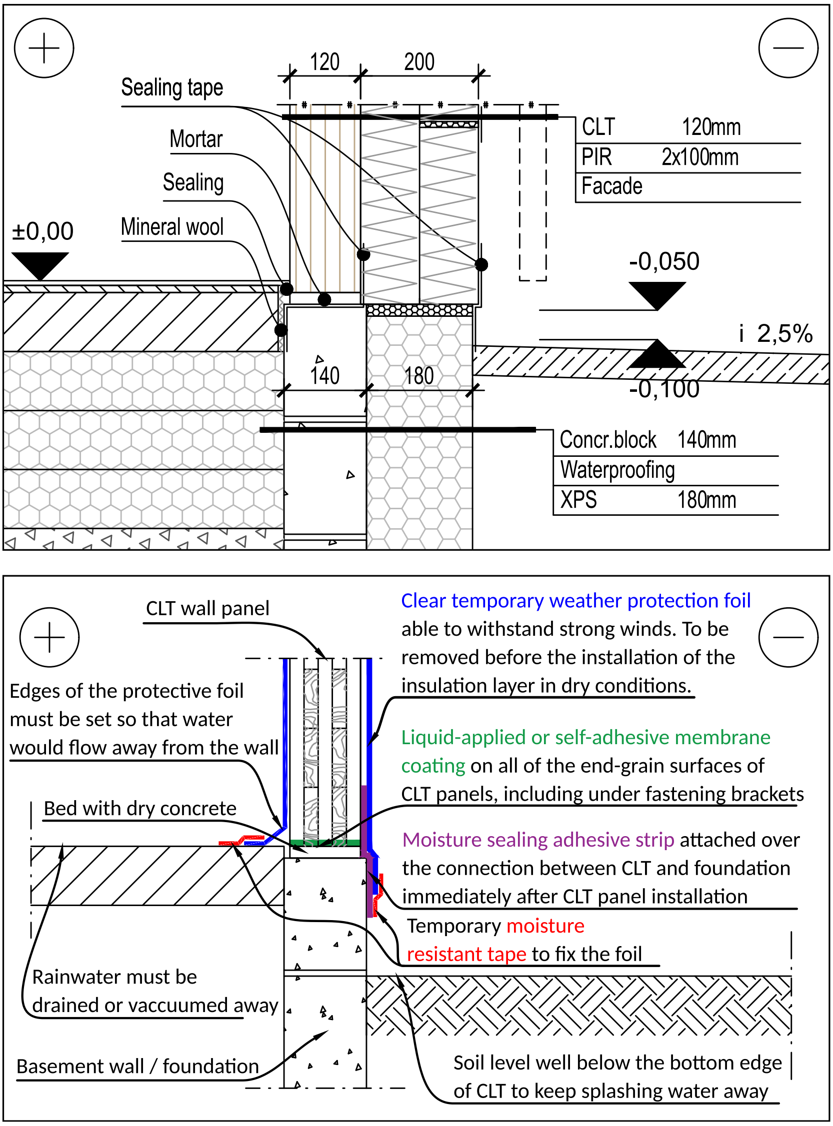
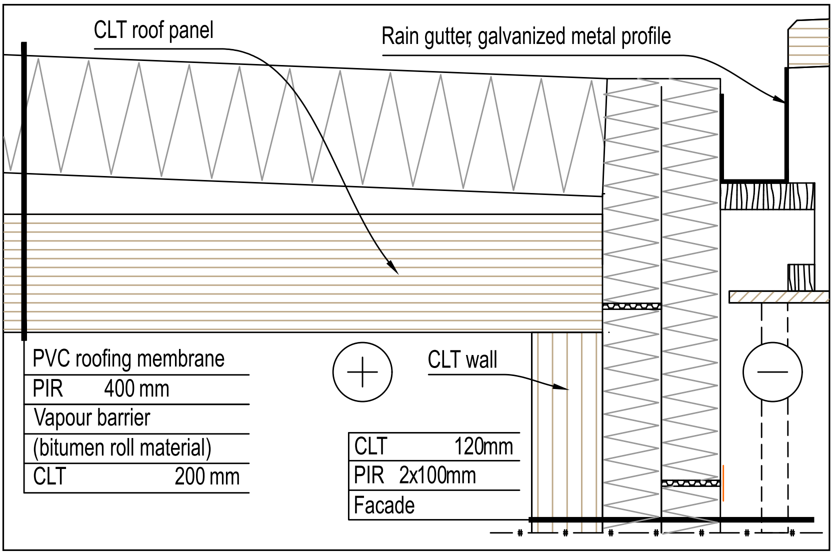


Figure 26. Design drawing (top) of the exterior wall to foundation connection and an example drawing (bottom) of the moisture safety design drawing for the same area.



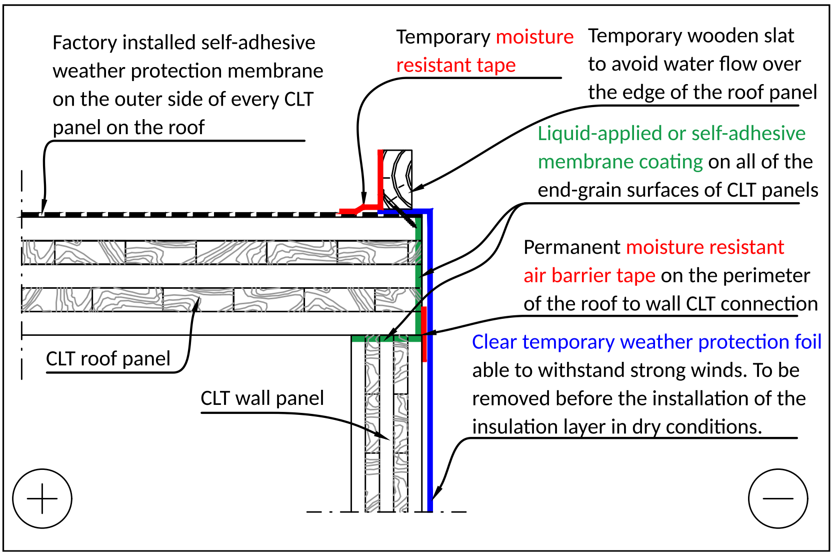


Figure 27. Design drawing (top) of the exterior wall to roof panel connection and an example drawing (bottom) of the moisture safety design drawing for the same area.

4.3 Moisture distribution in CLT after end-grain wetting

4.3.1 Experiment 1: electrical resistance-based MC measurements

Approximately 2800 MC measurements were taken over three weeks. Figure 28 presents the results for the surface (S*i*) and inner longitudinal (M*i*) layers of the CLT. All S*i* and M*i* references (where *i* denotes the distance in millimetres from the water contact surface) refer to Figure 28 in this section. The results in the figure are also divided into four groups depending on the conditions during the drying phase.

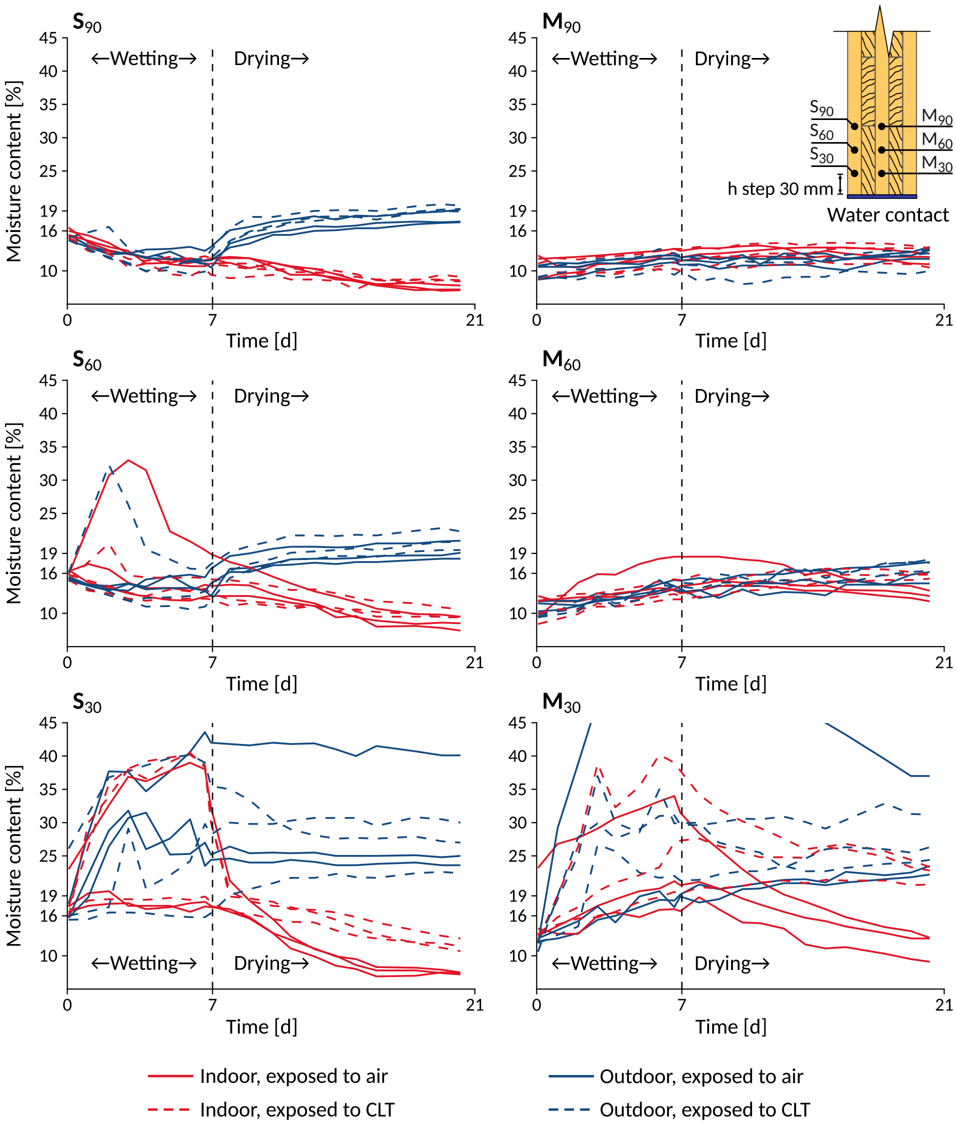


Figure 28. Measured MC during the wetting phase (0–7 days) and the drying phase (7–21 days). Measurements were taken at the depth of 5 mm (S_i: surface measurement points at a height of i mm), and at the depth of 50 mm (M_i: measurement points located in the inner longitudinal layer at a height of i mm). These results were published in Publication V.

The results indicate that MC generally increased rapidly during the wetting phase at the height of 30 mm above water contact in both the surface and inner longitudinal layers of the CLT TSs. In many TSs, MC at this height reached over 30 % in less than two days, however considerable variability was observed in the measurements at this height, as in some cases MC remained under 19 % throughout the entire wetting phase in both the surface (S_{30}) & and inner (M_{30}) layers.

At a height of 60 mm above water contact, modest yet stable increase in MC was observed in the inner layer (M_{60}) during the wetting phase. The mean MC of all TSs at M_{60} did not exceed 16 % after seven days of continuous water contact. At 90 mm from the water contact in the inner layer (M_{90}) there was a very small trend of increasing MC during the wetting phase and MC did not exceed 14 % there.

Contrary to the inner layers, there was a general trend of decreasing MC during the wetting phase in the surface layer at 60 mm and 90 mm from the water contact (S_{60} & S_{90}), with the exception of two outliers at S_{60}, in which case MC increased rapidly, reaching over 30 % within approximately three days. The general trend of decreasing MC during the wetting phase in the in the surface layer, both at S_{60} and S_{90}, was probably a result of the ambient conditions in the laboratory during the experiment. The equilibrium MC of timber under those conditions (mean temperature ≈ 21.6 °C, mean RH ≈ 29 %) would have been approximately 6 % (calculated using Equation 4–5 from Glass & Zelinka (2021)), which was lower than the initial MC of the TSs (10 % to 12 %, and up to 20 % on the outermost surface). The surface layer was also more susceptible to dry-out.

During the drying phase, MC in the surface layer decreased promptly in all TSs left to dry in the indoor environment (red lines in $S_{30–90}$ in Figure 28). At 30 mm from the water contact, moisture dry-out was slightly slower in the surface layers of the TSs with moisture trapping conditions at the wet surface (red dashed lines in S_{30} in Figure 28) than in TSs which wet surface was exposed to air (red continuous lines in S_{30} in Figure 28). By the end of the drying phase, MC in the latter group was about 3 % lower at S_{30}, though both fell below 16 % at roughly the same time. No such difference between the two groups was observed at S_{30} or S_{90}.

In the TSs exposed to outdoor air during the drying phase, MC began to rise in the surface layer (blue lines in $S_{30–90}$ in Figure 28) due to moisture absorption from the surrounding air. An exception was observed in a few cases at 30 mm from the water contact (S_{30}) where MC had reached very high levels by the end of the wetting phase and subsequently decreased slightly also under the outdoor conditions. The equilibrium MC was > 22 % in the outdoor test area (mean temperature ≈ 2 °C and mean RH ≈ 92 %). Thus, the increase in the surface MC was to be expected. In the outdoor drying condition, no consistent distinction in surface layer MC could be observed between TSs with the wetted surface placed against another CLT detail and those with the wetted surface exposed to air.

In the inner CLT layers, MC decreased during the drying phase only at the 30 mm height level, and only in the TSs left to dry in the indoor environment (red lines in M_{30} in Figure 28). At this height level in the case of the indoor drying TSs, a clear difference in moisture dry-out was observed between the TSs with moisture trapping conditions at the wet surface and the TSs which wet surface was exposed to air. In the TSs where the wet surface was exposed to indoor air, MC fell below 16 % within 6 ± 3 days, while in TSs which were also in the indoor environment but with another CLT detail connected to the wet end-grain surface, MC was above 19 % even by the end of the 14-day drying phase.

In the TSs placed in the outdoor environment, MC generally increased at all measured heights in the inner longitudinal CLT layer. An exception was observed in one sample at M_{30}, which had reached a very high MC by the end of the wetting phase and subsequently exhibited a drying trend during the drying phase, although it still retained the highest MC by the end of the drying phase. Excluding this outlier, the TSs subjected to moisture trapping conditions tended to exhibit higher MC values at M_{30} than those without within the group of TSs exposed to outdoor conditions.

At other heights in the inner layer of the TSs MC mostly continued to increase throughout the drying phase. As this happened similarly in both the indoor and outdoor testing environment, it is presumed that the increase in MC is from the moisture redistribution from wetting and not from adsorption from the ambient air.

To follow up on the earlier discussion of the water contact phase, the rate of moisture transfer from the water contact below the CLT TSs varied markedly, likely due to the heterogeneous nature of timber, as clearly illustrated in Figure 29. It is evident that, for the specific TS shown, moisture transfer at the measurement line and adjacent areas differed. In the two outliers in Figure 28 at S_{60}, where MC exceeded 30 %, the measurement points coincided with zones of intensive water uptake, while in most other TSs the measurement points happened to be at locations where the water uptake was less intensive, allowing dry-out toward the lab environment to dominate there.

However, as also illustrated in Figure 29, moisture stains on the surface of the CLT TSs in some areas extended beyond 100 mm height. Further details on these aspects are available in Publication V, which also includes data from measurement points at 120 mm and 150 mm above the water contact level.

Figure 30 shows a composite image of photographs taken from the section cuts of the TSs which were used in the first experiment. The image was created by stacking individual photos from all TSs using the "darken" blending mode, where darker areas in each subsequent image obscure lighter areas beneath, while lighter areas do not obscure darker ones. Differences between the longitudinal and transverse CLT layers are well visible.

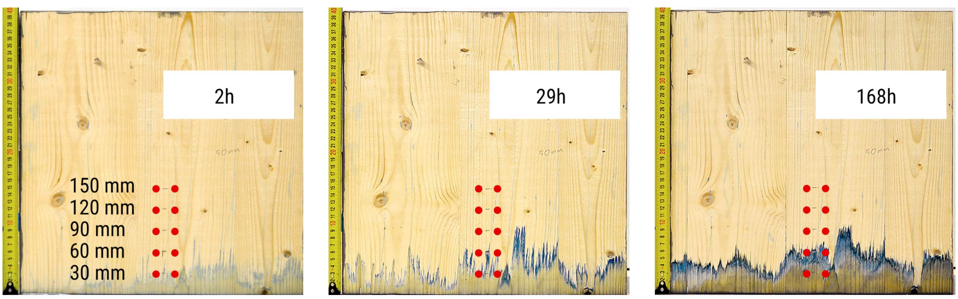


Figure 29. Photos of TS 20 at 2, 29 and 168 hours after the start of water contact. Water was dyed blue. Red dots mark the MC measurement points.

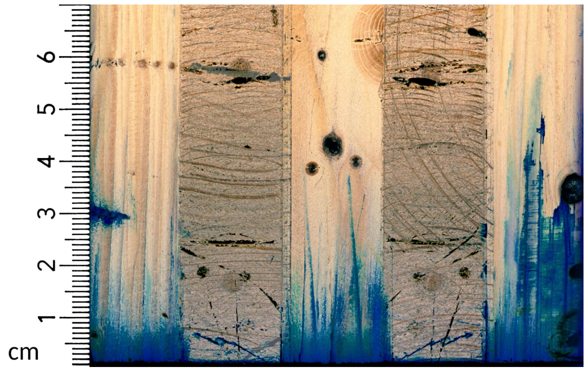


Figure 30. Composite image of all TSs after water contact from the first experiment. Transverse layers show very little staining while the longitudinal layers exhibit significant water adsorption.

Based on TS weight measurements, the average water uptake rate was calculated as 200 g/(m²·h) ± 54 g/(m²·h) for the first two hours, decreasing to 85 g/(m²·h) ± 23 g/(m²·h) over the next four hours and gradually reducing to 20 g/(m²·h) ± 7 g/(m²·h) after 70 hours, where it stabilised (Figure 31, left). The average water absorption coefficient A_W, calculated per EN ISO 15148:2003, was 3.51×10^{-3} kg/m²·s$^{0.5}$ for the five ply CLT TSs considering both longitudinal and transverse layers. A more detailed discussion of these results can be found in Publication V.

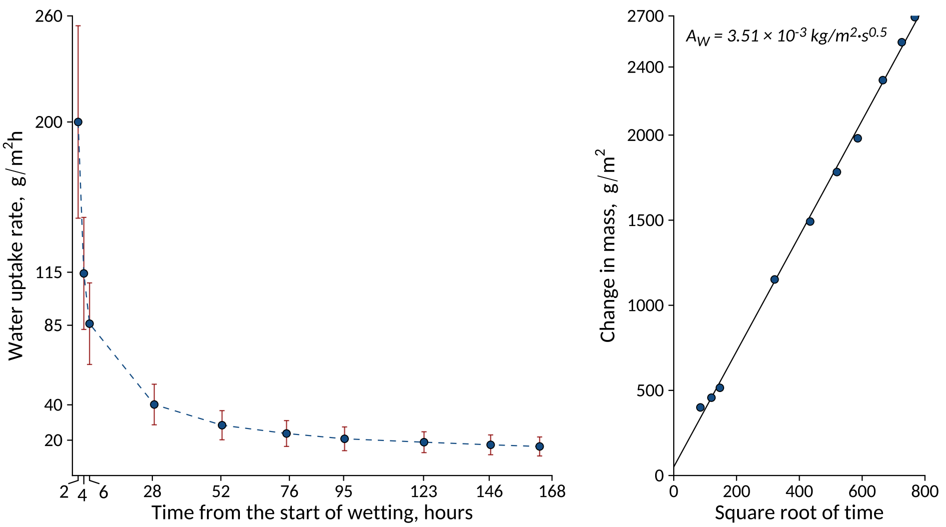


Figure 31. Water uptake rate during the test as an average of every TS (left) and change of mass against the square root of time for A_W calculations. These results are more detailed in Publication V.

4.3.2 Experiment 2: water absorption of timber in different grain directions

In the second experiment, 20 boards from the same batch of CLT panels as used previously were tested analyse MC distribution during one-dimensional (1D) isothermal water uptake and to separately determine the water absorption coefficients (A_W) for the longitudinal and transverse fibre directions. This was in contrast to Experiment 1 where a single A_W value was given for the entire end-grain surface of a five-ply CLT panel.

Figure 32 presents the results of MC measurements obtained using the electrical resistance-based method. The directionality of moisture absorption in wood is clearly evident. These results did not have a primary role themselves, but served as input for determining whether, and which, of the Delphin built-in material files could be reliably used for compiling anisotropic material files (as presented in Section 4.4.1). The 1D isothermal setup of the experiment also simplified simulation, to make possible discrepancies easier to detect and explain.

The gravimetrically determined A_W values were 0.0138 kg/(m^2·s$^{0.5}$) for the longitudinal direction and 0.0023 kg/(m^2·s$^{0.5}$) for the transverse direction. Wang et al. (2023) validated a CLT hygrothermal simulation model generated in Delphin, and in their study the A-values were 0.012 kg/(m^2·s$^{0.5}$) for the longitudinal direction and 0.0025 kg/(m^2·s$^{0.5}$) for the transverse direction. All of the values presented above are well within the range of measured A-values for softwoods (Glass & Zelinka, 2021).

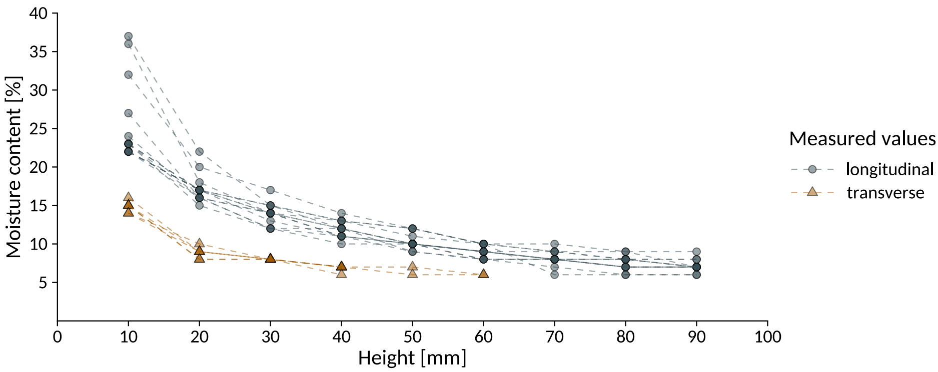


Figure 32. MC measurement results for timber boards subjected to continuous water contact via the end-grain surface (longitudinal) or side-grain surface (transverse).

4.3.3 Experiment 3: gravimetric MC measurements

In the third experiment, MC distribution was measured gravimetrically to gain more accurate data considering MC values above the fibre saturation. Measurements were taken at 7 mm vertical intervals for a higher spatial resolution compared to the 30 mm steps used in the first experiment.

Figure 33 (top left) shows that by the 4th hour of wetting, MC already exceeded fibre saturation (≈ 30 % MC) in the longitudinal fibre layers at ≈ 0–7 mm from the water contact surface, with an average MC of 64 %. At this height level, individual measurements exhibited considerable variation, ranging from 46 % to 78 %. Significant variability in measurement results was also observed after 8 and 24 hours of water contact. However, by 48 hours, the MC in five out of six measurement values had stabilised within the range of 127 % to 139 %.

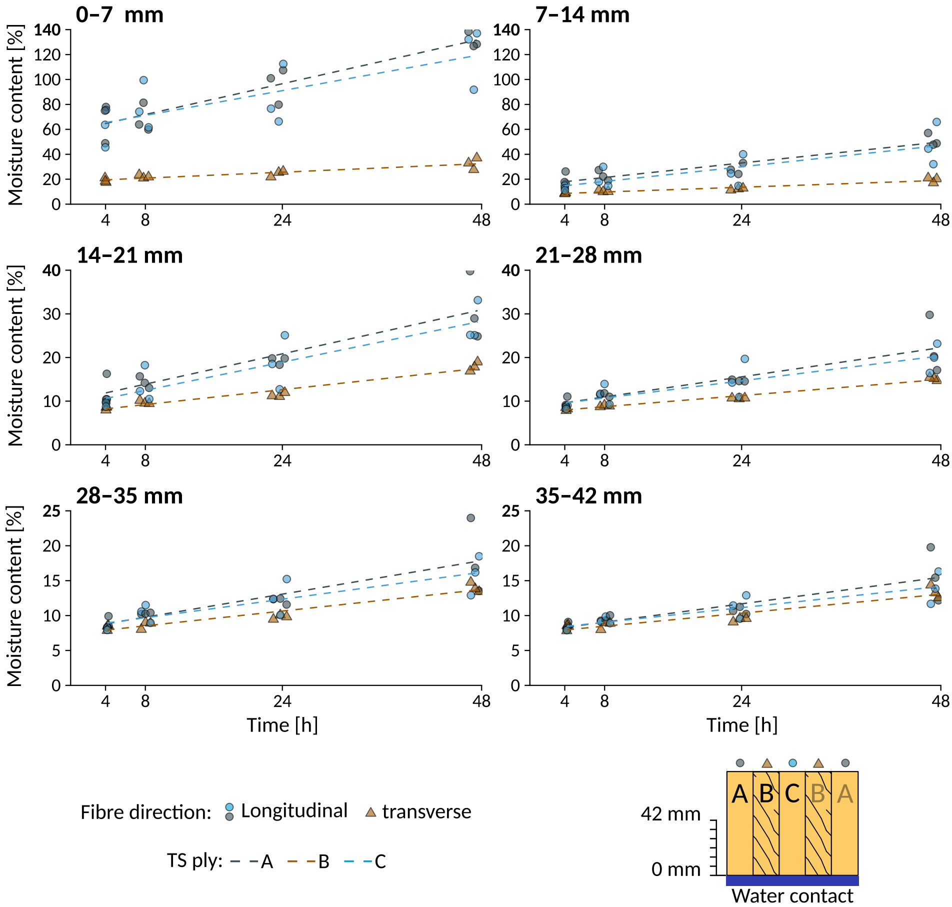


Figure 33. Gravimetric MC measurement results by ≈ 7 mm steps from the water contact surface in three layers of CLT test specimens which were subjected to water contact for 4, 8, 24 and 48 hours. Notice that the scale for the different plot facets varies from 25 % to 140 %.

By the 4th hour of wetting, the average MC in the transverse layer at ≈ 0–7 mm exceeded 16 % (Figure 33, top left). Subsequent increase of MC in the transverse layer at this height level was moderately slow and MC variation was significantly smaller than in the longitudinal layer. After 48 hours of water contact, average MC in the transverse layer at ≈ 0–7 mm height reached 33 %.

At ≈ 7–14 mm from the water contact surface (Figure 33, top right), the MC of both longitudinal fibre layers exceeded 16 % after 8 hours and some values reached up to 30 % MC within that time. By 48 hours of water contact the average MC for the longitudinal layers was above 40 % at ≈ 7–14 mm from the water contact surface. Variability of the results remained considerable. In the transverse layer at ≈ 7–14 mm, MC exceeded 16 % after 48 hours of water contact, with a maximum value of 21 %.

For the height level of ≈ 14–21 mm from the water contact surface (Figure 33, middle left), the MC in both longitudinal layers exceeded 16 % after 24 hours, ranging between 18 % and 20 %. In one instance, 16 % was already exceeded after 4 hours of water contact. After 48 hours, the average MC in the longitudinal layers at ≈ 14–21 mm height was 30 %. The increase of MC in the transverse layer at ≈ 14–21 mm height was slow during the first 24 hours of water contact, followed by a slightly more rapid rise of MC over the next 24 hours, eventually exceeding 16 % after 48 hours of water contact.

At ≈ 21–28 mm from water contact (Figure 33, middle right), MC did not exceeded 30 % in neither the transverse or longitudinal layers. A higher convergence of MC between the longitudinal and transverse layers was observed at this and higher measurement points.

At ≈ 28–35 mm (Figure 33, bottom left), the MC in the longitudinal layers increased slowly yet consistently from 9 % at 4 hours to 17 % at 48 hours. At ≈ 35–42 mm from the water contact (Figure 33, bottom right), no notable differences were observed between the longitudinal and transverse layers. Average MC in all layers at this depth ranged between 13 % and 16 % after 48 hours of water contact, with the innermost longitudinal layer differing from the transverse layer by less than one percentage point.

In summary, the results from the third experiment indicated relatively uniform MC increases in both the inner and outer longitudinal fibre layers across all examined height levels. At approximately 15 mm from the water contact MC exceeded 16 % within just 4 hours in the longitudinal layers. Moisture propagation in the transverse layer was slower, but in the bottom-most transverse layer (≈ 0–7 mm from water contact) MC exceeded 16 % after 4 hours of water contact. However, MC remained below 16 % in all transverse layers above 15 mm from the water contact level even after 24 hours of water contact. Figure 34 illustrates the distribution of the average MC of the TSs by exposure duration, CLT layer (A, C = longitudinal, B = transverse) and height from water contact.

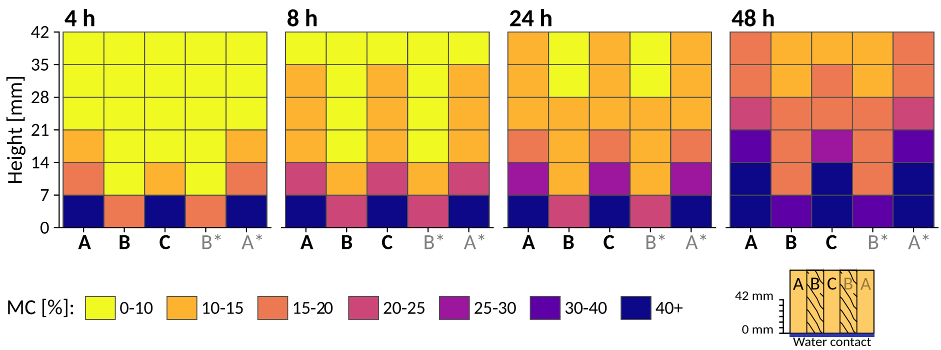


Figure 34. Average MC distribution in CLT after 4, 8, 24, and 48 hours of water contact.

4.4 Hygrothermal modelling, material properties, validation

4.4.1 Study of Delphin built-in material files

The suitability of the Delphin built-in material files for inclusion in further validation was assessed based Experiment 2 (Section 4.3.2). The material files that best aligned with the measurement results were then chosen for compiling the anisotropic material files.

Some material definitions produced vastly different simulation results compared to the measurements (Figure 35). Simulations with most spruce material files from the built-in database resulted in a much greater MC than the measurements indicated. The electrical resistance-based measurements showed a maximum MC of 37 % and 16 %, where some simulations indicated over 100 %. The accuracy of the electrical resistance-based measurements decreased at MC values above the fibre saturation point, but the difference of about 100 percentage points could not be explained by the measurement method uncertainty alone, especially in the case of transverse grain direction, where also the results from the gravimetric measurements (Section 4.3.3) were notably smaller than the simulation results with some material files.

Materials with the identification codes ID711 and ID807 showed a good correlation with the measurement data on longitudinal moisture transfer. The fit was less ideal for the transverse moisture transfer, but a reasonable agreement was achieved with the files ID695 and ID713 (Figure 35).

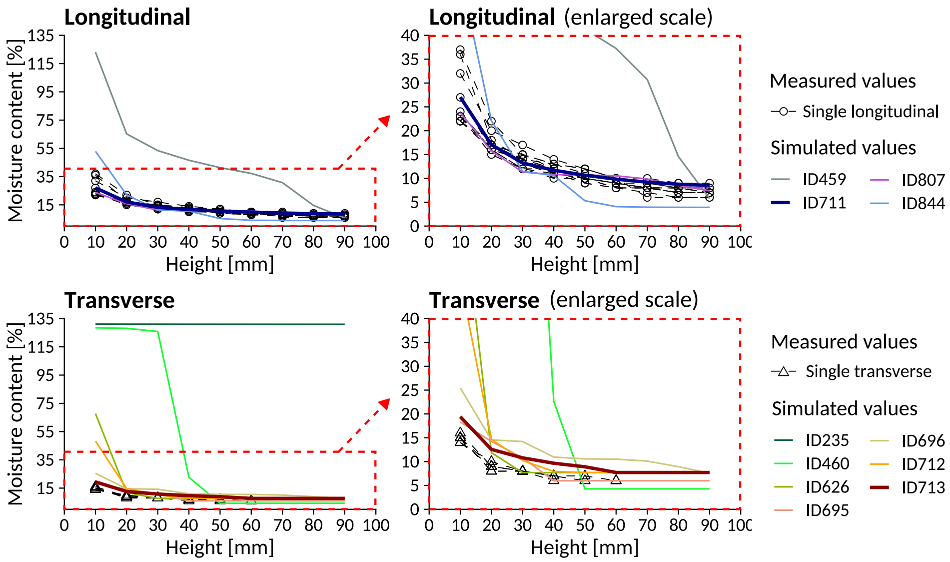


Figure 35. Comparison of MC measurements from Experiment 2 with simulations using spruce material files in the HAM simulation tool Delphin. ID codes refer to material file identification codes in the Delphin database. The left charts show MC values on a 135 % scale, while the right charts zoom in on the dashed box sections from the left for better readability (MC scale up to 40 %).

4.4.2 Isotropic vs anisotropic material transport model

Figure 36 shows the data for both isotropic and anisotropic transport models at M_{30} indoor (30 mm from water contact in the middle layer of the specimens which dried indoors) and S_{30} outdoor (30 mm from water contact in the surface layer of the specimens which dried outdoors). Results for both isotropic and anisotropic model are given considering three material property combinations: 1) based on unaltered definitions from the Delphin database (magenta), 2) altered for achieving the best fit (green), and 3) altered for achieving increased water uptake (blue).

Under moisture dry-out favouring conditions (M_{30} indoor, 7–21 days in Figure 36), the model, which considered isotropic material properties, predicted considerably faster moisture dry-out than the measurement data suggests. This was true for all of the isotropic material files (dashed lines in Figure 36). The isotropic material transport model consistently predicted lower MC, with a final difference of −10 % MC to −3 % MC compared to measured values. The anisotropic model showed a smaller difference between −3 % MC and +3 % MC and was better at replicating the outlying values during periods of intensive moisture uptake, specifically in the surface layer (S_{30} in Figure 36).

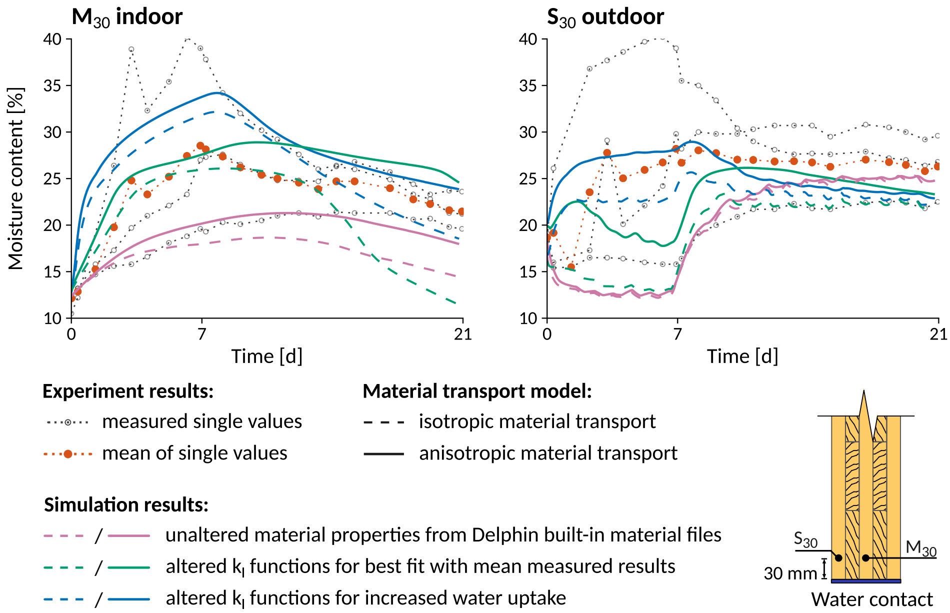


Figure 36. Comparison of simulated values for the isotropic material transport model (dashed lines) and for the anisotropic material transport model (continuous lines) with measured single values (dotted line & open circles) and the mean of the measured values (closed circles).

Replicating intensive moisture uptake in the surface layer proved particularly challenging for the isotropic model, where differences remained large even for the results which considered the material properties with increased water uptake. The two other material files performed even worse in the isotropic model, with results below the lowest measured values.

The isotropic material model (considering all studied material files) may be suitable for replicating 1D water uptake, e.g., in the inner layer during the wetting phase (M_{30} indoor, 0–7 days in Figure 36). However, the isotropic model became inadequate when multi-dimensional aspects started to dominate, such as when the moisture dry-out toward side faces became more prominent in the drying phase (M_{30} indoor, 7–21 days in Figure 36). In these cases, or when multi-dimensional moisture redistribution and dry-out was already significant (e.g., surface layer results, S_{30} in Figure 36), the anisotropic model proved more accurate.

4.4.3 Validation of the anisotropic simulation model and material files

Figure 37 and Figure 38 compare the simulated MC with the measured single values and with the mean of measured values from Experiment 1 (Section 4.3.1). Simulation results are shown for the three anisotropic material files and for the surface layer (S_i) and middle layer (M_i) of the CLT panel at height *i* mm from the water contact surface. Statistical indicators RMSE and MBE are given for each location in the figure.

Simulation results for the surface layer at the height level of 90 mm and 60 mm from the water contact boundary (S_{90} and S_{60} in Figure 37) correlated very well with the measurement results, both for the case where the moisture dry-out phase was in the dry indoor conditions and for the case where the dry-out phase was in the colder and more humid outdoor environment.

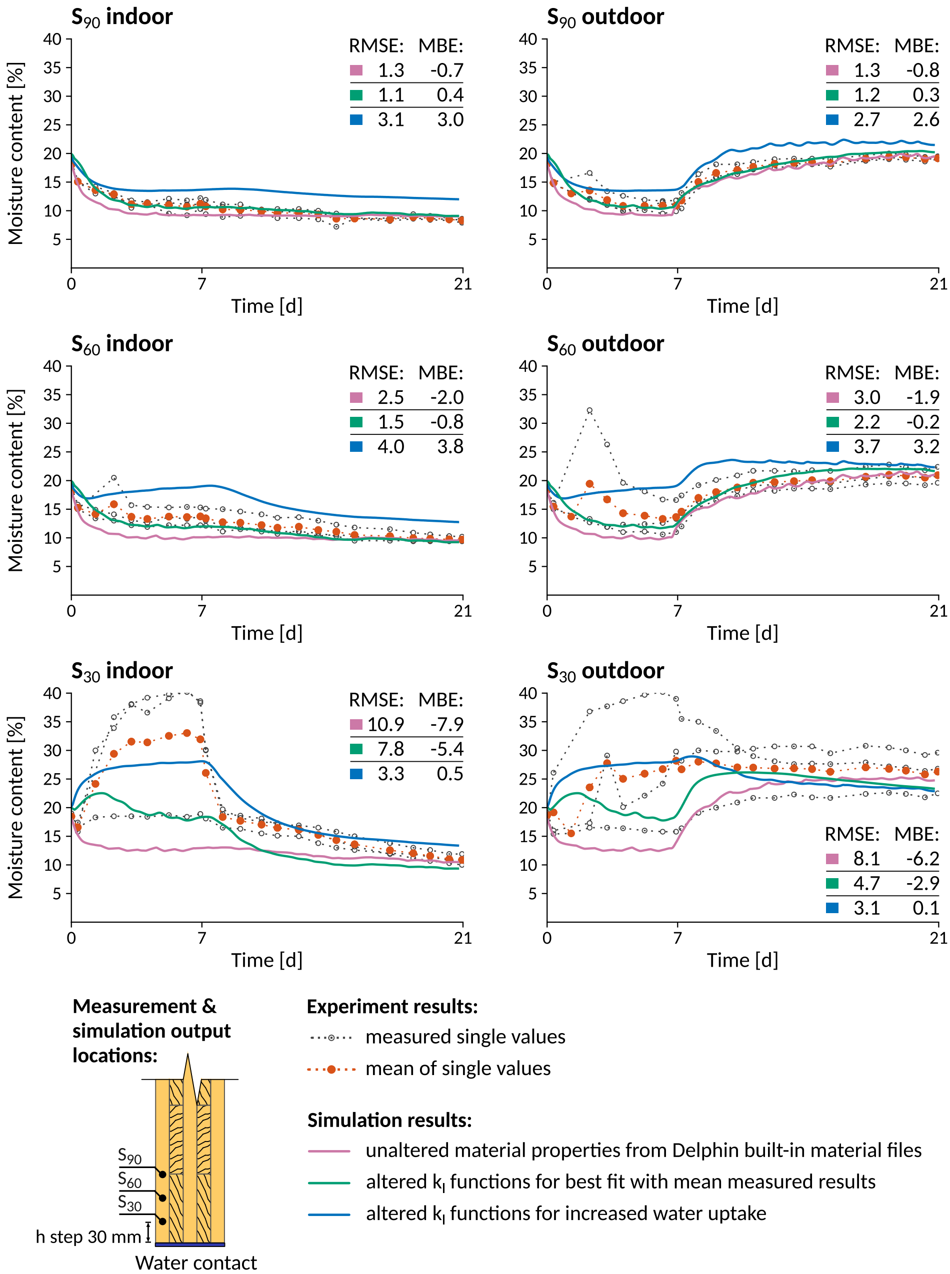


Figure 37. Comparison of simulated MC values (continuous lines) with measured single values (open circles) and the mean of measured values (closed circles). Measurement data from Experiment 1. Values for the outer longitudinal CLT ply.

However, simulating moisture transfer near the water contact (S_{30} in Figure 37) proved to be challenging, and the simulation results here deviated from measurement data considerably. The unaltered material file from the Delphin database produced the largest negative bias (MBE = −7.9 % for indoor drying conditions and MBE = −6.2 % for outdoor drying conditions), but the result obtained with the material file optimised for increased water uptake correlated better with the mean of the measurements (RMSE = 3.1 % to 3.3 % and MBE = 0.1 % to 0.5 %).

Simulation results for the inner CLT layer at higher measurement points (M_{90} and M_{60} in Figure 38) showed an adequate correlation with the unaltered material file (RMSE between 1.5 % and 2.5 %, MBE between −1.3 % and 2.0 %) and both files with altered material definitions led to an overestimation of moisture transfer (RMSE up to 8.8 % and MBE up to 8.3 %). On the other hand, at 30 mm from the water contact surface (M_{30} in Figure 38) the altered material files were necessary to cover the range of measurement results. The root mean square error (RMSE) for the best fit model was between 2.2 % and 2.8 %, while the mean bias error (MBE) was between 0.6 % and 2.3 %.

It was found that without altering the moisture storage function, specifically in the range of capillary pressure of approximately -10^6 Pa to -10^5 Pa corresponding to approximately 99.3 % to 99.9 % RH, it was not possible to simultaneously achieve a good correlation with the observed extensive water uptake near the end-grain edges (M_{30}) and limited water uptake at the higher measurement points (M_{60} and M_{90}) with the given material files. The moisture storage function was highly sensitive to alterations, which could produce vastly different results. These observations were in line with the findings of Wang et al. (2023), who also detected a significant impact of the moisture storage function to the simulation results.

The efficacy of the method of validating such simulation models with electrical resistance-based MC measurements is limited due to increased uncertainty of the measurements in the over hygroscopic range of MC in the CLT in the vicinity of the water contact surface. Therefore, the simulation results were also compared to the gravimetric MC measurement results (Experiment 3, Section 4.3.3). The comparison results are provided in Figure 39, where simulated values are shown as open rectangles and as continuous lines, while the means of measured values are shown as closed circles and dashed lines. Simulation results are again given for the three different anisotropic material files.

In this comparison, the altered material files produced a noticeably better fit with the mean of the measured values than the initial unaltered material file (Figure 39). The unaltered material file caused the MC to reach very high values (> 100 %) in the areas closest to the water contact, even though the mean of the gravimetric measurements did not indicate such high MC levels. The difference was largest among the results obtained from the transverse layer. According to the gravimetric measurements, MC in this layer should have remained below 30 % even in the areas closest to the water contact (average for the area between 0 mm and 7 mm from the water contact surface). This was also verified by generating a composite image of the TSs from the first experiment, where minimal staining was visible in the transverse layers (Figure 30). By the end of the dry-out phase, the correlation improved, but the unaltered material file resulted in more extensive moisture retention and thus longer dry-out times.

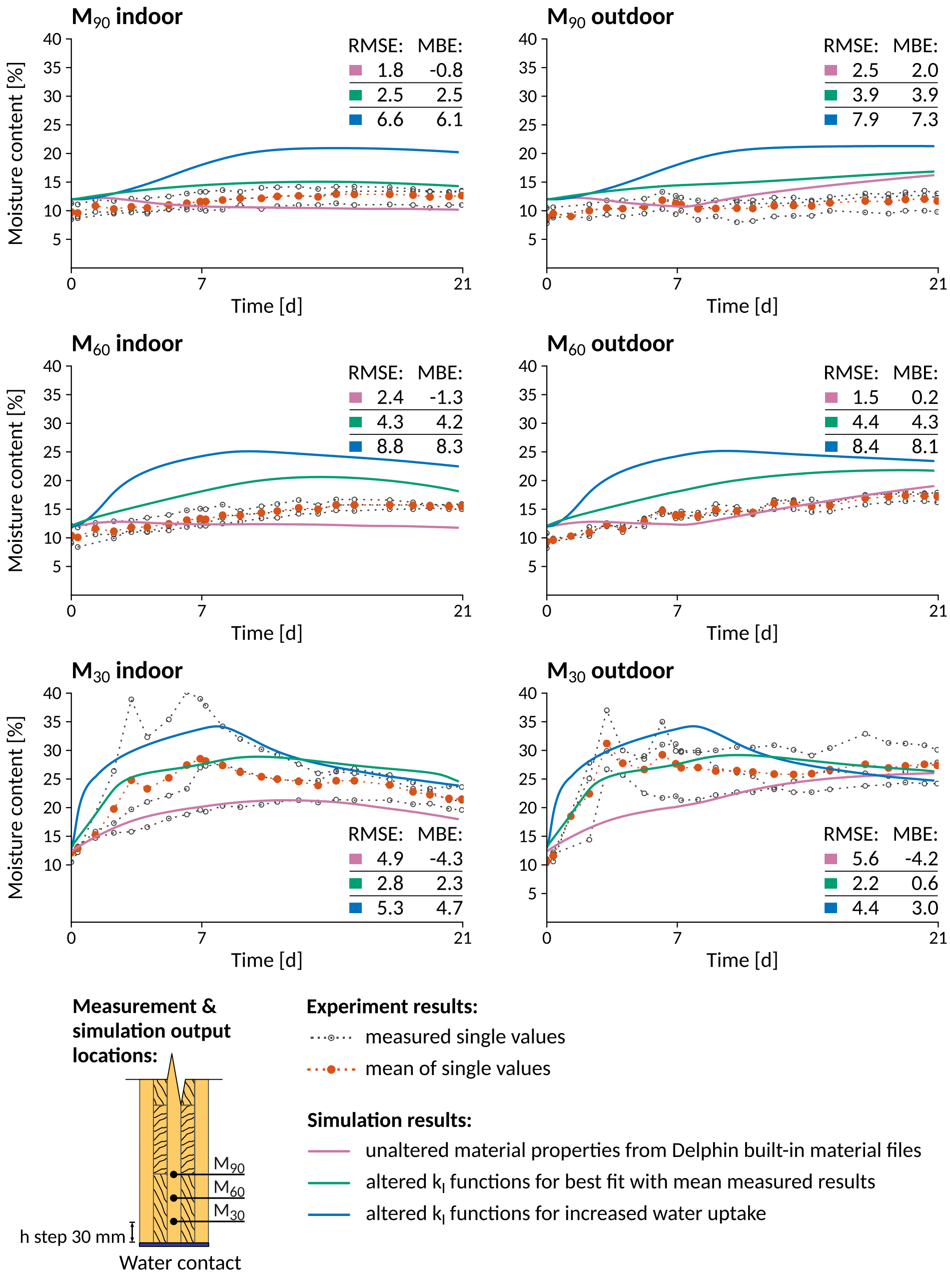


Figure 38. Comparison of simulated MC values (continuous lines) with measured single values (open circles) and the mean of measured values (closed circles). Measurement data from Experiment 1. Values for the inner longitudinal CLT ply.

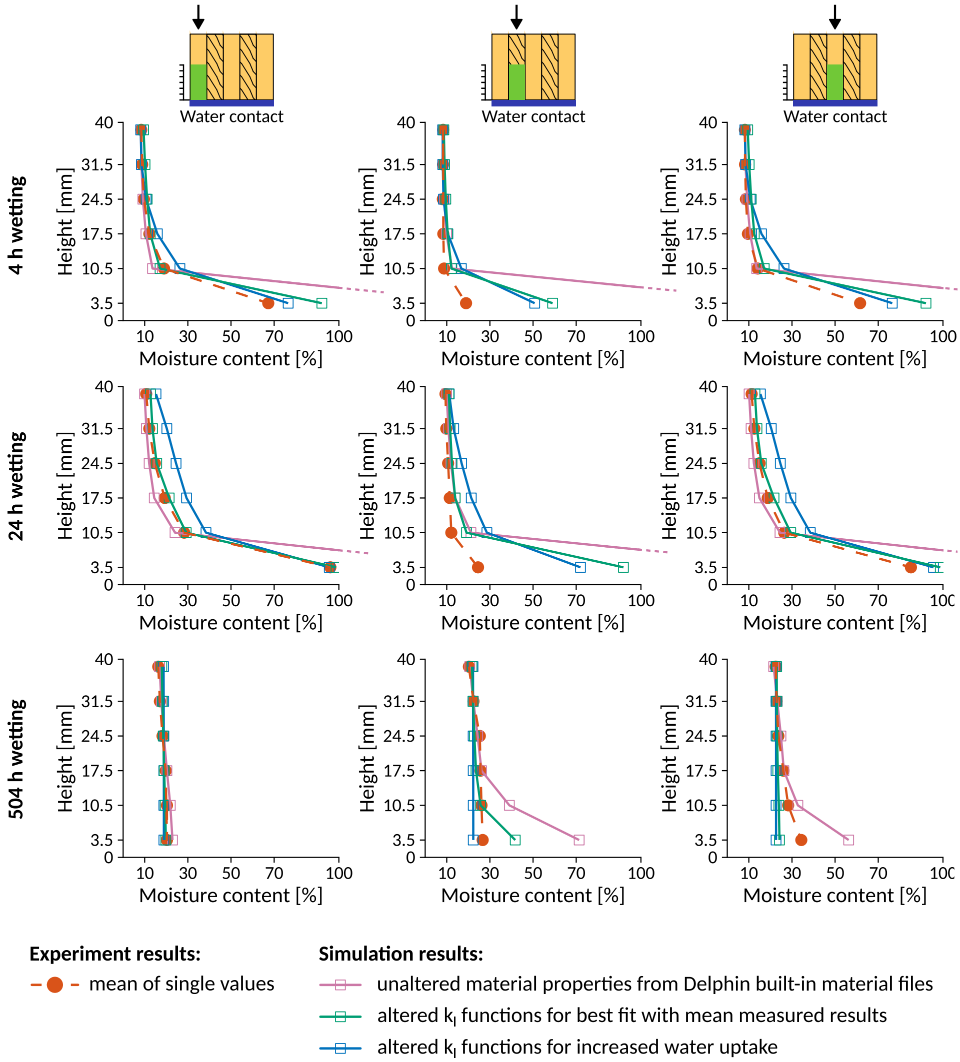


Figure 39. Comparison of simulated MC values. The left column represents the outer longitudinal CLT layer, middle column transverse layer and right column inner longitudinal layer. To avoid compressing the scale and impairing readability, the simulation results with values > 100 % are represented by a dashed portion of the magenta line. The reported times on the left (4–504 h) indicate the number of hours since the start of the wetting–drying test.

While the simulations done in this study showed some discrepancies compared to the experimental data, the correlation was deemed sufficient to allow the corresponding models to be used in the CLT end-grain moisture safety analysis. Depending on which process is more critical in a given situation – faster moisture absorption (represented by the altered material file for increased water uptake) or longer moisture retention – different material files may produce more critical results. Therefore, no single material file can be said to consistently yield results on the risk or safety side. With the selected and developed material files it was deemed possible to simulate both intensive water uptake and extended moisture retention and all the three selected and developed material files were used in further analysis.

4.5 Development of the MC-based two-step performance criterion

The initial MC values for this calculation were derived from the results of Experiment 3, see Figure 34 in Section 4.3.3. The calculation results (Figure 40) indicated that if the end-grain surface of CLT was exposed to water, the calculated maximum M on the inner face of CLT remained below 1 for scenarios where the initial MC of the CLT panel corresponded to that resulting from a maximum of 24 hours of continuous water contact. This was true for each simulated combination of humidity load and interior surface diffusion resistance (S_d 0.3–1 m) and with each material file. The mould index exceeded 1 in the case where the initial MC distribution was set at the level recorded after 48 hours of wetting. In this case, the mould index showed a tendency to increase for each ambient air and interior surface cover combination, except for the variant with low additional vapour resistance and low humidity load.

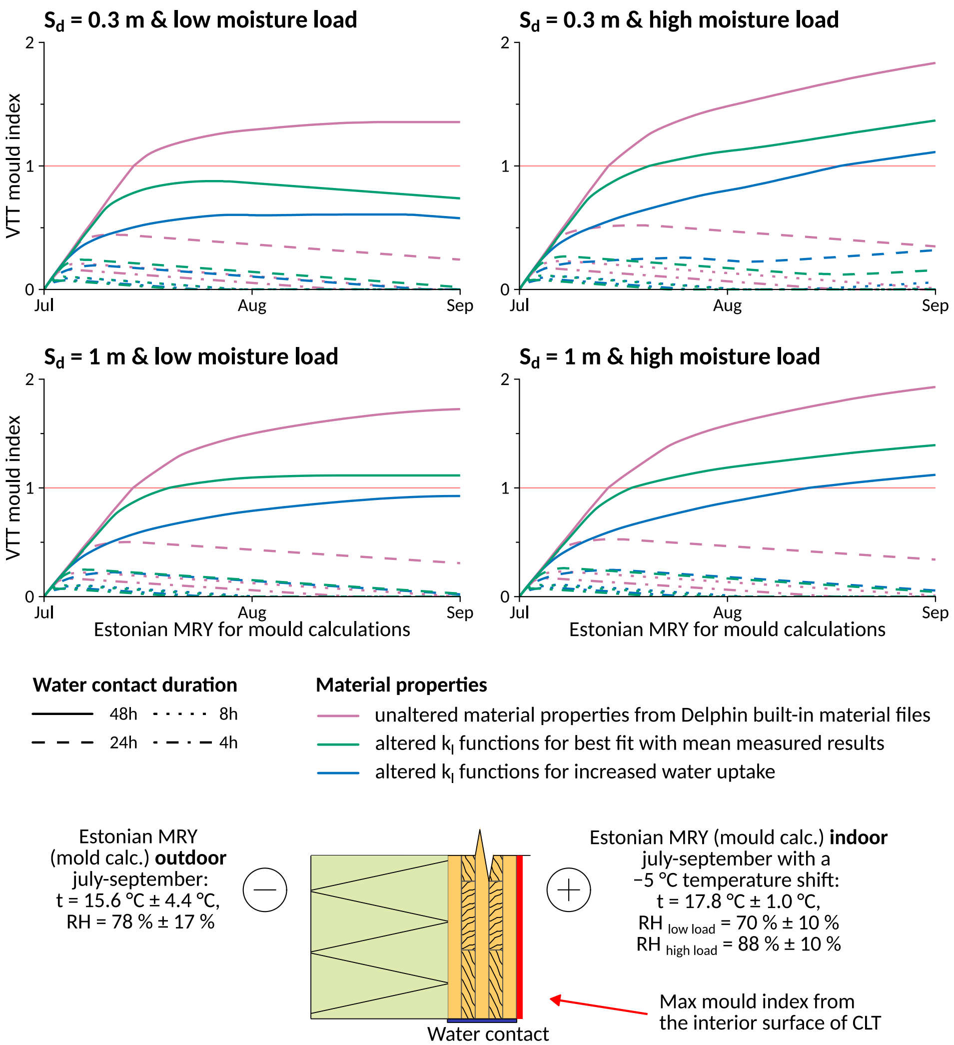


Figure 40. Results of mould index calculations for performance criterion development depending on initial MC distribution in CLT, additional water vapour resistance (S_d) of the interior surface and on indoor moisture load.

The most critical material file with regard to mould growth was the one compiled on the basis of the unaltered files from the Delphin database. This was probably due to the longer moisture dry-out time when using this material file, as was demonstrated in the validation of the model (Figure 39 in Section 4.4.3). The material definitions optimised for increased water uptake led to a faster moisture dry-out and thus resulted in a slower mould growth. Nonetheless, the increased dry-out rate did not lead to prevention of mould growth if the initial MC in the CLT was set based on what was achieved after 48 hours of water contact (see Figure 34 in Section 4.3.3). Thus, the MC distribution derived from the 24-hour wetting was set as the basis for defining the two-step MC performance criterion.

Wetting of 24 hours resulted in an MC of 13 % in the longitudinal layers and 10 % in the transverse layers at a height of approximately 30 mm above the water contact surface (see Figure 34 in section 4.3.3 for the initial MC distribution used in this analysis). There is supporting evidence in the literature suggesting that a 24-hour wetting period might be considered safe. Olsson et al. (2023) found that CLT surfaces exposed to one day of wetting followed by open drying did not exhibit mould growth. Similarly, Kukk, Kers, et al. (2022), in their study on the hygrothermal criteria for CLT surfaces, concluded that to prevent mould growth, the initial MC should not exceed 16 % for both interior and exterior surfaces. They further noted that if the interior surface is covered with vapour-permeable finishes, more lenient criteria may be acceptable.

However, the use of an initial MC below 13 % at the 30 mm height level (i.e. the MC value which corresponded to a day of wetting in the current analysis) may be overly conservative. The European standard for CLT (EN 16351:2021) specifies that, at the time of assembly, the MC of each timber board should be between 6 % and 15 %. It would therefore be illogical to impose a lower MC limit during the construction phase than that required during production. Given that the MC at 30 mm from the end-grain could be considered representative of the overall surface condition, adopting a threshold of 16 % at this height appears reasonable. Since the initial MC at this height was set lower in the simulations based on measured data, an additional analysis was conducted to evaluate whether increasing the initial MC to 16 % in regions previously assigned values between 10 % and 15 % would affect the outcome. The results showed minimal impact, with the maximum mould index remaining just below 1 even under the most critical environmental conditions. Consequently, adopting 16 % as the upper MC limit at 30 mm from the water contact surface in the outermost longitudinal ply was deemed safe.

For the area at approximately 10 mm from the water contact surface, the initial MC in the models where M did not exceed 1 was up to 28 % in the longitudinal layers and 12 % in the transverse layers (average of all measured test specimens). While the average MC of the bottom-most slice of the longitudinal layer was 28 %, it is probable that wood cell walls nearer to the water contact surface were saturated with water. Although the definition of wood fibre saturation point (FSP) is somewhat unclear (Thybring et al., 2022), in practical terms it is generally considered to be around 30 % (Glass & Zelinka, 2021). This level of MC implies a rather high risk in terms of biodegradation – the minimum MC conducive to the growth of wood decay fungi is also generally considered to be at the FSP, that is to say near 30 % (O. Schmidt, 2006). Brischke et al. (2017) have shown that loss of mass due to fungal decay in Norway spruce can also occur at a level below the FSP in a high RH environment. However, in environments where RH was up to 93 % and the calculated initial MC was approximately 25 % there was negligible mass loss and the wood MC also remained below the FSP (which they calculated to be 30.3 %) after a 16-week inoculation period. This provides the basis for setting the threshold MC in the bottom-most layer at 25 % for the two-step MC limit. For practical implementation, the MC limit should be verifiable using an electrical resistance-based MC measurement device. Consequently, the limit should fall within the measurement range to ensure sufficient accuracy. Generally, electrical resistance-based measurement devices are most accurate up to the FSP, although it also depends on the specific device. Some authors consider the usable upper limit of an electrical resistance based moisture meter to be 25 % (Olsson, 2021). It was thus deemed reasonable to set the performance criterion for the height of 10 mm from the end-grain surface at 25 % as opposed to the 28 % derived from the calculations. This difference could also be considered as a useful safety margin.

The target MC (performance criterion) for the CLT end-grain moisture safety analysis in this study wase initially established as 16 % MC at 30 mm and 25 % MC at 10 mm from the water contact surface in the CLT panel's longitudinal layers (with regard to the water uptake direction) when the panels were no longer exposed to precipitation and were about to be covered by additional structural layers. The target MC was intended to only apply for situations where at least the interior surface of the CLT panel was relatively open for moisture dry-out. Equation 3 expresses the performance criterion concisely.

$$OK = \begin{cases} MC_{10\,mm} \leq 25\,\% \\ MC_{30\,mm} \leq 16\,\%, \\ M < 1 \quad \text{throughout the analysed period} \end{cases} \qquad (3)$$

Further investigations and simulations under varying environmental conditions (detailed in Section 4.6) showed that MC often exceeded 16 % even without wetting incidents. That led to a decrease of the share of results considered successful (e.g. as seen for the cases where full-coverage weather protection (FWP) was implemented before the installation of CLT in Figure 42 and in Figure 43). This was due to hygroscopic moisture absorption from ambient air, particularly during prolonged exposure associated with extended installation and construction periods. It was also evident that the three different material file combinations behaved differently in this regard. The material properties optimised for the best fit with the mean of the measurement results predicted less moisture absorption and retention. When a filter was applied to include only those cases where the $MC_{10\,mm} \leq 25\,\%$ target was met, but the $MC_{30\,mm} \leq 16\,\%$ target was not, it became evident that the material file for the increased water uptake was overrepresented (43 % of such results), while the material file with the best fit to experimental data was least represented (26 % of such results) and the results with the unaltered material file comprised 31 % of such results. While it is possible that in a CLT panel there are areas which absorb water vapour very well, it is not the case for the entire panel due to the heterogeneous nature of wood and CLT being comprised of several timber boards. It is not known how the three options for the material properties are distributed in the timber stock in CLT production. In the current analysis, they were treated as equal. Furthermore, the MC target values were developed based on the critical MRY for mould growth calculations biasing the outcomes towards poorer performance. Of the outcomes categorised as unsuccessful due to exceeding the $MC_{30\,mm} \leq 16\,\%$ target in the analysis detailed in the next Section 4.6, only 9 % had the mould index exceed 1 and less than 0.2 % had $M > 2$. To mitigate the stringent nature of the performance criterion, it is possible to increase the $MC_{30\,mm}$ target, while maintaining the $MC_{10\,mm}$ target at 25 %. This proposal is further corroborated by the higher target (18 %) used by

Svensson Tengberg & Hagentoft (2021), but also by the European standard *Durability of wood and wood-based products* (EN 335:2013), which states that an MC of more than 20 % is usually necessary for the development of fungi.

For a more practical implementation, another solution would be to verify the $MC_{30\,mm}$ target compliance only if $MC_{10\,mm}$ exceeds a certain level, which would indicate either end-grain wetting or prolonged exposure to humid air, both of which may justify closer inspection. Previous research has shown that it is unlikely that mould growth on CLT would occur solely because of air humidity, contact with bulk water is typically required (Bolmsvik et al., 2023; Olsson, 2021; Svensson Tengberg & Bolmsvik, 2021). Moreover, recent research has also indicated that for spruce and pine, a 75 % or even more than 80 % RH might be too low for mould growth (Ryparová et al., 2022). It is thus proposed that for validating the target MC at the higher measurement point a risk detection at the lower measurement point should precede. For example if MC ≥ 19 % (as a middle ground of the 18 % used by Svensson Tengberg & Hagentoft (2021) and the 20 % limit of EN 335:2013) is detected at the 10 mm measurement point, then MC at 30 mm should also be validated. For the moisture retention curves used in the material files, the 19 % MC corresponds to approximately 86 % to 87 % RH. Ryparová et al. (2022) tested the initiation of mould growth on inoculated pine and spruce specimens at an RH of 75 %, 87 % and 95 % at a constant temperature of 22 °C. Mould growth was observed only at 87 % and 95 % RH, with microscopic signs appearing after a minimum of 7 days (19 days in transverse spruce) under these highly favourable conditions. Furthermore, the results from Experiment 3 showed (as detailed in Figure 33 in Section 4.3.3) that in the longitudinal layers of CLT, 19 % MC could be exceeded after four hours of wetting from the end-grain and after eight hours MC is over 19 % for half of the measurements taken in the height range of 7–14 mm from water contact. After 24 hours of water contact the measurement values at the same height range reached already over 30 % MC. This implies that MC < 19 % is only attainable with short wetting periods, during which the calculated M remained low in the mould calculations for the performance criterion development (Figure 40). Based on this, 19 % MC is deemed as a safe limit for the supplementary clause in the performance criterion. The performance criterion with the supplementary clause is expressed as follows in Equation 4. It is proposed as suitable for assessing moisture safety near CLT end-grain surfaces, where liquid water absorption can quickly exceed commonly used MC limits, yet short-term wetting may not pose an immediate risk. This MC criterion is intended to apply only when at least the interior surface of the CLT panel allows for moisture dry-out and should not be used when the wet areas are covered with layers which restrict moisture dry-out.

$$OK = \begin{cases} MC_{10\,mm} \leq 25\,\% \\ MC_{30\,mm} \leq 16\,\%, \text{when } MC_{10\,mm} \geq 19\,\% \\ M < 1 \quad \text{throughout the analysed period} \end{cases} \tag{4}$$

4.6 Analysis of moisture safety strategies considering end-grain wetting

The influence of various moisture safety strategies and environmental factors was studied through long-term simulations. The outcomes were evaluated using the two performance criteria described in the previous section and defined in Equations 3 and 4. First, the development of the mould index was analysed throughout the entire simulation period spanning the CLT installation duration and the post-installation period. Approximately 14 % of the studied combinations (n = 77, 760) yielded a mould index larger than 1 (M > 1) on the CLT surface. In the cases where the mould index exceeded 1 at both the 10 mm and 30 mm height levels, common features included the absence of end-grain protection (76 % of such cases) and the absence of face protection (65 %). The longest installation duration (16 weeks) was also well represented, accounting for 69 % of the cases with M > 1, while the share of such cases with a 16-week post-installation period was 52 %. Overall, the longer the total duration, the higher the risk of mould growth, regardless of other factors (Figure 41). This topic is discussed in greater detail in Publication III.

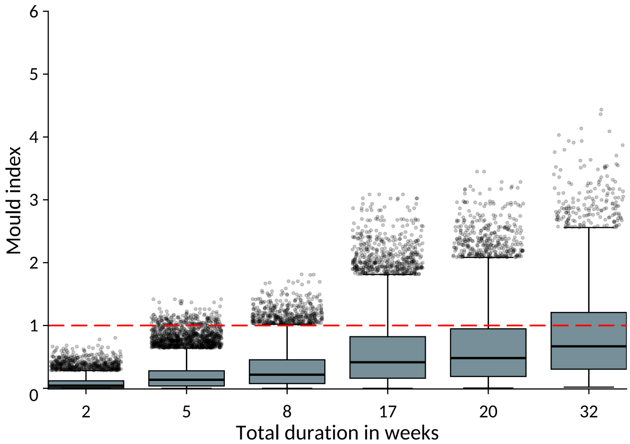


Figure 41. Maximum mould index for all simulated durations, including all moisture safety factor combinations.

The median value of M remained below 1 for all durations, but for the combinations with a total duration (installation duration + post-installation period) of 32 weeks, the third quartile of the mean M value of each observation was over 1. There were outlier instances with M > 1 in all the combinations except for the variant with a total duration of 2 weeks. In some outlying cases (2 % of all instances) the maximum mould index exceeded 2. This occurred when the total duration was 17 weeks or longer.

None of the cases where M exceeded 2 had FWP implemented before CLT installation, and only 4 % of those cases featured end-grain protection. M exceeded 2 in 25 % of the cases where CLT face protection was used (none of these had end-grain protection).

The results of the mould index calculations indicated that implementing FWP prior to installing CLT elements, for instance in the form of a tent-like structure, largely reduced the likelihood of mould formation, resulting in a 99 % probability of prevention of mould growth during the CLT installation stage and the subsequent construction period preceding the covering of the CLT panels with additional layers. This option was closely followed by CLT installation during winter (98 %) and performing a quick, 1-week installation (95 %). These three options were thus the safest ones as regarded mould growth during the CLT construction period when the CLT panels were not yet covered with additional layers. The factor producing the lowest probability of preventing mould growth was the 16-week installation period. An in-situ research by Bolmsvik et al. (2023) done at construction sites in Sweden (with monitoring periods of 2–5 months) showed that 75 % of the CLT specimens exposed to external weather conditions experienced mould growth, but none of the specimens under a weather protection structure did, which demonstrates the validity of the outcomes of the current study. The researchers also applied mould prediction models (MRD and MOGLI) based on the measured temperature and RH, but mould growth was predicted in only one case. This could have been due to they using air RH as an input, instead of RH on the surface of the specimens, which was used for input in the current work. Previous research has indicated that using wood surface RH as input is more accurate for mould growth analysis (Lie et al., 2019).

Mould growth is a complex process influenced by a number of factors including the type of substrate (which in this case was planed timber), humidity, temperature, and exposure time. It is possible that despite a high level of humidity (i.e., high timber MC), mould growth does not start due to a low temperature (as would be the case when building during winter) or because the period with suitable conditions is too short. However, conditions may change due to the covering of the CLT panels with additional material layers or due to an increase in ambient temperature from heating. Therefore, monitoring (and calculating) mould growth up to the point where the CLT is covered is only one aspect of moisture safety assurance. Ensuring that the MC of the CLT is within safe limits before covering the panel is as important as ensuring no mould growth. Here, the two-step MC performance criteria (as defined in Section 4.5) became relevant.

To consider an outcome successful in terms of both limiting mould growth and meeting the MC target, the MC as recorded at the final hour of the simulation must have fallen within the specified limits (Equations 3 and 4) and the mould index must have remained below 1 throughout the simulated period encompassing both the CLT installation stage and the time until additional material layers are added to the CLT.

The probabilities of a successful end-result (i.e., when both M and MC targets are met) for all the studied variables are presented in Figure 42. These values should be interpreted as the probability of success for the specified option, assuming all other variables are unknown.

With the initial performance criterion (Equation 3), the highest probability of success was achieved with installation starting in spring (58 %), followed by FWP (57 %) and CLT end-grain protection (52 %). If the only known factor was the duration of installation or post-installation period, the probability of success was between 38 % and 49 % for the duration of 1 to 4 weeks but dropped to 26 % for the 16-week installation period.

Evidently, if other parameters were unknown, the start during a favourable season could be considered as effective as FWP. Of course, other variables can influence the outcome markedly, but the results indicated that choosing the installation season could be a valid moisture safety measure. On the other hand, the results also showed that if, for example, there was a delay in the procurement process, moisture safety could be compromised due to the change of construction start season, as start in autumn was the least favourable option with a success rate of only 22 %. The options of having no FWP (success rate 23 %) and no CLT end-grain surface protection (24 %) were also undesirable. Svensson Tengberg & Hagentoft (2021) have previously also concluded that the season of construction has a significant effect on the moisture safety of CLT buildings. However, for their chosen location (southern and south-central Sweden) and performance targets, the favourable seasons were summer and early autumn, while winter was less favourable. The targets used by Svensson Tengberg & Hagentoft (2021) were similar to those in the current study: 1) MC < 18 % in the outer layer (0–20 mm) at the time of covering the surface, and 2) M < 1 on the surface of CLT. Yet, there were differences in the used material properties and in the way the employed simulation programs work. Tengberg and Hagentoft implemented the one-dimensional simulation program WUFI Pro and stated that they used the generic “Spruce radial” material from the WUFI database without considering material anisotropy or variations. The current study explicitly focused on the end-grain wetting of CLT, considered material anisotropy and variations, and used combinations of a larger number of variables in the analysis. Due to water absorption in the longitudinal wood grain direction and reduced moisture dry-out from the middle layers of CLT, the criticality of end-grain moisture safety may differ from that of the CLT surface layers explaining the differences of the results compared to those of Svensson Tengberg & Hagentoft (2021).

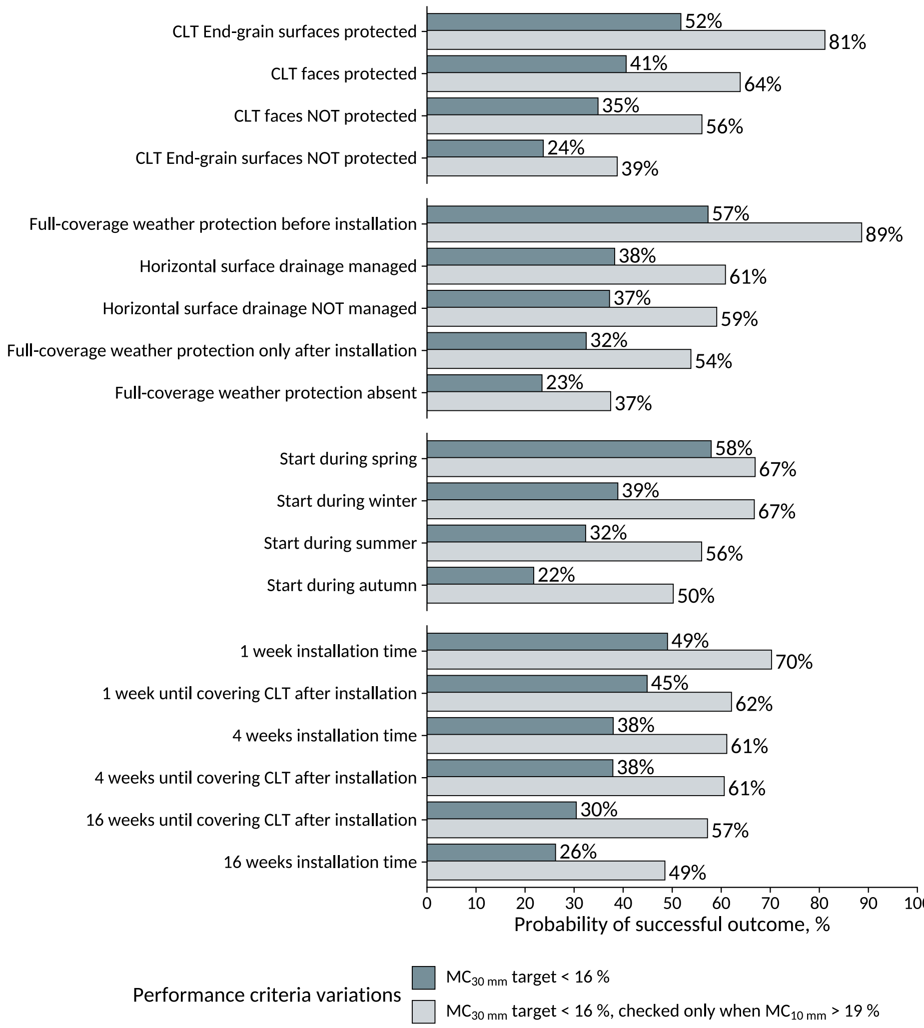


Figure 42. Probability of a successful outcome – defined as maximum mould index < 1 and $MC_{10\,mm}$ and $M_{C30\,mm}$ within specified limits (see Equations 3 and 4) – for all the studied variables.

Since the probabilities discussed above yielded only generalised information, as they were calculated considering all co-variations, the next step was to analyse combinations of certain selected subsets. Different protection strategies can be combined, and the results vary depending on the CLT installation duration, total construction duration and start season. Figure 43 shows the results for combinations of different FWP options and localised protection methods, divided into blocks according to the CLT installation duration. The start season, time duration after installation, and horizontal surface drainage implementation level were included as sub-variables.

With the original MC targets (Equation 3), the probability of a successful outcome was reduced to below 50 % even for the cases where FWP was implemented before the installation of CLT panels, if the installation duration was 16 weeks (Figure 43, bottom left). However, when the supplementary clause was used for the $MC_{30\ mm}$ 16 % target (i.e., updated performance criteria, Equation 4), the probability for success remained over 90 % and fell to 81 % only for the longest 16-week installation duration, if FWP was implemented before CLT installation. With the supplementary clause, the results were more convincing, as FWP should only fail in rare, extreme cases of very high ambient RH. If FWP was erected only after the CLT installation (Figure 43, centre column), the probability for success decreased greatly if the end-grain surface was not protected. This was true with both performance criteria variants. The reduction of the probability of success was especially evident when the installation duration was 4 weeks or more. In that case, the probability of success was less than 10 % without local protection (considering the original performance criterion, Equation 3). Adding side face protection in conjunction with end-grain protection contributed marginally to the success rate for shorter installation durations but became clearly advantageous for longer installation durations. Side face protection without end-grain protection had a negligible positive effect with regard to CLT end-grain moisture safety.

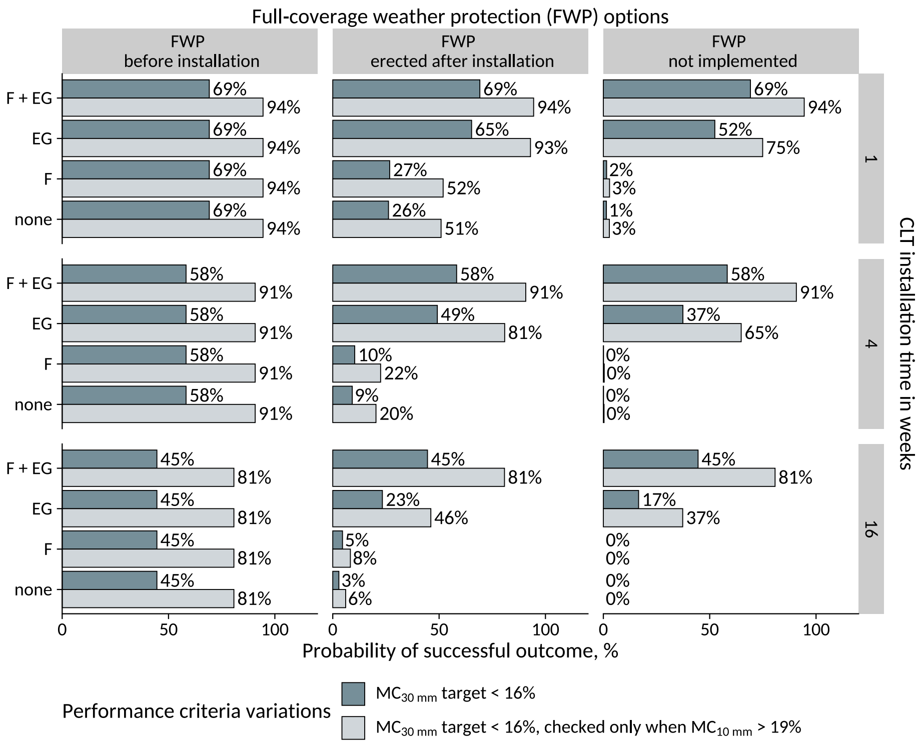


Figure 43. Probability of a successful end result (maximum M < 1 and $MC_{10\,mm}$ ≤ 25 %, $MC_{30\,mm}$ ≤ varies as per legend in the figure) for different FWP and local protection measures and CLT installation period durations. F = CLT vertical face protection, EG = CLT end-grain surface protection and F + EG = both CLT face and end-grain surface protection.

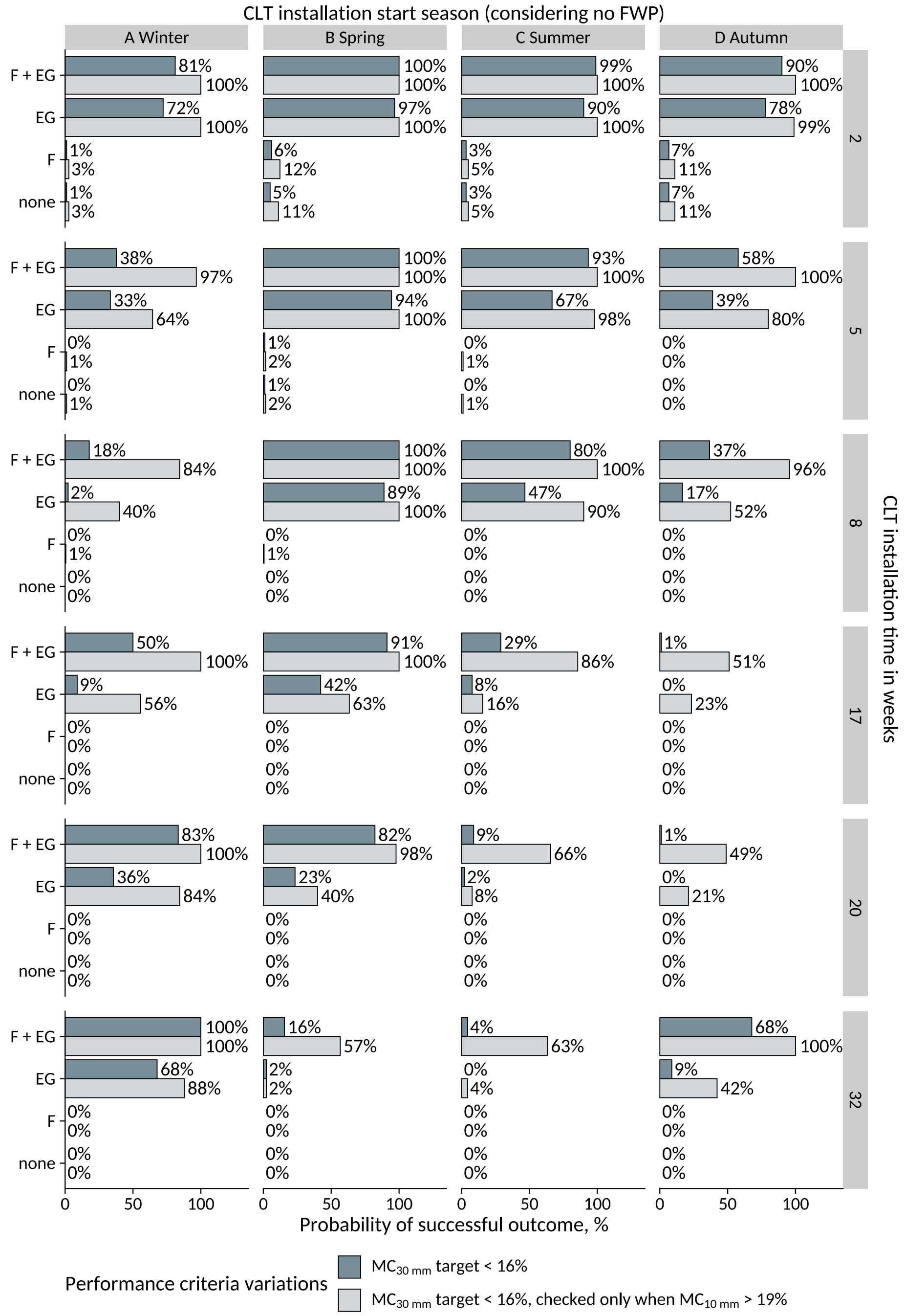


Figure 44. Probability of a successful end-result (maximum M < 1 and MC_{10mm} ≤ 25 %, MC_{30mm} ≤ varies as per legend in the figure) for the subset of combinations with no FWP. F = CLT vertical face protection, EG = CLT end-grain surface protection and F + EG = both CLT face and end-grain surface protection.

If FWP was not used (Figure 43, right column), it was almost certain that the MC targets were exceeded for the cases without end-grain protection, even when the installation duration was kept short. One of the hypotheses for this analysis was that a short installation duration might be enough to avoid end-grain wetting, but the calculations with the 30-year climate data showed that even for an installation duration as short as one week, it was highly likely that there was enough precipitation to cause excessive wetting. This was true regardless of the installation season (Figure 44) – the probability of success was negligible if neither FWP nor local protection measures were used (irrespective of the performance criterion selection). Nevertheless, starting in spring yielded slightly better results. It can also be seen from Figure 44 that when the original performance criterion for $MC_{30\ mm}$ (Equation 3) was used, the probability of success diminished rapidly with the increase in construction time when CLT installation started in summer, because the humid autumn season followed.

4.7 Anticipated moisture dry-out times for the analysed scenarios considering different MC targets

A comparison of the effects of different levels of FWP implementation revealed that allocating time for moisture dry-out even without heating, i.e., in outdoor climate conditions (but without precipitation) was beneficial. To analyse the anticipated moisture dry-out times, the development of MC was examined for cases without any local moisture protection and no FWP during installation, but with FWP after installation. In these scenarios, the CLT panels became wet and then had the opportunity to dry out under an FWP cover. The simulated moisture dry-out times for these cases are presented in Table 8. The mean moisture dry-out time was calculated by averaging the dry-out times achieved with the three different material files used in the simulations. The table also includes the minimum and maximum dry-out times (shown in parentheses) for each scenario, stemming from the material file variations.

For the area closer to the end-grain surface (10 mm), the limiting MC value was set to 25 %. If the CLT installation lasted for 1 week, the anticipated moisture dry-out time considering $MC_{10\ mm}$ target resulted in up to one week if the dry-out start season was spring or summer, up to two weeks if dry-out started in autumn and up to five weeks for a start during winter. If the CLT installation duration was four weeks, the same general pattern applied, but the dry-out times were longer: in spring the moisture still dried out in approximately one week, but in summer it could take up to two weeks, and when the dry-out started in autumn or winter, it took one to seven weeks to achieve the $MC_{10\ mm} \leq 25\ \%$ target with the average being 5–6 weeks for the colder seasons (Table 8). In the case of the longest installation time of 16 weeks and thus very high initial MC, the average dry-out time was at least two months for autumn and winter. This was in agreement with the on-site observations and measurements (4.1) which revealed that in buildings where the total time of exposure to precipitation was between 15 and 21 weeks and the start season for moisture dry-out was autumn, the dry-out times were up to four months and in several cases using additional heating or drying equipment was necessary.

Table 8. Mean moisture dry-out times in weeks until the specified target MC (MCi) at i mm from the water contact surface was achieved. The values in parentheses are the shortest and longest dry-out times for the different material files.

Drying start season	**Installation duration in weeks**	**Time in weeks until target MC_i at the height *i* is achieved**			
		$MC_{10\ mm}$ ≤ 25 %	**$MC_{30\ mm}$ ≤ 20 %**	**$MC_{30\ mm}$ ≤ 18 %**	**$MC_{30\ mm}$ ≤ 16 %**
Winter	1	**3** *(1–5)*	**7** *(5–8)*	**10**	**13** *(12–15)*
	4	**6** *(2–7)*	**8** *(7–8)*	**9** *(8–10)*	**12** *(11–13)*
	16	**8** *(4–9)*	**10** *(8–10)*	**12** *(10–12)*	**13**
Spring	1	**0,3** *(0,1–1)*	**0,6** *(0,1–0,2)*	**0,7** *(0,2–0,4)*	**1**
	4	**0,5** *(0,2–1)*	**0,9** *(0,1–0,3)*	**1** *(0,1–1)*	**3** *(1–4)*
	16	**1** *(0,3–2)*	**2** *(1–2)*	**3**	**4** *(3–6)*
Summer	1	**0,7** *(0,2–1)*	**1** *(0,1–1)*	**2** *(0,3–1)*	
	4	**1** *(0,2–2)*	**2** *(1–2)*	**> 16**	**> 16**
	16	**2** *(0,3–2)*	**3** *(2–3)*		
Autumn	1	**1** (0,3–2)	**2** (1–2)		
	4	**5** (1–7)	**15** (14–16)	**> 16**	**> 16**
	16	**10** (4–13)	**> 16**		

At 30 mm from the water contact surface, the MC was expected return to below 16 %, but for most cases, this seemed unobtainable, except for when the moisture started to dry out in spring (Table 8). In Estonia, the mean relative humidity of the outdoor air is at its lowest (68 %) for week 20 in spring, based on 30 years of climate data. However, it gradually increases throughout the summer and autumn, reaching 90 % on average by week 47. Thus, obtaining MC values below 16 % at 30 mm from the water contact surface is not particularly likely, except in spring. For further consideration, the dry-out times for achieving the $MC_{30\ mm}$ target were given for three values: 16 %, 18 % and 20 % respectively.

If the target MC at 30 mm height was set at 20 %, unassisted moisture dry-out (i.e., achieving 20 % or less) became possible for the summer season as well. The average MC decreased to below 20 % in about one week and stabilised above 16 % if the CLT structure was exposed to the elements only for one week and the dry-out started in the summer season. If the structure was left exposed for four weeks and the dry-out started during the summer season, it took two weeks for the $MC_{30\ mm}$ level to drop below 20 % followed by stabilisation at around 18 %. However, for the 16-week installation period, the MC stabilised at around 20 % after approximately three weeks of unassisted drying in the summer season. If the dry-out start season was winter, the MC remained higher than 20 % for at least two months, regardless of the initial MC. If the dry-out period started in autumn, the 20 % target was attainable only if the installation duration was one week, while with longer installation periods that entailed a higher initial MC, the MC remained well above 20 % for more than two months.

Researchers have observed fungal growth in CLT structures under construction when the MC of the wood surface reaches or exceeds 19 % (Olsson, 2021) and thus the 20 % target is not advisable. The observed cases where the MC remained elevated for long periods were likely the same ones in which the mould index exceeded 1 or even 2 in the previous analysis (Figure 41). It is evident that unassisted moisture dry-out is not a feasible moisture safety practice except if the dry-out starts in spring (i.e., during a period when the relative humidity of the outdoor air is at its lowest) or if it starts in summer after a period of precipitation exposure shorter than a month (in that case, $MC_{30\,mm}$ ≤ 18 % is attainable; see Table 8). During winter and autumn, the moisture dry-out potential is insufficient for the excess moisture to leave in a timely manner without assisted drying.

During the seasons with a lower moisture dry-out potential, there was a larger variation of dry-out times between cases with different material definitions. The materials which were optimised for increased water uptake exhibited shorter moisture dry-out times. It is possible that some areas of a CLT panel dry out quicker than others, but the opposite is also possible. It is not feasible to perform moisture measurements with a very high spatial resolution, and therefore it is possible that areas requiring a longer dry-out during the construction period remain unidentified. It is hence sensible to base the moisture safety plan on at least the mean values given in Table 8, or even on the maximum moisture dry-out times (shown in parentheses in Table 8) for a more conservative approach. If the moisture dry-out time exceeds what is feasible within the construction schedule, assisted moisture dry-out is recommended.

Table 9 provides a summary of the results for the most typical combinations used in practice. The post-installation FWP can be achieved through different methods capable of eliminating exposure to rainwater in an effective manner comparable to the use of an FWP structure.

Table 9. Results for common moisture safety scenarios using both $MC_{30\,mm}$ target criteria. Results given for both the original performance criteria (Equation 3) and the updated criteria with the supplementary clause (Equation 4). HSD = horizontal surface water drainage implementation.

FWP, face protect., start season, HSD	**Time after inst. (weeks)**	**Inst. duration**	**End-grain protect.**	**Probability of success (%)**	
				M < 1 and $MC_{10\,mm}$ ≤ 25 %, **$MC_{30\,mm}$ ≤ 16 %**	M < 1 and $MC_{10\,mm}$ ≤ 25 %, **$MC_{30\,mm}$ ≤ 16 % but checked only if $MC_{10\,mm}$ ≥ 19 %**
FWP after installation, side surfaces protected, start season varies, active moisture management by horizontal surface drainage considered	1	1	yes	**93**	**100**
			no	**20**	**29**
		4	yes	**72**	**99**
			no	**3**	**6**
		16	yes	**43**	**84**
			no	**0**	**0**
	4	1	yes	**72**	**99**
			no	**27**	**51**
		4	yes	**59**	**95**
			no	**6**	**14**
		16	yes	**44**	**78**
			no	**0**	**0**

A post-installation period of one week prior to covering the CLT with additional material layers is deemed reasonable, but four weeks may also be acceptable if the construction schedule allows it. Since the CLT side surfaces are typically covered with protection foil, only the combinations with face protection were accounted for. The options related to the installation season and implementation of horizontal surface drainage were allowed to vary. According to the presented results, if end-grain protection was used in combination with a short installation period followed by a one-week moisture dry-out period, the likelihood of success stood at 93 % if the original target for $MC_{30\ mm}$ (Equation 3) was used. This would be a similar strategy which Time et al. (2023) investigated. In their study, the strategy included installation during the driest period, the end-grain surfaces were protected and moisture dry-out was allowed before covering the structures. However, as the research in this thesis showed, in the absence of end-grain protection, with the other variables left unchanged, the probability of success dropped to 20 %. For the installation durations of four weeks and sixteen weeks, the probability of success was negligible without end-grain protection, but increased to 72 % and 43 %, respectively, with the inclusion of end-grain protection. If the post-installation period was extended from one week to four weeks (while FWP was implemented) the probability of success for the variants without end-grain protection increased very slightly due to the improved moisture dry-out, but if the start season was unknown (i.e., the cases were distributed equally among all seasons), the success rate remained low for all cases with no end-grain protection. If the updated $MC_{30\ mm}$ target was used (Equation 4), the number of cases yielding a successful outcome increased, but the likelihood of success in the absence of end-grain protection and with variables such as the start season left undefined still remained modest, even when the shortest installation duration was used.

4.8 Interannual variability and correlation with climatic factors

Additionally, the interannual variability of success ratios and their correlation with climatic factors were analysed. There was quite a large variability in the share of successful results between different simulated years (Figure 45, top left). The mean value was 38 % while the standard deviation was 5 percent points. Some outlying cases differed from the mean value more than 10 percentage points. Over time, there was a trend towards a smaller share of successful results, but the correlation was weak. The correlation was also assessed using yearly mean temperature, mean relative humidity, and rainfall amounts. A modest correlation was identified with the yearly rain amount and a stronger association was revealed with the mean outdoor air relative humidity.

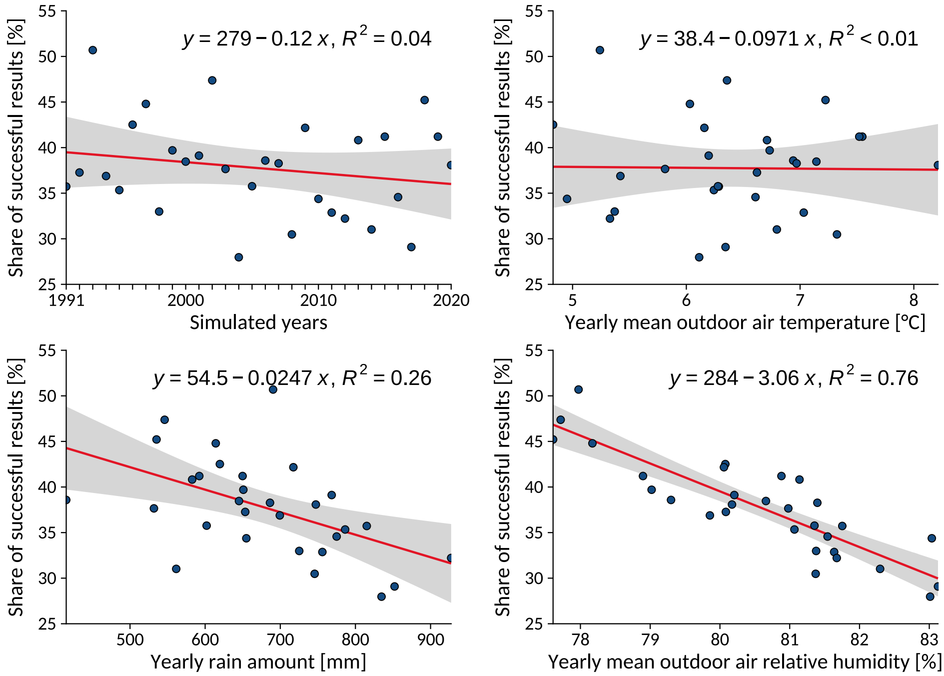


Figure 45. Interannual variability of the share of successful results. Correlation of the share of successful results (y-axis) with simulated years (top left), with yearly mean outdoor air temperature (top right), with yearly rain amount (bottom left), and with yearly mean outdoor air relative humidity (bottom right).

4.9 Efficacy of the optimised moisture safety strategies in practice

The efficacy of moisture safety strategies in practice was assessed through a field study of the buildings G and H. The method used to identify moisture issues and evaluate the effectiveness of protective measures followed the same approach described in Sections 3.1 and 3.2. By the time these buildings were under construction, prior experience allowed for a more targeted and efficient investigation, as key risk areas and early indicators of moisture issues had already been identified during previous investigations.

4.9.1 Analysis of customer specifications and requirements

For the building G, the institutional client (Riigi Kinnisvara AS, the state real estate development and management company), an expert in property development and management, mandated the use of previously established technical requirements for non-residential buildings, which included moisture safety requirements (Riigi Kinnisvara AS, 2021). The client required the preparation of a moisture safety plan and the appointment of a moisture expert. Additionally, the client of the building G mandated that timber MC must remain below 18 %, and that CLT must be installed under an FWP structure (a tent roof with side walls). However, the parties involved in the project agreed to change this during the construction and the FWP structure was only erected after the installation of the CLT.

The institutional customer of the building H is a local municipality (the capital city Tallinn), which has considerable expertise in procuring building design and construction. However, no specific moisture requirements were set; only laws, regulations, and general instructions such as the previously mentioned technical requirements for non-residential buildings by the state real estate development company were referred to in the procurement. Detailed requirements for moisture safety, such as the maximum allowable timber MC, control methods, measurement frequency, worker training, and documentation, were not mandated in the procurement of the building H. The development of a construction period moisture safety method was to be decided and adopted by the CLT producer and general contractor.

4.9.2 Analysis of the design documentation

The project documentation of the building G advised to install CLT under an FWP structure, or treat the bottom end-grain surfaces with a moisture-proof sealer, wrap panels in thermal film (Figure 46), and apply water resistant self-adhesive protective membranes to floor panels. Drawings for additional weather protection solutions were not provided, as the use of an FWP structure was specified. Moisture safety was partly covered in the architectural section of the project documentation, but the topic remained brief and general in the structural design section, which concentrated only on the load-bearing capacity of the building and overlooked moisture loads during construction.

MC limit values were provided inconsistently in the architectural design documentation, with some sections requiring < 18 % and others < 16 %. Additionally, a guideline was provided for the relative humidity limit (to prevent mould growth): < 80 % (at air temperatures above +5°C), unless specified otherwise by the product manufacturer. The structural part of the project documentation set another conflicting limit for timber moisture content: < 15 % but did not give a guideline for air RH limit. Overall, the moisture safety section in the project documentation for the building G was limited, though still more detailed than typical for Estonia.

The architectural section of the project documentation of the building H also covered the moisture safety topic in a general manner and did not specify any limiting MC or RH values. The structural section of the design documentation of the building H specified that the CLT panels should be covered with a weather-resistant packaging foil from the factory which should be kept on the panels during the installation process and until the building was made weatherproof. According to the structural design drawings for the building H, liquid waterproofing was required for the bottom end-grain surface of the first-floor CLT panels, but not for the second-floor panels. Additionally, the limiting value of the MC for the CLT panels was given as 15 %.

Figure 46. Installation of the first CLT panels (delivered wrapped in white plastic film) at Building G.

4.9.3 Realisation of the predicted outcomes of moisture safety strategies

Moisture was managed in both buildings with varying degrees in thoroughness and moisture protection methods. For the builder of the building G, it was the third large CLT construction they erected, but for the builder and customer of the building H, it was only the first. In the building G, the CLT installation took approximately five weeks per section (the building was divided into three sections, each of which was sequentially covered with an FWP structure). Ideally, the assembly of the FWP structure should be done in parallel with the installation of the CLT panels so that when the installation of a section is finished, so that it would become protected from precipitation immediately. But in this case, there was an approximately two-to-three-week period after the installation when the CLT panels were still exposed to precipitation and were then covered with the weather protection structure (Figure 47).

Figure 47. A temporary FWP structure at different stages on the building G.

In Figure 48 the planned and incidental moisture safety strategies of the case study buildings are superimposed on the moisture safety strategy analysis framework used in the previous analysis, as described in Section 3.6, with corresponding results detailed in Section 4.6. Each building's path on the chart reflects the combined influence of the building design, customer specifications, design documentation, and decisions made during construction. The probability of a successful outcome for each specific path is provided at the end of the path. This probability was calculated based on 30 years of climate data and three material files, resulting in 90 calculations for each path, i.e., each strategy.

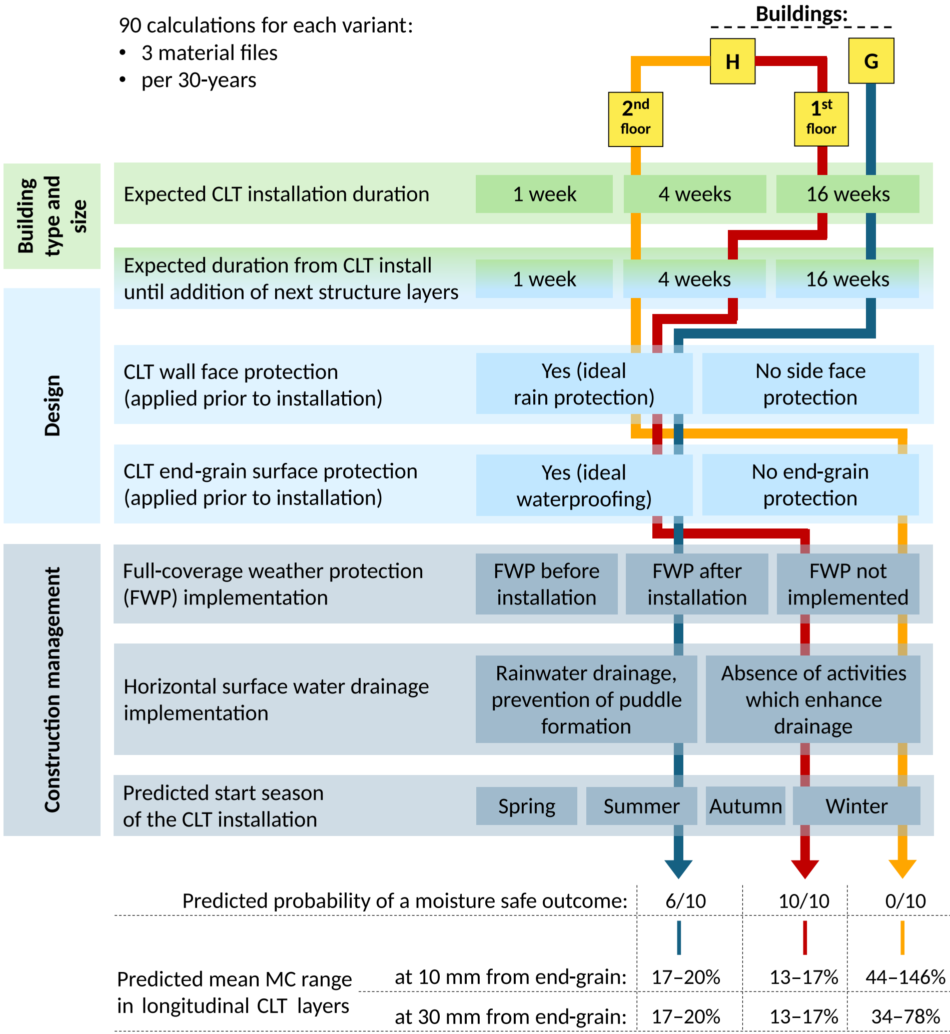


Figure 48. CLT moisture safety process variables with superimposed lines representing the moisture safety strategies of the studied buildings. The building H is divided into floor 1 and floor 2 due to differing end-grain surface protection of the CLT panels on each floor. The durations which the strategy paths pass are close to the actual construction timelines (though not identical).

Within the moisture safety analysis framework, installation time for the building G was regarded as the entire period from the CLT installation start to the moment when each section of the building was fully covered with the FWP structure. The closest match for installation duration in the moisture safety analysis framework was thus 16 weeks for the building G, which best approximates the actual ca eight-week exposure time, adding a safety margin over the four-week choice. Following the installation period, the CLT panels were under the FWP structure, exposed to ambient air for eight to ten weeks, facilitating moisture dry-out until additional structure layers were added. Therefore, the sixteen-week option was also suitable for this step in the moisture safety analysis framework. A similar timeline applied to all the sections of the building G.

The CLT installation in the building H took approximately eight or four weeks, depending on whether the start was counted from the installation start of the first or second floor's panels. Since different end-grain protection methods were used on the first and second floor, the outcomes for both were analysed separately. The installation duration was set at sixteen weeks for the first-floor panels and four weeks for the second-floor panels in the moisture safety analysis framework. After the installation, the CLT on both floors of the building H remained exposed for approximately a month until it was covered with insulation.

Protecting the side faces of the CLT wall panels with packaging foil is well established in Estonia and was used in both buildings G and H. However, for the end-grain surface different methods were implemented: in the building G, a liquid-applied-water-blocking coating was applied to all CLT wall panels, whereas in the building H an adhesive membrane was applied to the first-floor panels only, leaving those on the second floor unprotected. In the building G, a more thorough process was implemented for horizontal surface water drainage, as the client mandated the preparation of a moisture safety plan. The installation start season was summer for the CLT panels in the building G and winter for the building H.

Each path led to an outcome which was calculated on the basis of the results of the hygrothermal simulation models. For the building G, the predicted probability of a moisture safe outcome was 6/10, despite the consideration of ideal side face and end-grain surface protection measures and implementing an FWP structure after the installation of the CLT panels. The main culprit for a somewhat less desirable prediction was the long period after the installation when the CLT panels were still exposed to outside air during autumn. Consequently, the predicted average MC at 10 mm and 30 mm from the end-grain surface was between 17 and 20 %. While the criterion in Equation 4 was met 6 times out of 10 (when considering the 30-year climate data for Tallinn, Estonia and three anisotropic spruce material files), there were, on average, 4 out of 10 instances where MC may have exceeded the set target ($MC_{30\ mm} \leq 16$ %, when $MC_{10\ mm} \geq 19$ %) due to hygroscopic moisture absorption from extended exposure to ambient air and thus a moisture safe outcome was not guaranteed.

For the case of the first floor in the building H, the predicted probability of a moisture-safe outcome was 10/10. In this case there were two main contributors to a better outlook compared to the building G: a shorter post-installation period and installation start during winter. However, for the second floor of the building H, a moisture-safe outcome was not anticipated, as the predicted MC in the bottom part of the wall panels reached 34 % to 146 %. This was due to the lack of end-grain surface protection, leading the surface to be exposed to water contact repeatedly. Previous laboratory tests showed that 48 hours of continuous water contact could increase the MC in the bottom 7 mm of a CLT wall panel over 130 % (Figure 34 in Section 4.3.3). This suggests that the predicted MC values could be realistic, given the 8-week period which the CLT panel for the second floor of the building H was exposed to precipitation.

The chosen strategy for the building G should have provided protection against wetting for both the CLT side faces and the bottom end-grain surfaces. A less-than-ideal outcome for moisture safety was predicted only due to the long period after the installation of the CLT when the panels were still exposed to outside air during autumn, but on average the expected MC in the wall panel bottom area should have ranged between 17 % and 20 %. On-site measurements about a month after the installation started indicated MC values exceeding 21 % and even over 30 % (Figure 49, P1).

Figure 49. Moisture measurements (P1), waterproofing membrane damage (P2), and timber swelling (P3) in the building G.

While the specific cause of higher-than-expected MC could not be identified, visual inspection revealed potential damage to the Riwega ELLE-Plan (S_d < 5 m) liquid-applied end-grain waterproofing membrane (Figure 49, P2). While many wet areas appeared visually undamaged, potential damage to the membrane on the surface under the panels could not be confirmed due to inaccessible panel undersides. Swelling and warping of timber in the CLT panels correlated with wet areas (Figure 49, P3). Nevertheless, the waterproofing membrane provided adequate moisture protection in most areas.

The points where the liquid-applied waterproofing membrane was damaged functioned similarly to end-grain zones without protection. Weather data from a nearby weather station indicated that during the period up to the assembly of the FWP structure, the building G received approximately 70 mm of rain (presented previously in Figure 14, in Section 4.1.1). This was mostly diverted, but as the measurements indicated – some areas still got wet. Figure 50 shows the measured MC (point) values and simulated MC values (continuous lines) based on the actual climate data from both building's construction period and based on the main moisture protection strategy. In the case of the building G, the calculations were also made for the hypothetical variant which excluded the end-grain surface protections, although the main strategy assumed ideal end-grain protection. The measured values are also divided into two based on whether their first MC value was over 19 % or not. The measured MC values which exceeded 19 % were deemed to be taken from the areas where a probable end-grain protection damage was present. Most measured values remained below the values simulated with an ideal end-grain protection. Both the simulated and measured results for the variant with a functioning end-grain protection reflected the tendency for MC increase over time which affirmed the risk indicated by the moisture safety analysis framework (Figure 48).

Fortunately, the long period under the FWP structure without additional wall assembly layers also provided time for moisture dry-out. The measured values from the areas with presumed end-grain protection damage correlated well with the simulation where no end-grain protection was assumed. Both of these indicated a moisture dry-out over time. A long period after the CLT installation when the panels were exposed to outside air had a dual effect: it caused an increase in MC in the panels yet also allowed excess moisture dry-out from previous wetting incidents.

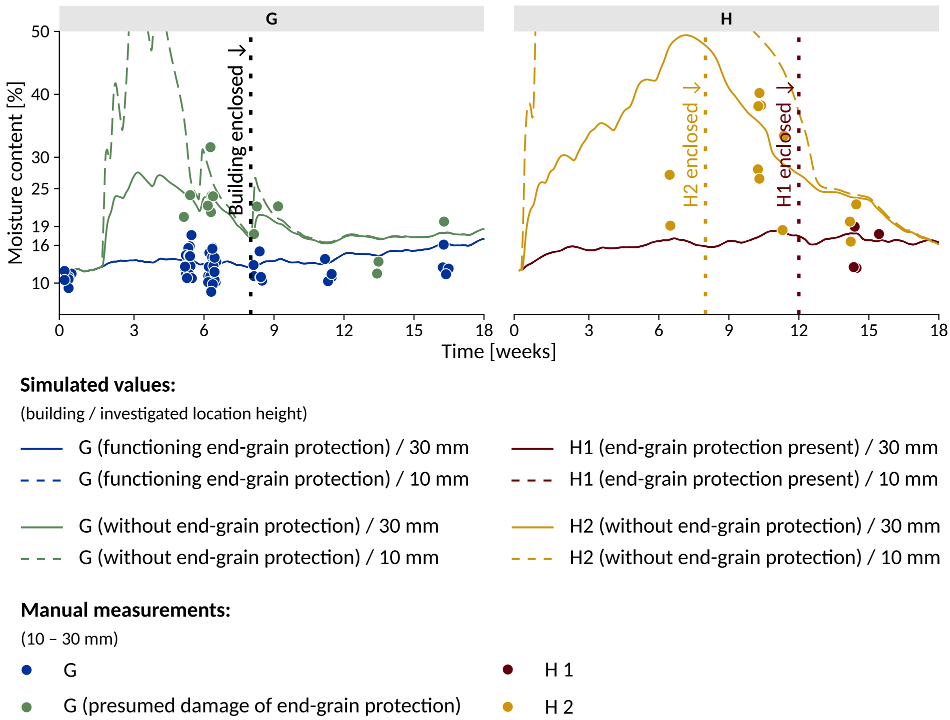


Figure 50. Measured and simulated MC of the external wall bottom areas of the buildings G and H. The time scale is provided relative to the installation start time. The simulated MC is the average of the three material files used in the simulations.

In the case of the first floor in the building H, there were neither visual indications of end-grain moisture ingress nor swelling of timber boards, nor did the measurements indicate elevated MC (Figure 50, right chart, dark red points and lines). The moisture safety strategy was effective, and the fabric-based self-adhesive waterproofing membrane (Riwega VSK Micro, S_d > 2 m) on the bottom areas of the first-floor CLT panels performed well. No damage was identified in the fabric-based waterproofing membrane as opposed to the liquid applied membrane coating used in the building G. The nearly 100 mm of rain (Figure 14, in Section 4.1.1) was effectively diverted.

For the second-floor panels in building H, the moisture safety estimation method predicted a moisture unsafe outcome (0/10, Figure 48) due to the absent bottom end-grain surface protection. The simulation with the actual climate data also indicated very high MC reaching well over 30 % (Figure 50, right chart, yellow lines). This was confirmed by manual measurements (Figure 50, right chart, yellow points and Figure 51, P1). While the calculated cumulative precipitation amount for the second floor in the building H was the lowest of the studied buildings, the recorded MC measurements were nevertheless the highest. This could be linked to the absence of end-grain protection. In this case, the moisture safety prediction was correct.

Visual findings also confirmed that the wet areas exhibited swelling (Figure 51, P2). After the discovery of the wet CLT on the second floor, large air fans were brought on the site to accelerate the moisture dry-out (Figure 51, P3). Fortunately, the installation start was during winter and the main period when moisture was dried out was during spring, which is the period with the highest moisture dry-out potential in Estonia.

The simulated MC showed a sufficient correlation with the measured values throughout the dry-out period (Figure 50, right chart) though it was slightly higher – likely because of increased air change from the fans. Safe MC was achieved at approximately 8 weeks after the building was enclosed. Furthermore, most walls were left exposed in the final interior, allowing for extended moisture dry-out periods without disrupting the construction schedule (Figure 51, P4 & P5).

Figure 51 Moisture measurements (top left), timber swelling (top middle) and accelerated air drying (top right) in the building G. The bottom photos show the second-floor interior before completion and handover to the client.

4.9.4 Effectiveness of moisture safety measures

Regarding the effectiveness of moisture safety measures, local protection has demonstrated its benefits. An approach proposed in the early stages of this PhD research (presented in Figure 26 and Figure 27 in Section 4.2) was found to be effective. For instance, the panels on the first floor of the building H remained free from moisture ingress despite the absence of an FWP structure, relying solely on local protection. It has been suggested that if expected rainfall exceeds 40 mm or construction lasts longer than a few weeks, a roof cover becomes essential (Öberg & Wiege, 2018) or that CLT construction should preferably have complete weather protection. However, the results show that with local protection measures and scheduling the installation of CLT for a favourable season a moisture-safe outcome can be achieved, even when installation times exceed a few weeks and the measured cumulative precipitation amounts exceed 40 mm. Nevertheless, despite their potential effectiveness, local protection measures are not infallible. In the case shown in Figure 25 (in Section 4.1.2), the failure appears to be linked to the sequence of membrane installation over the floor panel joints. In contrast, Figure 49 (middle) illustrates damage to a liquid-applied membrane coating, likely caused by mechanical impact.

Further research on local moisture protection solutions for CLT is needed. Key areas of interest include understanding how, when, and why protection measures such as membranes or coatings fail, and whether moisture entering through failure points poses a significant risk. Additionally, it is important to assess how effectively these protection measures allow moisture to dry out.

The damage observed in local protection measures points to the advantages of FWP, which remains a more fail-safe method. Tengberg & Bolmsvik (2021) also showed that an FWP structure significantly reduces the risk of mould growth on CLT elements. But at the same time and somewhat counterintuitively, as demonstrated by the case of the building G and the simulation results for its case, prolonged exposure under an FWP structure can introduce risks. Extended exposure to outdoor air, even without contact with bulk water, can increase timber MC. This shows the importance of rapid enclosure of CLT, irrespective of the use of an FWP structure. A rapid enclosure strategy, along with ensuring that wet CLT panels are not covered, was emphasised in Time et al. (2023). Additionally, regular MC measurements remain essential even when wetting mitigation practices are in place, as evidenced by the case of the building G. To enhance monitoring, integrating systems like those described by Vestergaard Kellgren et al. (2023) into CLT construction would be beneficial, regardless of the chosen moisture safety strategy.

4.9.5 Prediction of the moisture safety outcomes & the procurement process

For the building G, the analysis framework predicted, using 30 years of climate data, that the extended period after installation during which the CLT remained exposed to outdoor air (though protected from precipitation) would lower the likelihood of a moisture-safe outcome. On-site measurements and the results of the hygrothermal simulation, using actual climate data from the construction period, confirmed an increasing trend in the MC of the CLT panels, supporting the prediction. However, if the end-grain waterproofing membrane had not been damaged, the actual result would have been largely, if not entirely, positive, especially when focusing on the moisture safety of the CLT wall panel bottom end-grain areas.

For the building H, the predictions matched the actual outcomes, with the measured and simulated MC values aligning sufficiently. On the first floor, the fabric-based waterproofing at the bottom end-grain edges proved more effective than the thin liquid-applied-waterproofing membrane used in the building G. For the second floor of the building H, the moisture safety strategy analysis predicted a high-risk scenario with no chance of success (in terms of guaranteeing a moisture-safe outcome) and a very high MC. This proved to be the actual outcome. Had the interior finishing system been something other than exposed CLT and had the construction schedule allowed less time for moisture dry-out, the consequences would have been much more problematic. If the moisture safety strategy had been analysed in advance, a solution without end-grain protection might not have been selected. However, this remains speculative and lacks supporting evidence.

The pre-analysis of moisture safety strategies in advance could be beneficial and if included in the early stages of moisture safety planning process. However, additional analysis of similar case studies is required to fully confirm the method's reliability and practical applicability. Mjörnell et al. (2011) specified that a risk analysis could be carried out in order to estimate the moisture safety as a part of the overall moisture safety planning process. The experience from this PhD study suggests that the risk analysis should address not only the moisture performance of the designed structures but also the chosen moisture safety strategies. The moisture safety strategy analysis method could be useful here, offering potential to streamline decision-making.

The findings from the observations are somewhat inconclusive regarding the inclusion of moisture safety in the procurement process. Although the inclusion of moisture safety was more prominent in the case of the building G, there still was occasional excessive wetting (due to the occasional failure of the thin local protection membrane) and material needed to be replaced (in the case of the risky floor panel connection joint). In case of the building H, the initial solution for the first-floor panels yielded a moisture safe outcome, even though a specific moisture safety planning for the construction period was not mandated by the customer. Nevertheless, the solution that proved effective was specified during the design phase, indicating that, in a broader sense, moisture safety was incorporated into the design of the building H, which helped to reach good results with the first-floor wall panels. Unfortunately, the same design did not include the moisture safety solution used for the first-floor panels in the second-floor panels. This shows the delicacy of moisture-safe design. It is clear that a well-thought-out design and the accompanying drawings of moisture safety solutions in the design process of buildings are important.

While the general contractor for the building G was more experienced in CLT construction, the results do not show a clear correlation between experience and the outcome. Clearer connections with the outcomes stem from the moisture safety design. Neither of the case study buildings had a sophisticated moisture safety project, and the analysis of the construction processes suggests that both buildings would have benefited from a detailed moisture safety project, predictive analyses, and preliminary risk assessment.

The general contractors of the studied case buildings demonstrated commendable overall performance; despite the presence of some moisture issues, which, while not entirely avoidable, show the challenges of achieving flawless construction practices and indicate the continuous need for further efforts to improve moisture safety.

4.10 Limitations and future research

The presented results are subject to several limitations. First, the study was conducted during a period of continuous growth in CLT use as a structural material. As such the findings may reflect early-stage practices or trends that could change, and thus the conclusions might need re-evaluation in light of future developments. The work also does not claim to be exhaustive, as the subject of moisture safety allows for further investigation. Each subsection of the results could be expanded, and additional perspectives may be explored.

Second, several technical and methodological limitations must be acknowledged. For example, the study is based on the climate of Estonia, which is characterised by cold winters and mild summers, with significant precipitation throughout the year (Köppen classification Dfb). The results may not be directly applicable to other climates with different precipitation and dry-out conditions. Nevertheless, the analytical framework developed for evaluating moisture safety strategies can be applied elsewhere by substituting the input climate data.

The validation of the moisture safety strategy prediction method relied on two buildings, which allowed for limited systematisation possibilities. Further validation with additional case study buildings would be beneficial. Ongoing work aims to address this, as new CLT buildings are continuing to be built, and site observations are ongoing. Validation using data from other countries would also be valuable. However, this requires more than a simple comparison of moisture measurement results.

A thorough site observation study – or at least an analysis of photographs, construction logbooks, and interviews with relevant stakeholders – is necessary to adequately explain potential discrepancies between the predicted and actual outcomes. These requirements currently pose challenges to international validation. An additional limitation of the method arises from the selection of risk areas included in the analysis. The analysis of moisture safety strategies focused on the bottom end-grain areas of wall panels, as they are the most vulnerable to moisture ingress. Horizontal panels were assumed to be protected by waterproofing membranes, which has become a common practice. Expanding the analysis to include additional risk points would increase complexity, which is why the current study remained focused on the primary risk area. Nevertheless, ongoing efforts aim to address these aspects.

Further analysis of the temporal relationship between rainfall and MC would be valuable. However, such analysis requires rainfall measurements at the construction sites, which were not available in this study. Data from nearby weather stations may not be adequate, as spatial variability in rainfall can reduce the accuracy of correlations, particularly when seeking close alignment between rainfall events and MC responses. This is therefore identified as a topic for future research.

The hygrothermal simulation model is validated only with measurements conducted on spruce. However, other wood species are also used in CLT manufacturing. Nevertheless, the work demonstrates the usefulness and accuracy of the 2D anisotropic hygrothermal simulation, which can serve as a basis for future work with other wood species. Future work focusing on the influence of glue lines would also be valuable.

It is acknowledged that continuous measurement of MC in the areas identified as critical in terms of moisture ingress would have been beneficia, as the quality of the single point measurements taken with common electrical resistance-based moisture meters may have been affected by variability between the different instruments and also by differing weather and site conditions during the field study. However, any potential deviations in the field data are not considered to critically affect the main conclusions of the thesis. Installing continuous measurement devices was not feasible due to practical constraints and/or restrictions from the customer and general contractor. Given that one of the aims was to develop a flexible, easy-to-use MC-based performance criterion suitable for common electrical resistance-based devices, using data from such instruments was considered appropriate. To address their limitations in high-MC conditions, gravimetric measurements were also employed. Future studies incorporating continuous MC monitoring would, however, be valuable.

Additionally, there was a large variability in the water uptake rate and extent, which the three different files for the anisotropic spruce material aimed to replicate. While the replication was sufficient, it is not known how these varying properties are distributed among a typical batch of timber boards that comprise a CLT panel. For a reliable distribution information, a separate comprehensive study is needed, although it would still have a great level of uncertainty deriving from the uncertainty of the growth conditions of the timber. Currently, the analysis assumes equal distribution of the properties. Alternatively, including only the material file that leads to the most critical conditions could be used instead, as moisture damage occurs first in the areas where the material properties favour damage occurrence and it is sensible to aim for zero damage.

For the development of the novel two-step MC-based performance criterion, additional analysis could be useful in future studies. For instance, more incremental changes of initial MC or performing a broader, possibly stochastic analysis of various environmental conditions would help to further specify the performance criterion before its validation in situ. Also, different layer thicknesses of CLT exist and might affect the result. Future improvements in the performance criterion can include the influence of the panel layout.

When considering directions for future research, attention should be given to the implications of the observed trends. The findings indicate that achieving moisture safety is generally more feasible during drier years. However, analysis of the 30-year climate dataset revealed a contrary trend, namely, an increase in average relative humidity over the years. Future research could investigate this issue further, with attention to extrapolating insights from the current numerical results to assess the prospects for ensuring moisture safety under changing climate.

5 Conclusions

This study examined the challenges of ensuring moisture safety of cross-laminated timber buildings during the construction phase via field observations and measurements from eight CLT buildings, laboratory tests, and hygrothermal simulations. It contributed by identifying areas most susceptible to moisture exposure and provided practical recommendations alongside valuable empirical data on wetting and drying behaviour. The study also validated a 2D anisotropic hygrothermal simulation model and used it to propose an improved performance criterion, specifically addressing water absorption through end-grain surfaces. Finally, a moisture safety strategy assessment method was tested in the context of CLT construction, and the efficacy of moisture safety measures was evaluated in practice.

5.1 Key findings from field observations and laboratory tests

Initial field observations of six CLT buildings gave a thorough answer to the first and third research questions (**RQ1** and **RQ3**). The bottom areas of wall panels were found to be the most susceptible to wetting. Other vulnerable areas included the side end-grain surfaces of roof and floor panels, and window and roof skylight opening perimeters. It was concluded that it is not feasible to rely solely on a fast construction process to ensure that CLT panels remain dry before being built in.

CLT panels and connection joints were exposed to precipitation from two to twenty-one weeks, depending on the size and complexity of the studied buildings. The average exposure time for the studied non-single-family buildings was around three months. Cumulative precipitation near the construction sites during CLT exposure to precipitation ranged from 56 mm to 335 mm for the larger buildings and 14 mm to 229 mm for the detached houses. Various types of moisture damage were reported, including the delamination of CLT, concerns about structural integrity due to excessive swelling and shrinkage at the CLT connection joints, mould growth, and staining of CLT from water uptake. However, there were also indications that very short-term wetting of CLT end-grain surfaces may not lead to serious issues (excluding visual ones), provided that conditions prevent mould growth and allow for timely drying.

Results from the laboratory tests provided additional insight into the third research question (**RQ3**), indicating that while moisture uptake in the end-grain areas of CLT panels was significant, it remained localised. After 24 hours of wetting through the bottom end-grain surface, gravimetric MC measurements showed an average MC of nearly 100 % in the longitudinal plies of CLT within the bottom 7 mm and approximately 27 % in the 7–14 mm height level from the water contact. In the transverse plies, MC reached ~24 % in the bottom 7 mm and ~ 12 % at 7–14 mm from the wetted surface at the same time. After 48 hours of wetting, the average MC rose to ~ 125 % and ~ 50 % in the longitudinal plies, and to ~ 30 % and ~ 20 % in the transverse plies at the respective height levels. At 30 mm from the water contact, MC in the longitudinal plies exceeded 30 % in less than two days. At 60 mm and higher, the MC increase was progressively smaller.

Laboratory tests confirmed the on-site measurements, indicating that moisture dry-out from a CLT wall panel, which has absorbed moisture through the end-grain surface and is installed on a floor panel or foundation joint, is very limited. Ensuring low MC near the end-grain surfaces during CLT construction, when exposed to the elements, is practically impossible (**RQ3**). Some form of moisture protection is always warranted for these joints.

The field observations also contributed to addressing the second research question (**RQ2**). The topic was revisited in the final stages of the research through the observation of the construction process of two additional CLT buildings. The field study in these buildings was informed by insights gained from previous field and laboratory studies, as well as simulation results. It was concluded that even with a well-planned moisture safety strategy and an experienced contractor, moisture safety could still be compromised in certain areas. Detailed moisture protection solutions must be clearly specified during the design phase, as design quality seems to outweigh contractor expertise in ensuring moisture safety. As such, drafts of technical details, including proposals for local protection measures, were developed for CLT connection joints (**RQ2**).

Experience from the construction sites also indicated that the discrepancy where measured MC was above suggested limits but without severe negative consequences created contention and hindered efficient construction processes. This led to the development of the two-step MC-based performance criterion for CLT end-grain moisture safety which would give an answer to the fourth research question (**RQ4**).

5.2 The two-step MC-based performance criterion

The two-step MC-based performance criterion for the CLT end-grain moisture safety was initially established as MC ≤ 25 % at 10 mm from the water contact surface and MC ≤ 16 % at 30 mm from the water contact surface in the longitudinal plies of CLT.

Simulations indicated that if the end-grain surface of CLT is exposed to water, the maximum mould index on the inner face of CLT remains below 1 for scenarios where the initial MC did not exceed the levels reached after 24 hours of water contact from the bottom end-grain surface. This criterion could be applied once the CLT panels were shielded from precipitation and set to be covered with vapour-permeable layers or left exposed. However, further analysis indicated that the initial limits might be too stringent, as MC in the outer layers of CLT could often exceed 16 % due to hygroscopic moisture absorption from ambient air which might not lead to mould growth, providing other conditions are unfavourable.

A supplementary clause was added to the performance criteria. Specifically, the target compliance of MC at 30 mm from the bottom surface of CLT panels would only be necessary to verify if the MC at 10 mm from bottom surface exceeds 19 %. This would indicate that the absorption of liquid water through the end-grain surface might have occurred, or the panel had been exposed to humid air for long enough that closer scrutiny was warranted. The results demonstrated that, in case of water contact, a MC below 19 % at 10 mm from the contact surface (i.e., near the bottom end-grain surface) could only be sustained with very short wetting periods. For the short wetting periods (≤ 24 h), the calculated mould index did not exceed 1. Based on this, the two-step MC-based performance criterion for the end-grain moisture safety of CLT panels was defined as follows: MC ≤ 25 % at 10 mm from the water contact surface and MC ≤ 16 % at 30 mm, if MC > 19 % at 10 mm from the water contact surface in the longitudinal plies of CLT. It is proposed as suitable for assessing moisture safety near CLT end-grain surfaces, where liquid water absorption can quickly exceed commonly used MC limits, yet short-term wetting may not pose an immediate risk (**RQ4**). This MC criterion is intended to apply only when at least the interior surface of the CLT panel allows for moisture dry-out.

5.3 Moisture safety strategies for CLT construction

Hygrothermal modelling with long-term climate data was the basis for answering the fifth research question (**RQ5**). The calculations with the 30-year climate data showed that even for an installation duration as short as one week, it was highly likely that there would be enough precipitation to cause excessive wetting, confirming the findings from the field study. The most significant positive impact on CLT end-grain moisture safety resulted from the implementation of end-grain protection or scheduling installation to begin in spring (**RQ5**). Spring is the most favourable season for installation, while autumn is the worst (considering the Estonian climate). Side face protection and enhanced horizontal surface drainage provided marginal benefits, particularly when combined with longer installation durations. Although FWP was found to provide the most effective moisture safety, other approaches, such as integrating local protection and scheduling construction at favourable times, may offer adequate moisture safety in favourable cases. The thesis also presented anticipated moisture dry-out times for selected strategies that do not rely on FWP (**RQ5**).

Allocating time for moisture dry-out even without heating, i.e., in outdoor climate conditions (but without precipitation) was found to be beneficial, but it is evident that unassisted moisture dry-out is not a feasible moisture safety practice except if the dry-out starts in spring (i.e., during a period when the relative humidity of the outdoor air is at its lowest) or if it starts in summer after a short period of precipitation exposure. During winter and autumn (for the Estonian climate), the moisture dry-out potential is insufficient.

Additionally, the interannual variability of the analysed moisture safety strategies and their correlation with climatic factors were analysed. There was quite a large variability in the share of successful results between different simulated years. However, it was indicated that there was a correlation, albeit a weak one, that achieving a moisture safe outcome was more difficult with more recent years, which might be due to the increasing average RH conditions through the years. A modest correlation was identified with the yearly rain amount, and a stronger association was shown with the mean outdoor air relative humidity.

The results from the moisture safety analysis were used for predicting the outcome of the selected and incidental moisture safety strategies in the two later studied buildings. The prediction method was deemed broadly accurate. The initial hypothesis – that the moisture safety strategy predicted to result in poorer outcomes by the analysis method would indeed lead to worse conditions in practice – was confirmed (**RQ6**). Likewise, the strategy predicted to perform better yielded superior results. A guaranteed moisture-safe outcome was predicted 6 out of 10 times for one of the studied buildings, 10 out of 10 times for the first-floor wall panels in the second building, and 0 out of 10 times for the second-floor wall panels in the second building. For the latter variant, with no guarantee of success (in terms of ensuring a moisture-safe outcome) the simulation model also predicted a very high MC in the bottom area of the CLT wall panels. This proved to be the actual outcome. It was suggested that incorporating a preliminary analysis of moisture safety strategies during the early stages of the planning process could be beneficial.

5.4 Insights from 2D anisotropic model validation

It was demonstrated that accurate simulation of water uptake through CLT end-grain surfaces, moisture redistribution, and subsequent moisture dry-out towards the surrounding environment required a two-dimensional (2D) hygrothermal model that accounts for the anisotropic properties of timber. Additionally, it was indicated that selecting material files based on the water absorption coefficient was insufficient, and thorough validation was recommended.

The function of anisotropic modelling in the hygrothermal simulation tool IBK Delphin is still experimental as of 2025. Custom material files of anisotropic spruce have to be compiled. An initial evaluation of the spruce material definitions available in the software's database was conducted by comparing the simulation results with a simple one-dimensional (1D) water uptake test. The analysis indicated that several existing definitions led to significant discrepancies between simulated and measured moisture uptake. Only two definitions were found to be appropriate for constructing the anisotropic material files.

Additional adjustments to liquid conductivity and moisture storage were necessary to achieve a sufficient fit between the results from the 2D anisotropic dynamic model and the measurement data. It was found that without altering the moisture storage function, specifically in the range of capillary pressure of approximately -10^6 Pa to -10^5 Pa corresponding to approximately 99.3 % to 99.9 % RH, it was not possible to simultaneously achieve a good correlation with the observed extensive water uptake near the end-grain surfaces and limited water uptake at the measurement points further away from the water contact surface with the given material files. The moisture storage function is highly sensitive to alterations and small changes can produce vastly different results. The built-in material definitions in the Delphin database have quite a large variation in the storage functions and substantial validation is necessary when dealing with simulations that take account of over-hygroscopic moisture flow. Due to the heterogeneous nature of wood, significant variations in water uptake intensity can occur within individual timber boards, warranting the use of multiple material definitions.

5.5 Recommendations for practice

The practical conclusions and recommendations for construction are:

- Detailed moisture protection solutions must be clearly specified during the design phase, as design quality seems to outweigh contractor expertise in ensuring moisture safety.
- Local protection can suffice without an full-coverage weather protection structure, but this carries higher risks and demands a responsive, adaptive moisture safety process. A preliminary risk assessment is advised when relying on local protection or considering the exclusion of protection measures.
- The end-grain protection of CLT wall panels is effective, though local protection measures can fail or be damaged, warranting regular moisture monitoring. The swelling and warping of CLT can indicate excess MC even without water uptake marks on the surface of CLT.

- Floor panel edges, particularly at cut-out grooves in panel-to-panel joints, should be moisture-protected similarly to wall panel bottom surfaces, ideally during the manufacturing stage of CLT.
- Delaying full-coverage weather protection after CLT installation creates a window for potential wetting incidents, as local protection can be damaged or incomplete.
- Installing CLT under a full-coverage weather protection structure ensures the highest moisture safety, however prolonged exposure to outside air, even under full-coverage weather protection, raises MC in CLT.
- Scheduling the installation start of CLT to a dry period is highly beneficial (in Estonia's case, installation start during spring is recommended).
- The inclusion of moisture dry-out periods in the moisture management plan for CLT before covering it with additional layers is recommended.
- Moisture dry-out periods should consider the exposure time during installation and the season of the dry-out period. Unassisted dry-out is feasible only during a relatively dry season (e.g., spring in Estonia), at other times, additional equipment is warranted to ensure a timely moisture dry-out.
- After an exposure time of four weeks, the moisture dry-out time is likely longer than one month if the dry-out starts during a colder and more humid season.
- Shorter installation/exposure durations should be aimed for (preferably less than a month).
- Short-term wetting of CLT end-grain surfaces might not pose an immediate risk, however if wetting occurs, efforts should be made to reduce MC below 25 % at 10 mm from the end-grain surface in the longitudinal layer (with regard to the water uptake direction); MC target should be below 16 % elsewhere (required to measure when MC at 10 mm is ≥ 19 %). This MC criterion is valid only if wet areas are exposed or covered with vapour-permeable layers.

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Acknowledgements

First and foremost, I would like to express my deepest gratitude to my supervisor, Professor Targo Kalamees, for his consistent support and encouragement throughout my doctoral studies. I have been continually inspired by his expertise in building physics and his extraordinary dedication, whether in academic work, sport, or any professional endeavour. I have grown both academically and personally, and I hold my supervisor's work and achievements in the highest regard.

I am sincerely thankful that in the early spring of 2018, Professor Kalamees responded positively when I cautiously expressed my interest in pursuing a PhD. He took me onboard and provided all the necessary resources and made it possible for me to work remotely, which was not a common option at the time. In retrospect, this added to the difficulty of the journey, as I frequently had to rely solely on myself. This is not intended to suggest insufficient support, but simply to acknowledge that a large part of my PhD journey involved working alone and often while travelling on trains and buses.

When not travelling, immersed in thought at my home office, or conducting field studies, I was likely working at the Tartu College of Tallinn University of Technology or collaborating with my colleagues in the Nearly Zero Energy Buildings (nZEB) Research Group in Tallinn. I am honoured to be part of both institutions. Officially, I have been a member of the nZEB Research Group, however considering the significant amount of time spent at the Tartu College, I feel equally integrated into that community as well. This brings me to Professor Aime Ruus, who warmly offered me a place to work at the Tartu College early in my PhD studies. Our numerous and fruitful discussions have spanned both research and broader aspects of professional growth. I consider Professor Ruus to be a mentor throughout my PhD journey and her support has been invaluable. I also thank Mihkel Kiviste, Jiří Tintěra, Jüri Resev and others in the Tartu College.

Returning to the nZEB Research Group, I want to emphasize the very warm welcome I received when I began my doctoral studies at TalTech. Despite my sporadic visits to Tallinn, I immediately felt at home within the group. All members of the research group have supported this work in various ways: by fostering a unique and stimulating academic environment, encouraging me through challenging moments, and contributing to insightful discussions on methodology and results. A special thank goes to Jaanus Hallik, who first introduced me to simulation sciences back in 2010. His wise words have guided me in various ways throughout the years. I also wish to express my deep gratitude to Paul Klõšeiko, who taught me the intricacies of hygrothermal simulations. Without this knowledge, the thesis would not have been possible, or at the very least, it would have taken a completely different direction. The thesis was also shaped by Villu Kukk, particularly during our extensive fieldwork on CLT buildings. Simo Ilomets, Martin Talvik and Kristina Vilba deserve special mention for our collaboration in developing a new course on moisture safety, which has proven to be well-received. I am also grateful to Laura Kadaru and Ene Pähn for all kinds of administrative support, and to Professor Jarek Kurnitski, Tuule Mall Parts, Endrik Arumägi, Kalle Kuusk, Karl-Villem Võsa, Raimo Simson, Anti Hamburg, Alo Mikola, Martin Thalfeldt, Ergo Pikas, Helena Kuivjõgi, Lauri Lihtmaa, Siim Lomp, Henri Olak, Elisa Iliste, Ülar Palmiste, and other members of the nZEB research group for their encouragement and support and humour throughout my journey. I would also like to thank Eero Tuhkanen from the Structural Engineering Research Group and Renee Puusepp from the Timber Architecture Research Centre PAKK at the Estonian Academy of Arts with whom I have had inspiring collaborations.

I wish to thank the graduate students I have supervised, who have significantly contributed to my research. I acknowledge the CLT and glulam producer Arcwood by Peetri Puit OÜ for supplying the CLT test specimens, and I extend my gratitude to all the clients and general contractors involved with the field study buildings.

Karin Muoni is sincerely thanked for enhancing the clarity and conciseness of the language in this thesis, as well as in many of my other publications. I acknowledge the use of OpenAI’s large language models to support improvements in the clarity and conciseness of a few selected paragraphs of this thesis. The content was subsequently reviewed and edited by me, and generative AI was not used for any other purpose.

I am also thankful to Dr. Tõnu Mauring for providing my entry point into the field of energy-efficient and sustainable buildings, for supervising both my BSc and MSc theses in the University of Tartu, and for creating many opportunities, including introducing me to Professor Targo Kalamees.

I deeply thank all my friends and close ones for their support in every form throughout the various phases of my life and work. My greatest gratitude goes to my mother, whose encouragement has meant the world to me. She has always guided me towards knowledge and sophistication, and I believe that is a significant reason why I embarked on my PhD journey in the first place. That said, embarking on such a journey undoubtedly requires a touch of entrepreneurship, which I like to think I inherited from my adventurous father. And finally, my heartfelt gratitude goes to my dear partner Liisa, for enduring this journey with me and for the countless deep and insightful conversations, often about the most specific details of building physics, academic writing, or about the built environment in general, no matter the time and place. Thank you!

Financial support

I sincerely thank all the institutions involved, and gratefully acknowledge the financial support received from: Tallinn University of Technology, the Estonian Research Council (grants PRG483 and PRG2732), the Estonian Ministry of Education and Research (grant TK230), the European Commission (grants 754177, 856602, VFP21038, and VEU22001).

Support for short-term stays abroad was provided by the Estonian Education and Youth Board (former Archimedes Foundation) and by the Estonian Doctoral School.

I deeply appreciate the generous support I received from the Foundation of Karl Õiger Scholarship Fund toward the final stage of my PhD studies.

PUBLICATION I

Kalbe, K., Kukk, V., & Kalamees, T. (2020). Identification and improvement of critical joints in CLT construction without weather protection. 12th Nordic Symposium on Building Physics (NSB 2020, Tallinn, Estonia), E3S Web of Conferences, 172, 10002. https://doi.org/10.1051/e3sconf/202017210002

Identification and improvement of critical joints in CLT construction without weather protection

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Abstract. Wetting of timber structures during erection can have a harmful effect on their durability and could lead to adverse health effects. The probability of dampness related problems is very high when timber is exposed to free water. However, it is not always possible to implement full weather protection and thus there is a need for cost optimal solutions to increase the moisture safety of precipitation-exposed timber construction. In this study we observed the construction works and monitored the timber moisture content (MC) of a cross-laminated timber (CLT) building and proposed a set of activities and designed connection details that could help to avoid moisture ingress during the installation of CLT panels. Our findings showed that the most sensitive area to wetting is the end-grain on the CLT panel and the MC remained within critical limits in structures where drying was prohibited. Therefore, the most vulnerable section of the CLT structure is the foundation connection. We suggest using liquid-applied membrane coating on the cut edges of CLT panels to protect the end grain and to cover the horizontal CLT panels with self-adhesive membranes and vertical CLT panels with temporary clear weather protection foils.

1 Introduction

Wetting of timber structures during erection can have a harmful effect on their durability [1–3] and could lead to adverse health effects due to microbial growth [4–7]. Furthermore, the Construction Products Regulation [8] states that "The construction works must be designed and built in such a way that they will … not be a threat to the hygiene or health and safety … as a result of … dampness in parts of the construction works or on surfaces within the construction works."

The probability of dampness related problems is very high when timber is exposed to free water [9,10]. Mjörnell and Olsson recommend, in their recent study, to use moisture safe and robust structures, weather protection, and moisture safe construction methods [11]. Using whole building weather protection (such as a tent) would be the safest method to achieve this. However, there is a reluctancy on the construction market to implement this procedure because of concerns about increasing construction costs and thus it is an ongoing practice to erect timber buildings without protecting them from precipitation. A cost optimal solution between the two approaches would be implementing specific construction methodology to increase the moisture safety of precipitation-exposed timber construction.

In this study we analysed the construction works of a cross-laminated timber (CLT) building to determine the most critical joints of this CLT construction and proposed a set of activities that could help to avoid moisture ingress during the installation of CLT panels.

2 Methods

In this work, we used the observational method to investigate wetting incidents during the construction of a two-storey building with a total floor area of 1320 m^2 (Fig. 1). The building is located in Estonia where there is a cold and humid continental climate with warm summers – Dfb under the Köppen-Geiger climate classification [12]. All of the above-ground load bearing structures, including exterior walls, intermediate walls, and ceilings were made of CLT or glulam. This makes the building a good reference to other similar buildings as the main joint solutions presented here can be found in most CLT buildings. The walls were insulated with polyisocyanurate (PIR) insulation boards and the roof was insulated with expanded polystyrene (EPS) boards. The construction was exposed to precipitation and protective measures

Fig. 1. Observed CLT construction without weather protection.

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were used partially. For example, the CLT panels were covered with polyethylene (PE) foil during transport, but the foil was partially removed after the installation of the CLT panels. Furthermore, there was no moisture safety management implemented. Therefore, the timber structure was vulnerable to moisture ingress and thus proved to be suitable to determine the critical joints of precipitation-exposed CLT construction.

We observed particular aspects of the construction process and wetting incidents without further interaction similarly to human sciences [13], where the observational method is common [14]. We visited the site regularly and captured as much of the occurring issues as objectively and promptly as possible. We looked for signs of water ingress – such as stained wood, shrinkage or swelling, or the presence of free water on the surface of the structures. For covered areas we looked for gaps and/or faults in the material and further inspected the timber structure beneath it. We then measured the timber moisture content (MC) and marked the point of measurement for future repeated measurements (Fig. 2, left). We also made photos and videos of the findings and of the overall construction process and analysed them later. We proceeded to analyse the possible water ingress pathways and proposed measures and construction methods to avoid or lessen possible water damage.

MC in CLT structures was measured according to the EN 13183-2:2002 standard with an electrical resistance-based wood moisture meter, the Gann Hydromette LG 3. The measuring range of the moisture meter was 4 to 30% with a resolution of 0.1% and an accuracy of ±1%. The uncertainty increases considerably with measurement values over fibre saturation point (≈ 30%). Nevertheless, we opted to report all the measurement readings as is. Values over 30% have a lower accuracy but are helpful to describe the extent of wetting. The moisture meter consisted of a measuring device and a ram-in electrode (Fig. 2, left). We used 60 mm long Teflon insulated pins for the ram-in electrode. The pins had 10 mm long uninsulated peaks that made it possible to measure the MC at different depths in the CLT. We selected a fixed depth of 30 mm (measuring range 20 to 30 mm, Fig. 2, right). The MC was measured at a height of 30 mm from the lower edge of the CLT wall panels, as the preliminary observations suggested that the cut edges of wall panels are the most critical. We chose 20 measurement points around the perimeter and, in addition, 3 points on the intermediate ceiling to intermediate wall and 2 intermediate ceiling to window connections (measured from the end-grain). We made a total of six measurement rounds on the 13th September, 4th October, 25th October, 11th November and 19th December 2019 and 31st January 2020. In order to take into account the possible influence of weather on the MC, we acquired weather data (hourly values of outdoor temperature, relative humidity (RH), and precipitation) from the local national weather station (Fig. 3).

Fig. 2. Measuring the timber MC from a previously marked spot (left) using Teflon insulated electrode pins (right). Measuring depth was marked on the pins with contrasting tape.

To estimate the criticality of MC, we used the limit values of 17% for possible risk of mould growth [15,16], 20% for low and over 26% for higher risk of decay initiation [17].

3 Results and Discussion

3.1 On-site measurements and findings

During the first observation of the construction process, we mapped the most critical locations, i.e. places where the CLT panels received most wetting. We determined that the main focus in further MC measurements should be at the exterior wall to foundation connection around the perimeter of the building.

In Figure 3 there is a summarising graph of weather data presented in the time axis, including different construction phases that occurred over the course of the observation period. Precipitation occurred throughout the construction time and there were only a few completely dry periods, which is common during autumn in a cold and humid climate.

The installation of CLT panels (from 14.08.2019 to 06.09.2019) took place during the period of highest precipitation amounts. The average precipitation amount was 1.4 mm/h and the maximum reached 8.5 mm/h. We made the first round of MC measurements on the 13th September, after the CLT panels were installed. The ceilings were covered with water and water was flowing down the walls. It was clear that the CLT structures had been exposed to a sizeable amount of water. MC exceeded 17% in most measurement points around the perimeter, over 20% in more than half and over 26% in three points. The average outdoor temperature during the period was 17°C and the average relative humidity was 80%. Figure 4 shows all the measured values and calculated average values for each visit. Smoothed lines are presented between the average values of each visit to show the trend of MC over the visits.

The installation of the panels was followed by the sealing of the skylight shafts, between the 16th and 20th September, and the installation of the roof insulation and cover membrane, between the 25th September and 10th October. During this period the precipitation amount was lower (average 0.6 mm/h, maximum 4.6 mm/h). The MC during this period, measured on 4th October, was above 17% in almost all points around the perimeter and exceeded 20% in most points. We detected an increase of the overall average MC to 22.3%, 1.1% higher compared to the average of the first measurements (21.2%).

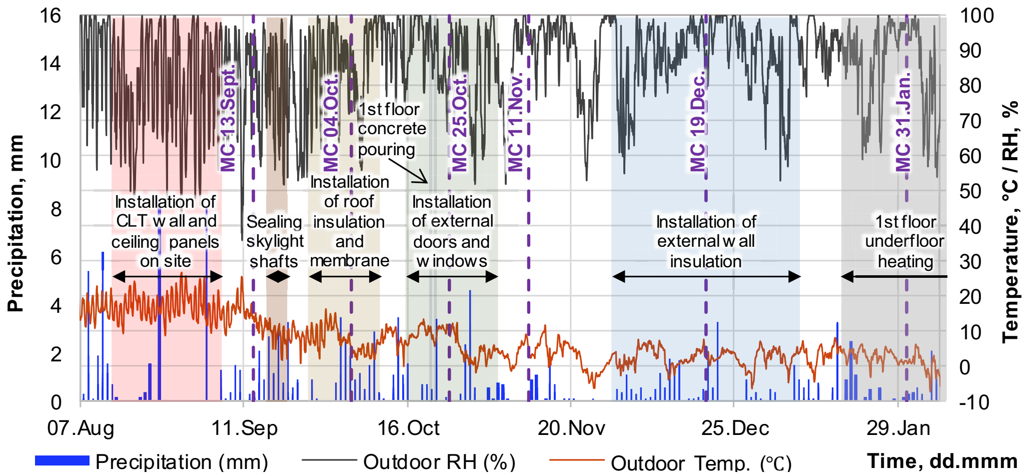

Fig. 3. Weather data during the construction period and MC measurements (MC 13 Sept.- MC 19 Dec.).

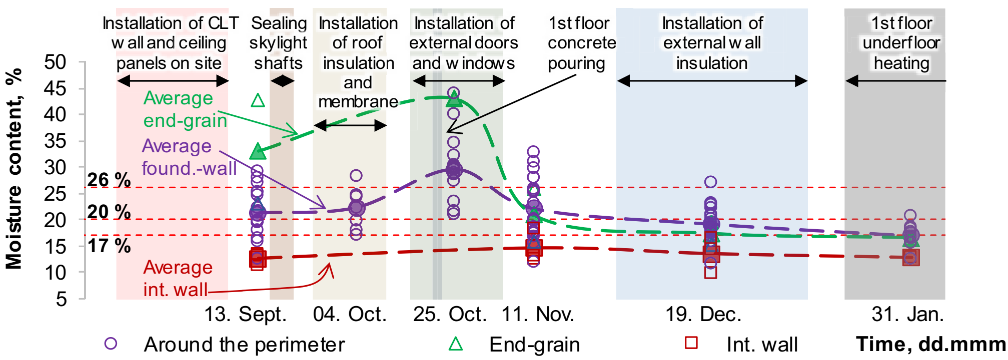

Fig. 4. MC of the CLT panels during distinct phases of construction. The filled markers show the average values of the measurements and the dashed lines represent the trend of average values. There were no measurements for the end grain on 4th October. The red dotted lines represent limiting values for mould growth and decay initiation.

The average outdoor temperature during the period was 8°C and the average relative humidity was 83%.

The next construction phase was the installation of external doors and windows, between the 16th October and 4th November, which also included the first-floor concrete pouring on the 21st and 22nd October. The average precipitation was 0.8 mm/h and the maximum reached 4.6 mm/h. We measured MC again on the 25th October and the results showed a significant increase in MC. Average MC around the perimeter had risen to 29.5% and the average measured from end-grain reached 43%. MC was above 20% in all points and exceeded 26% in most points. This phenomenon might have occurred because of the concrete pouring on the 1st floor just before the measurements. Concrete pouring is a very moisture-intensive task and leads to great moisture excess. This prohibited the moisture dry-out from the CLT and might have increased the moisture content on surface layers because of the hygroscopic properties of timber. Moreover, it is possible that some of the wet, uncured concrete could have made contact with the CLT (Fig. 5). This further confirms our suggestion that the most critical joint is the exterior wall to foundation connection.

Measurements taken 16 days later, on November 11th, showed that the average MC had fallen back to 22%, but still half of the points had a MC more than 20% and five of them had more than 26%. The outdoor average temperature was 7°C and the relative humidity was 87% during the installation of external door and windows.

Fig. 5. CLT exterior wall and newly poured 1st floor concrete screed. Note the discoloration of timber from the previous wetting incident (dashed arrow) and new wetting mark (solid arrow) possibly from the concrete pouring.

The installation of external wall insulation was between November 29th and January 8th. During this period the average precipitation amount was 0.4 mm/h (maximum 3.3 mm/h). The average outdoor temperature was 2.4°C and the average relative humidity was 89%. However, after the windows and external doors were installed, a temporary air heating system was put into use, which increased the indoor temperature to about 15°C and reduced the indoor RH. This, together with the use of dehumidifiers, led to the decrease of timber MC. By December 19th, the average MC around the perimeter had dropped to 19.1% and the average of end-grain measurements dropped to 17.3%. In most of the measured points the MC reached below 20%.

The first-floor underfloor heating was turned on for the first time on January 17th. The last measurements were taken two weeks after on January 31th. The average MC around the perimeter was 16.9%, the average of end-grain measurements was 16.5% and the average of intermediate wall was 12.7%. The precipitation amount during the period between January 17th and February 2nd was the lowest among the entire observed period (average 0.3 mm/h and maximum 2.1 mm/h). The average outdoor temperature was 2.9°C and the average relative humidity was 89%. MC reached below 17% in most of the measured points during the last observed period.

In addition to the measurements at the exterior wall to foundation connection around the perimeter, we also measured the MC from the CLT panels at the intermediate ceiling to intermediate wall connection. The MC at this location was between 11% and 14% at the first measurement round. This was also the case for a panel covered with water, but as we measured MC from a fixed depth we detected an MC of 11% in the 30 mm deep layer. After the last round (31th Jan.) the MC did not reach above 13%. This indicates that intermediate CLT wall panels, which were more weather-protected, remained dry (< 17%) during the entire construction period.

We observed that the bottom edges of the CLT panels at the exterior wall to foundation connection were repeatedly exposed to rainwater and the measured MC of these regions remained consistently high throughout the observation period. The measurements from the end-grain showed that the initial high moisture content decreased after the installation of windows and external doors to a level at which the risk of moisture damage would not be expected. The areas where we could measure the MC in end-grain were open to indoor air and moisture dry-out was favourable. The MC measured from intermediate ceiling to intermediate wall connection remained low (< 17%) during the entire construction period. The intermediate walls were covered with ceiling and roof structures early during the installation of CLT panels and became protected from rain.

These results suggest that weather-protected structures stayed dry, and structures that were exposed to drying also reached a low MC over time, but in structures where drying was prohibited, the MC remained critical. This confirms our initial assessment as well as the need for weather protection for exterior wall to foundation connection. Schmidt et al. [18] also found in their laboratory test that the end grain of CLT panels in moisture trapping conditions were critical and could lead to a small accumulation of moisture during multiple cycles of wetting. Scotta et al. [19] claimed in their study that the foundation connection is the most critical and not completely solved in wooden buildings and where moisture damages are most likely to occur. They proposed to use a special self-developed aluminium bottom rail between the CLT wall panel and the foundation.

Mould growth rate depends greatly on the initial moisture content of the wood [20]. Several studies have shown that CLT in a closed wall assembly poses a risk of mould growth during service life if its MC exceeds 17% [15,16]. Although the MC levels decreased below the mould growth threshold for many of the measured locations, we still suggest making a mould growth analysis when the indoor temperature has been over 20 °C for at least eight weeks.

Wetting not only poses a risk of microbial growth, but also affects the appearance of the wood surface by producing non-aesthetic stains. In the observed building, the CLT external wall panels will be used as interior decoration. Unfortunately, we noticed the "wetting marks" in numerous panels (e.g. Fig 5.). These proved to be difficult, costly and time-consuming to remove or alleviate. Drying out of moisture also causes volume shrinkage of the wood, which can result in noticeable cracks on the surface if the moisture content has been high. Large cracks were observed on the surfaces of the CLT panels in the given construction, which may result in lower airtightness of the building. V. Kukk *et al.* [21] and H. Skogstad *et al.* [22] found in their researches that cracks caused by volumetric shrinkage due to large changes in moisture content significantly increased the air leakage of CLT panels.

3.2 Critical joints and improvement proposition

After analysing the on-site measurements, we identified that the critical areas of precipitation-exposed CLT structures are on the cut edges of the CLT panels. This is mostly because the water absorption rate is much higher in the longitudinal direction of timber [23] and the end-grain part of the timber boards comprising the CLT are exposed on the cut edges.

Our observations led to the determination of six critical joints, where the end-grain is exposed to precipitation and where the moisture dry-out capacity is prohibited because of surrounding structures or the way the CLT panel is positioned in the joint. These joints are: 1) exterior wall to foundation connection (Fig. 6, a); 2) intermediate ceiling to intermediate wall connection (Fig. 6, b); 3) intermediate ceiling to external wall connection (Fig. 6, c); 4) intermediate ceiling to window connection (Fig. 6, d); 5) roof to exterior wall connection (Fig. 6, e), and 6) roof to skylight shaft connection (Fig. 6, f). On Figures 7 – 12 there are the project drawings of these joints (left) and drawings with our proposal for wetting mitigation practices (right).

The most critical junction proved to be the exterior wall to foundation connection. There was a rubber band under the exterior wall edge to prevent moisture ingress,

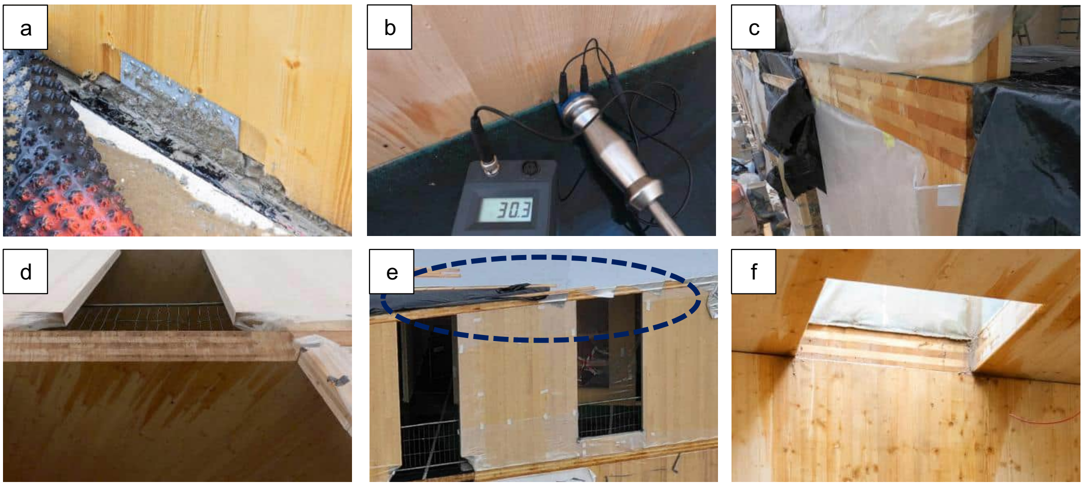

Fig. 6. Photographs of CLT junctions where wetting occurred frequently during our observation: a) exterior wall to foundation connection; b) intermediate ceiling to intermediate wall connection; c) intermediate ceiling to external wall connection; d) intermediate ceiling to window connection; e) roof to exterior wall connection and f) roof to skylight shaft connection.

but in many cases this solution did not prevent the wetting of the CLT (e.g. Fig. 6a). Water got between the rubber band and timber, thus decreasing the effectiveness of the rubber band. Moreover, the end-grain part around the fastening bracket was directly exposed to water. It was evident that sealing the fastening area with a rubber band is a complicated task. Therefore, in addition to the rubber band, we suggest using a liquid-applied membrane (Fig. 7), which must be installed in the factory and which will cover the whole cut-edge of the CLT panel regardless of cut-outs for fastening or other irregularities. Additionally, we suggest using a clear foil to protect the sides of the CLT panels from direct water contact. The foil must be clear, because it is then easier to detect accidental water flow behind it. The foil should also withstand strong winds. Thin packaging foils are thus not recommended. The foils must be fixed to the plinth immediately after installation with a water-resistant tape to prevent splashing water getting under the foil. An extra moisture-sealing adhesive strip is necessary to make the CLT to concrete connection airtight. This adhesive strip will also further prevent water from getting under the CLT panel.

The same overall practice as described earlier should be followed with all the other junctions. Furthermore, the intermediate ceiling and roof panels must be covered with weather protection membranes (Fig. 8-12), because water could accumulate on the horizontal panels and cause critical wetting. The membrane used on the intermediate ceiling must be suitable for indoor use, i.e. not emitting harmful substances. The membranes on the horizontal panels must be installed in the factory and all the connection joints and feed throughs must be taped with water resistant tape on site immediately after the installation of the CLT panels. The membranes must tolerate loads e.g. from walking and storing construction materials and from brushing or vacuuming off excess water. The excess water must not drip over the edges of the intermediate ceiling nor the edge of the roof. To ensure this, a temporary wooden slat must be installed in front of the window opening and on the perimeter of the roof (Fig. 10, 11).

The wetting mitigation practices we proposed are developed on the example of a specific building. For other building projects, these solutions should be used as guidelines and adapted based on the specificity, complexity, construction time and size of each project.

If the ceiling and roof panels are installed immediately after intermediate wall panels, then the necessity to treat the cut edges of the intermediate walls is debatable. However, this is not often the case, especially for larger buildings and we suggest to always protect the cut edges of CLT, even the bottom edges of intermediate wall panels, to avoid wetting as in Figure 6b, where there is a weather protection membrane cover on the ceiling, but the intermediate wall is untreated and has visibly taken up water.

We suggest using the protective measures together with fast installation process and if wetting incidents do occur, then moisture must be dried out before covering the structures.

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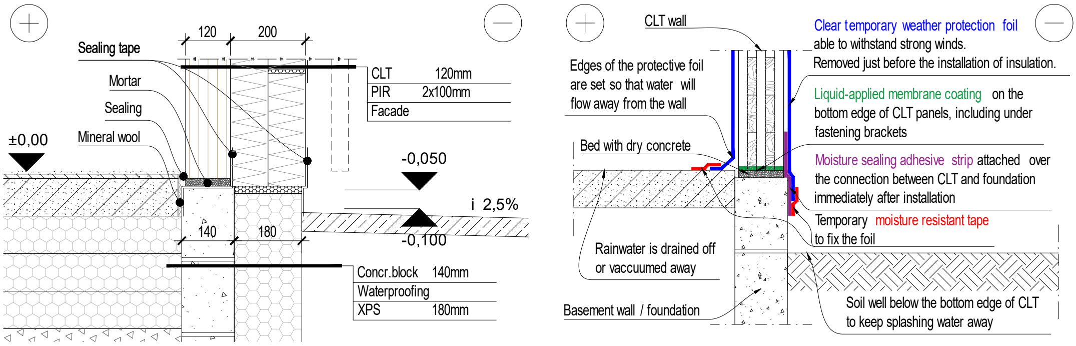

Fig. 7. Design drawing (left) of the exterior wall to foundation connection and our proposal (right) of wetting mitigation practices.

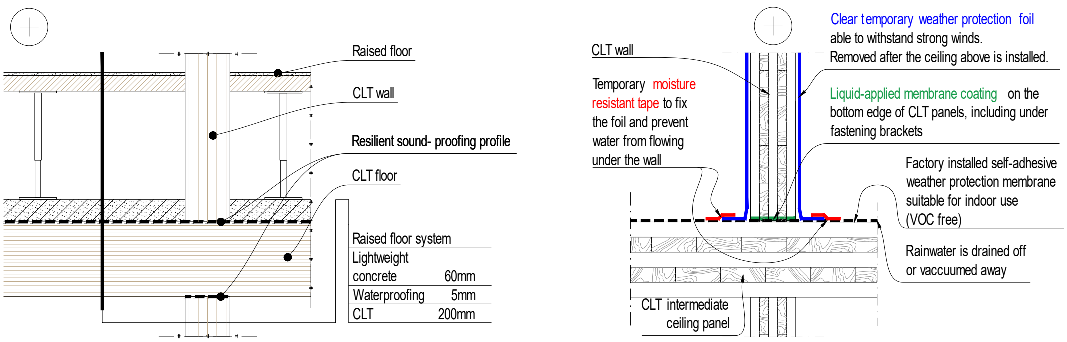

Fig. 8. Design drawing (left) of the intermediate ceiling to intermediate wall connection and our proposal (right) of wetting mitigation practices.

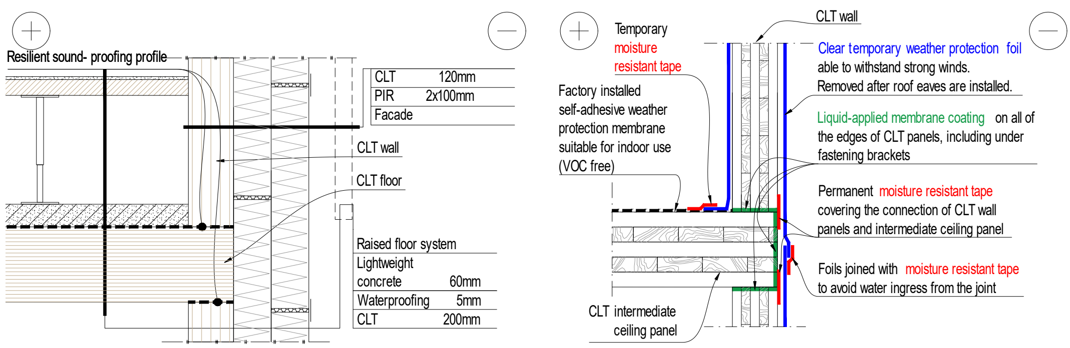

Fig. 9. Design drawing (left) of the intermediate ceiling to external wall connection and our proposal (right) of wetting mitigation practices.

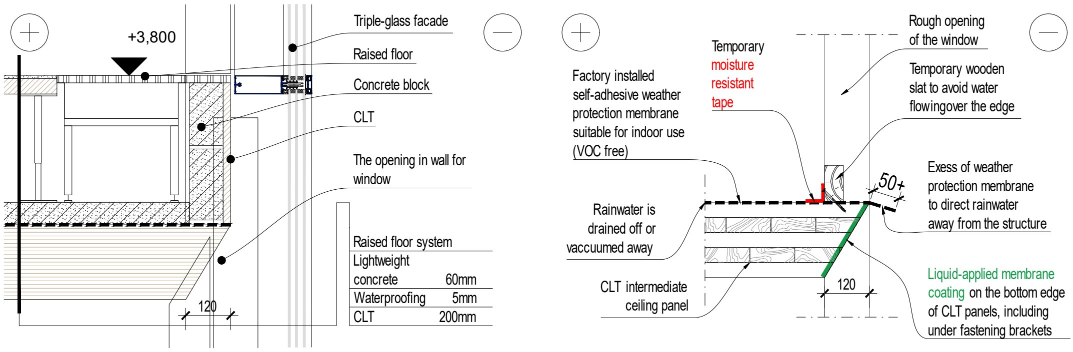

Fig. 10. Design drawing (left) of the intermediate ceiling to window connection and our proposal (right) of wetting mitigation practices.

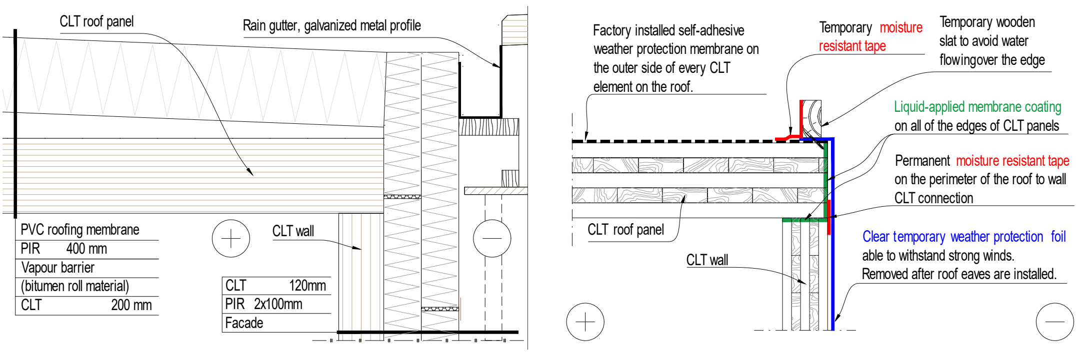

Fig. 11. Design drawing (left) of the roof to exterior wall connection and our proposal (right) of wetting mitigation practices.

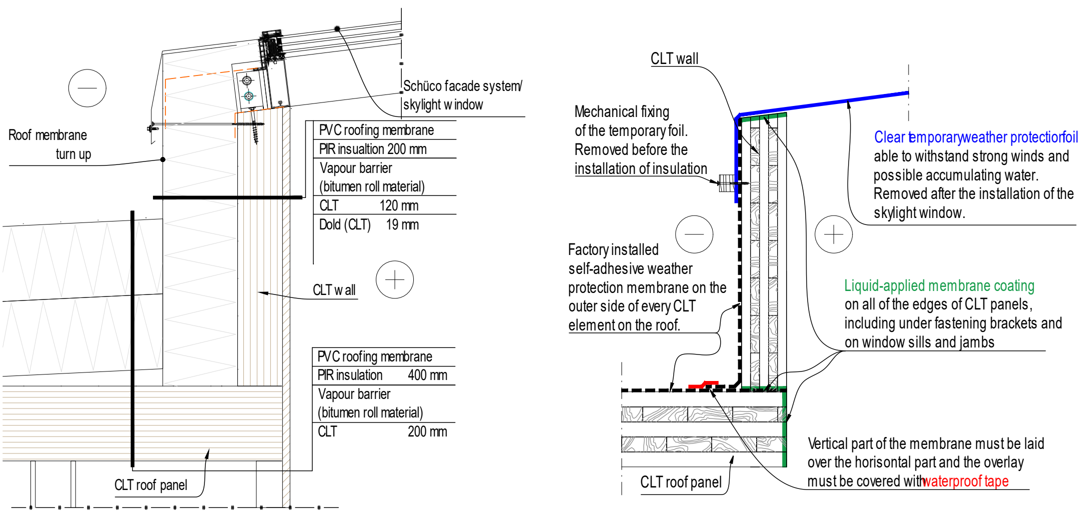

Fig. 12. Design drawing (left) of roof to skylight shaft connection and our proposal (right) of wetting mitigation practices.

4 Conclusions

We observed the construction process of a CLT building over the course of about four months from the installation of CLT panels to the installation of exterior wall insulation. We made five measurement rounds to measure the moisture content in 25 specific spots determined on the first observation round. We identified the joints where most wetting incidents occurred, and the measured moisture content was the highest. Our findings correlate with other studies and showed that the most sensitive area to wetting is the end-grain on the CLT panel. When it was exposed to drying it reached a low MC level (< 17 %) over time, but in structures where drying was prohibited, the MC remained within critical limits. Therefore, the most vulnerable section of the CLT structure is the foundation connection. Vulnerable joints are also the external wall and intermediate ceiling and roof connection and intermediate ceiling and window opening and intermediate wall connection, where the more water absorbing end-grain wood is exposed.

We suggest using liquid-applied membrane coating on the cut edges of CLT panels to protect the end grain. Additionally, we suggest protecting the horizontal CLT panels with self-adhesive membranes, and vertical CLT panels with temporary clear weather protection foils which can withstand strong winds. We provided drawings with specific descriptions of the wetting mitigation practices. These should be taken as general guidelines and should be adapted to every project specifically.

This research was supported by the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE (grant No. 2014-2020.4.01.15-0016) funded by the European Regional Development Fund and by the Estonian Research Council (grant No. PRG483), and by the European Commission through the H2020 projects Finest Twins (grant No. 856602) and NERO (grant No. 754177).

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PUBLICATION II

Kalbe, K., Kalamees, T., Kukk, V., Ruus, A., & Annuk, A. (2022). Wetting circumstances, expected moisture content, and drying performance of CLT end-grain edges based on field measurements and laboratory analysis. Building and Environment, 221, 109245. https://doi.org/10.1016/J.BUILDENV.2022.109245

Building and Environment 221 (2022) 109245

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Wetting circumstances, expected moisture content, and drying performance of CLT end-grain edges based on field measurements and laboratory analysis

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ARTICLE INFO

Keywords:
Moisture distribution
Dry-out
Moisture safety
Field study
Laboratory test

ABSTRACT

The moisture safety of cross-laminated timber (CLT) has gained attention as a result of feedback from construction sites and efforts have been made to protect CLT panel surfaces from wetting. However, the end-grain water absorption of CLT has often been overlooked. This study presents data from six CLT buildings where systematic moisture content (MC) measurements were made from when the CLT panels were installed until the commissioning of the buildings. Field measurement results were verified in a laboratory test where moisture uptake and moisture dry-out were monitored. On-site measurements showed that the wetting of CLT end-grain edges was common. Moisture absorption was detected in the end-grain edges in all the studied buildings and often MC > 25% persisted for many months until specific heating or drying was applied. Critical MC occurred after single rain events which suggests that a fast construction process is not always enough to avoid moisture ingress. Protection foils or membranes on the CLT panel faces did not help avoid end-grain wetting in the CLT joints. Protruding details such as floor panels or rubber bands under wall panels facilitated water intrusion. Areas with the CLT end grain exposed to ambient air experienced delamination post wetting. Laboratory test results confirmed very limited moisture dry-out in a typical CLT wall to floor joint but a potential to dry-out if the end-grain edges were exposed to dry and warm air. Specific methods to block water absorption into CLT end-grain edges should be used and joint detailing is crucial.

1. Introduction

The basic requirement for construction works on sustainable use of natural resources includes the use of environmentally compatible raw materials and the durability of construction works [1]. The use of wood for construction fulfils the first aspect well. However, in wet conditions timber is less durable than other materials (e.g., concrete, brick, steel) and special attention should be paid to moisture safety during construction process. There is a need to provide more information about the moisture relations of timber products such as cross laminated timber (CLT) and explain the causes of moisture intrusion in order to better protect timber structures from moisture. This need is illustrated by a recent Swedish survey where it became apparent that one of the main reasons not to select wood products for the construction of multi-storey residential buildings is a concern about mould and moisture [2]. Moisture has a key role in wood deterioration [3] and laboratory studies with fungi-inoculated CLT indicate that CLT is vulnerable to decay if it becomes wet and is contaminated [4,5]. Moreover, concerning results have also been published from field studies. Austigard and Mattsson [6] published fungal examination data from 11 massive timber buildings out of which 10 were CLT buildings. Five of the studied CLT buildings were under construction at the time of microbial sampling. Decay damage caused by brown-rot fungi was detected in two CLT buildings in the construction phase and in four CLT buildings in the use phase. In one of the decay cases detected during the construction phase, damage was found up to 2 cm into the CLT. Decay during the construction period is typically not expected because of unfavourable conditions, but the authors argued that the outside temperature was higher than usual during the construction period of this building, which could have provided suitable conditions for microbial growth. In addition, mould was

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https://doi.org/10.1016/j.buildenv.2022.109245
Received 4 March 2022; Received in revised form 27 April 2022; Accepted 25 May 2022
Available online 28 May 2022
0360-1323/

detected in four buildings in the construction phase and in two buildings in the use phase. The main causes listed for the microbial damage were water intrusion during the construction phase or constructional errors. Many fungi they detected were tolerant to low temperatures. This implies that moisture intrusion during the construction period is a high-risk factor for the durability of CLT, because other conditions for microbial growth might be present and are not readily adjustable (such as an unusually high temperature outside). A key takeaway from Austigard and Mattsson's [6] work is to avoid covering wet CLT surfaces with layers that inhibit moisture dry-out, because it poses a high risk of microbial growth. In another study where the construction of CLT buildings were monitored, and CLT exposure to bulk water was detected, the author reported that half of the 200 samples collected for microbial analysis had mould growth and about a third had moderate or severe mould growth [7]. Most of the wood surface moisture measurement points had moisture content (MC) of at least 19%. This is in line with other findings reporting that there could be a possibility of mould growth even in conditions when RH $<$ 80% [8] which corresponds to timber equilibrium MC of about 16% (calculated with equation 4-5 given by Glass and Zelinka [9]). Olsson [7] deduced that when exposing CLT to free water (e.g., not using weather protection), it is very difficult to avoid microbial growth on the panels. However, CLT buildings are often erected without weather protection and errors during construction happen. It is thus necessary to analyse the pathways of moisture intrusion. Previous case studies and on site monitoring have concentrated on CLT floor and roof panels [10–12] but rarely on CLT connection joints. Moreover, there are self-adhering membranes available on the market to protect both horizontal and vertical CLT surfaces from wetting [13,14] and thus the risk of wetting CLT faces can be minimised with existing solutions. Some of these products are also permeable to water vapour and therefore reduce the risks described by Austigard and Mattsson [6]. However, information about CLT end-grain moisture uptake and moisture intrusion pathways or about the means of avoiding end-grain wetting is scarce. CLT wall assemblies have been studied but with the focus on hygrothermal performance without contact with bulk water [15–18]. Most laboratory research including CLT exposure to bulk water has mainly concentrated on the wetting and drying of CLT faces where water contact or rain load have been subjected to the top or bottom side of the panels. Some studies have specifically excluded water absorption through the panel edges and thus the effects of end-grain wetting by sealing the edges with moisture blocking tapes, membranes or epoxy during the wetting or moisture uptake tests [19–22]. In other studies the end-grain or cut edges of floor panels have been exposed to water run-off, but the reported results have still focused on the panel faces with little data about moisture distribution in the vicinity of the end-grain edges [12,23,24]. Schmidt et al. [24] measured MC in the wetted panel in various locations but the measuring points nearest to the edges were ca 20 cm from the unsealed end-grain edge and about 10 cm from the half-lap connection. The results from near the half-lap connection showed high moisture gain and retention, even after 130 cumulative days of drying. The authors state that repeated wetting of end-grain joints when coupled with moisture trapping conditions could lead to moisture accumulation in the panel.

End-grain wetting could also be an issue in panel-to-panel joints where the connection is perpendicular. Occurrences of bottom edges of CLT panels being subjected to water contact have been reported previously [25]. Results from a long-term moisture monitoring study where one of the monitoring locations was near the CLT wall panel bottom connection showed that the lower locations generally peaked at slightly higher MCs and that vertical plies experienced higher MCs and slower drying than the horizontal ones [26]. In this study the authors also measured MC in the upper section of a shear wall where discontinuous measurements were taken 3.8 and 14 cm from the upper edge of the panel and these results consistently showed MC values approaching or exceeding the fibre saturation point. It seems that high levels of MC could concentrate into a small area near the end-grain edges. Moisture content cycling has been shown to influence the energy dissipation capacity of connection systems of CLT [27] and data about moisture distribution in a wetted joint could provide useful information about initial conditions for hygrothermal modelling or for risk assessment of connector performance as fastenings are often located on the bottom edges of vertical panels. Niklewski et al. [28] studied the moisture conditions of bridge timber members exposed to rain over the course of a 12-month period. They measured the highest MC levels in glue-laminated timber columns where moisture was absorbed via the bottom end-grain edge and reported that MC was rarely below 20% with a median of $>$27.5%. Albeit concerning, these results are not directly applicable to CLT which is typically used in heated buildings where the timber members are exposed to precipitation only during the construction period. Further investigation of the wicking effect of vertical CLT plies in connection joints could be useful.

One of the arguments of exposing CLT to the elements could be a fast construction process. Tengberg and Hagentoft [29] made a comprehensive risk assessment of CLT and they were convinced that in the Swedish climate any structure would be exposed to precipitation if not protected from the weather. Information about typical precipitation loads during the construction of various CLT buildings could be useful to assess whether the strategy of a fast construction process without weather protection is a valid option and if, then how fast it should be.

In order to address the issues described above six CLT buildings in Estonia were chosen for the analysis of moisture management throughout the construction period. An additional laboratory test was done to further investigate the findings from the on-site measurements. The aim of this study is to present:

- Information about precipitation amounts during the construction of various CLT buildings and an analysis whether fast construction alone is a plausible method to avoid critical levels of CLT moisture content during the construction process.
- Description about moisture ingress pathways into CLT end-grain edges at panel connection joints during the construction period.
- Expected MC in the critical/vulnerable joints with monitoring data about moisture dry-out temporal kinetics and the effect of moisture trapping conditions.
- Moisture distribution diagrams in the end-grain panel edges based on a laboratory test of one-week continuous water contact followed by a two-week moisture dry-out period in four distinct conditions.

2. Methods

2.1. Field measurements

2.1.1. Studied buildings and moisture measurements

The construction process was followed, and moisture content measured in six CLT buildings in Estonia (Table 1, Fig. 1). Most buildings had the entire load bearing structure and partition walls made of CLT with the exception of building A where there were additional pre-cast concrete walls and an existing laboratory hall to be renovated (excluded from the study). In each case the CLT panels were made out of Norway spruce lumber with the outer layers in the vertical direction (longitudinal wood grain in parallel to the height of the building). In building A, the outer two layers of the CLT panel were both in the same direction, but in all the other buildings the CLT layer composition was typical i.e. adjacent layers were always perpendicular to each other. In each case the wood was untreated, and the edges of the lumber boards were not glued together.

The construction sites were visited, timber MC was measured regularly, and the situation was noted as objectively and promptly as possible. The delivered CLT panels and packaging were inspected and gaps and/or faults in the material were looked for. On the installed panels signs of moisture (or moisture damages) – such as the presence of free water on the surface of the structures, stained wood, shrinkage or

Table 1
Characterisation of the studied buildings.

Building	A	B	C	D	E	F
Usage type	Educational	Administrative	Healthcare	Detached houses		
Year finished	2020	2020	2020	2020	2020	2013
City/Region	Tallinn, Harjumaa	Saue, Harjumaa	Kadrina, Lääne-Virumaa	Harjumaa	Harjumaa	Põlvamaa
Floors above ground	3	2	1	2	1	2
Above ground floor area, m^2	1695	1320	555	165	238	195
Insulation system of walls	MW[a] + vent. façade	PIR[a] + vent. façade	MW + vent. façade	PIR + vent. façade		CW[a] + vent. façade
Insulation system of roofs	VB[a] + PIR	VB + EPS[a]	VB + MW	CLT not used	VB + PIR	VB + EPS
Main CLT composition & thickness, mm	7-ply 240–260	3 & 5 ply 120–200	3 & 7 ply 120–220	5-ply 100		3 & 5 ply 100–140
Surface protection foils used	Yes	Yes	Yes	No	No	No
Moisture management	Moisture safety plan, regular inspection rounds, water removal, mechanical drying, cleaning, replacement of materials	Construction managed in the way of business-*as*-usual (no moisture management plan implemented, only casual moisture measurements and incidental water removal, in individual cases local mechanical drying).				

[a] MW = mineral wool, PIR = polyisocyanurate insulation panels, CW = cellulose wool, EPS = expanded polystyrene insulation panels, VB = vapour barrier.

Fig. 1. Photos of buildings A, B and C taken during the CLT installation phase. Photos of the detached houses are not shown due to privacy concerns. Building A was covered with a full coverage weather protection after CLT installation (A2).

swelling – were searched for. In most cases the construction process was observed until the commissioning of the building. The photos and videos of the construction process were saved and analysed later to pinpoint the most critical or typical moisture ingress areas.

Timber MC was measured according to the EN 13183–2:2002 [30] with electrical resistance-based wood moisture meters Gann Hydromette LG 3, Gann Hydromette CH 17 and Logica Holzmeister LG9 NG. All MC measurements were taken with 60 mm long Teflon insulated pins which had 10 mm uninsulated peaks making it possible to measure MC at different depths depending on how far the electrodes were rammed in. Different buildings had CLT panels with different layer (ply) composition (Table 1) and relative measurement depth varied among the buildings and measurement locations. MC was measured in the surface layer (5–10 mm deep) and in the inner (middle) layers (20–50 mm deep, mostly in the 2nd ply, in rare cases in the 3rd ply). The inner measurements were taken from the perpendicular plies (or horizontal plies in the case of wall panels) with the exception of building A where both outer layers of the CLT panels were in the same direction and thus were parallel to the panel length (vertical in the case of wall panels).

Some authors present MC values above 30% (≈ fibre saturation point) as equal to 30%, but the measured values in this study have been reported as they were. The MC readings above 30% are less accurate but indicate very wet wood. This information could be significant when discussing moisture dry-out because the actual mass of water in the timber is then certainly greater than the 30% value would indicate.

The procedure for the MC measurements on the field was as follows: 1) visual inspection of the entire building for wet areas; 2) MC measurements in all the visually wet areas; 3) MC measurements in nearby visually dry, but structurally similar areas. During each visit the procedure was repeated. The MC measurements were never taken from the same probe holes, but in close proximity in the same CLT panel. If more than one sample was taken from the same location during a visit, then only the result with the highest MC value was recorded. The number of visits and measurements varied among the buildings. In some cases, individual MC measurements were taken during other inspection rounds leading to the collection of only a few samples per visit. In other cases, the samples were collected only during dedicated CLT moisture inspection rounds which resulted in numerous samples per visit. Approximately 250 individual MC measurements were collected throughout the study from the different buildings and locations. The MC measurements in-situ were taken after the start of the water contact, which exact time is unknown and varied among the measurement points.

Preliminary inspection and first MC measurements showed that most often the wet area was in the vicinity of the CLT panel edges [25]. Therefore, the measurements were taken 30 mm from the panel edges in different connection joints and new measurements were taken at the same height but up to 100 mm from the original measurement to either left or right (Fig. 2). The samples were collected from different elements with similar conditions. The results for each specific area of interest were analysed together e.g., the MC measurement results for the wall panel bottom connection for a specific building included data from several measurement points throughout the building in structurally similar areas where wetting was determined.

2.1.2. Precipitation analysis

The precipitation load of the CLT buildings during the installation and subsequent (precipitation open) construction works were analysed. The installation time was defined as the time period starting with the unloading of the CLT panels on site and ending with the installation of the last CLT detail (typically a roof/ceiling panel or a top floor wall panel). Of the post-installation construction works the period when there were at least some parts of the CLT panels still exposed to precipitation were included. In building A the construction site was covered with full coverage weather protection (a temporary tent) and thus the "end" of the precipitation open construction works was regarded as the moment when all parts of the building were covered with a weather protection tent. In the case of other buildings, the CLT was typically without a protective tent or covering (at least partially) until the insulation layer was fully installed. In those cases the end of the precipitation open construction (considering CLT) was regarded as the end of insulation installation.

Precipitation data was gathered from the nearest weather stations. The average distance between a meteorological station and a studied building in the coastal area was ≈10 km (buildings A, B, D, E). The two buildings in the inland area (C, F) were both ≈ 23 km from the respective nearest meteorological station. Precipitation has a high spatial and temporal variability [31] and thus there was probably a disparity between the actual rainfall on the construction site and the absolute precipitation amount recorded in the meteorological station. However, in Estonia topography is overall rather similar (there are no large elevation differences, the highest peak is just over 300 m) and the chosen meteorological stations were in the same climatic area as the studied buildings. This gives a basis to assume that the frequency and general intensity of precipitation events over a longer period are similar in the nearby weather stations and on the construction sites and provide an insight of probable moisture load on the CLT.

2.2. Laboratory test of moisture uptake

2.2.1. Test setup and test specimens

A laboratory test was set up to verify the findings of the field measurements and study the moisture distribution in the CLT panels in a more detailed manner. The moisture uptake test was prepared based on initial knowledge gathered from the field measurements. More control over the samples and environment in the laboratory increases the statistical significance of the findings compared to the field measurements where unknown variables could influence the results. The test was based on the European standard EN ISO 15148 [32] which describes the procedure to determine the water absorption coefficient of a building material by partial immersion. Differently from the standard procedure side faces of the test specimens were not sealed and electrical resistance-based moisture measurements described in the following chapter were added. The results of the water absorption coefficient measurement have been published earlier by Kalbe et al. [33] and are not discussed in this article.

In preparation of the moisture uptake test a five-layer 100 mm thick CLT panel was cut into twelve 400 mm by 400 mm test specimens (TSs). The initial MC of the panel was ≈12% upon delivery. Liquid plastic coating (IKO MS Detail) was applied to three edges of the TSs to block moisture transfer through these surfaces (Fig. 3a). The bottom edge and side faces of the TSs were left untreated and completely open.

This imitated a CLT panel which would be exposed to free water from the bottom edge and moisture dry-out would only be possible through the bottom edge or through the side faces of a CLT panel. The TSs were stabilised in a controlled environment before the moisture uptake

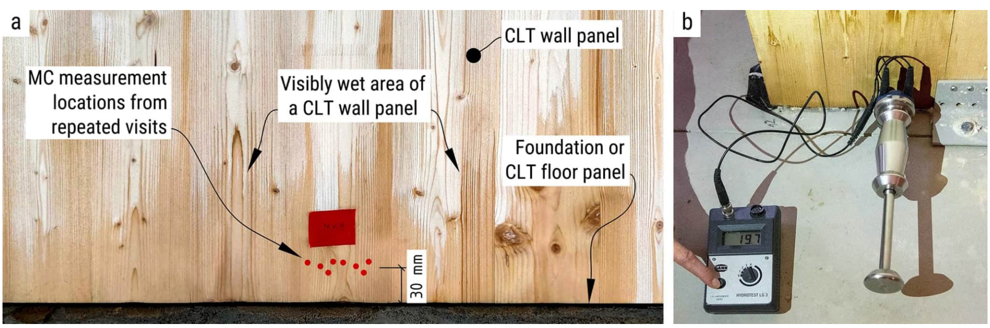

Fig. 2. Moisture content (MC) data collection method during the field measurements. All the MC measurements were taken approximately 30 mm from the panel edges (a) and measurement results from different locations, but with similar structural conditions (b) were later plotted together for a generalised assessment of the MC in the areas of interest.

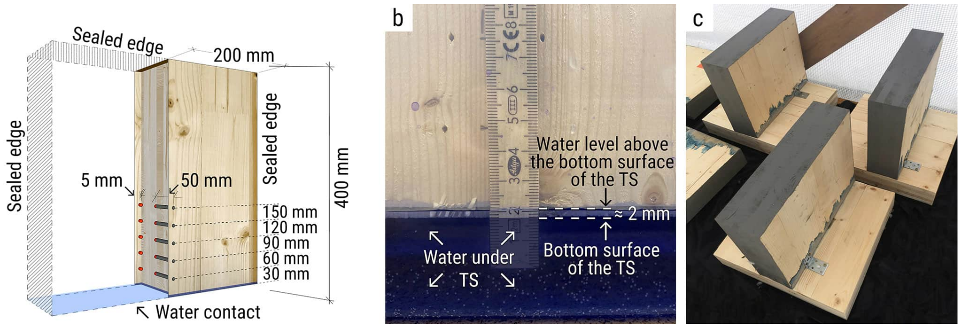

Fig. 3. A diagram of the test specimen (TS) with moisture measurement points shown (a), a TS submersed ≈ 2 mm into water (b) and TSs drying in the outdoor shelter (c).

analysis started.

The untreated bottom end-grain edges of the TSs were placed in containers with continuous water contact conditions for seven days. The water level in the containers was kept constant at about 1 mm–2 mm above the bottom level of the TSs (Fig. 3b) by regularly adding small amounts of water. Attention was paid to ensure that water contact remained constant, and that the TSs would be level regarding the water surface. The TSs were held in place by blunt pins which maximised the water contact and reduced possible surface effects at the contact plane. Blue ink (Parker Quink) was added to water to illustrate moisture transport in the CLT better. Parker Quink has been deemed suitable for staining fungal structures in mycological studies [34].

The TSs were held in water contact for 168 h in indoor conditions. Initial information from the on-site observations suggested that the moisture dry-out of CLT end-grain should be studied in at least four conditions: TSs in indoor and outdoor conditions with uninhibited moisture dry-out, and additionally with another CLT detail against the wet surface (moisture trapping conditions) (Table 2). The TSs were held in the aforementioned conditions for two weeks. The outdoor drying area was protected from precipitation but open to air movement (Fig. 3c).

The average water vapour pressure difference between the indoor air and the wet surfaces of the TSs (≈100% RH) was ≈1800 Pa which provided a good drying potential. Water vapour pressure difference between the ambient air in the outdoor shelter and the air directly at the wet TS surface was about 50 Pa providing a marginal drying potential.

2.2.2. *Moisture measurements and moisture distribution diagrams*

Moisture content (MC) measurements were made according to EN 13183–2 (2002) with Logica Holzmeister LG9 NG electrical resistance-based wood moisture meter (expanded uncertainty 0.8% for MC values between 12% and 22%) with 60 mm Teflon insulated pins with 10 mm uninsulated peaks. MC was measured at two depths from the side faces (5 mm and 50 mm) and at five height levels (30 mm, 60 mm, 90 mm, 120 mm, and 150 mm from the water level (Fig. 4)). The 5 mm deep measurements describe MC in the surface layer of the CLT and the 50 mm deep measurements describe conditions in the inner (3rd) layer of the 5-layer CLT. The electrode pins for the surface and inner layer measurements were rammed in from the opposite sides of the TS. The electrodes for the corresponding measurement layer were always inserted into the CLT perpendicular to wood grain (Fig. 4). The wood grain direction was the same in both layers with the end-grain part exposed to free water. MC measurements were performed daily throughout the test period from wetting (one week) to drying (two weeks).

Spatial moisture distribution diagrams were composed on the basis of the laboratory test data. For the gradual illustration of moisture distribution, linear interpolation was used to fill the datapoints between the measurement points (Fig. 4).

Table 2
Test conditions during the drying period of the laboratory test.

	Indoor conditions t[a] ≈ +21.6 °C (SD[a] = 0.8 °C) RH[a] ≈ 29% (SD = 5%)	Outdoor conditions t ≈ +2.1 °C (SD = 2.7 °C) RH ≈ 92% (SD = 5%)
Wet surface exposed to air	Group A (3 TSs)	Group B (3 TSs)
Wet surface against CLT (Fig. 3c)	Group C (3 TSs)	Group D (3 TSs)

[a] SD = standard deviation; temperature (t) and relative humidity (RH) were measured with a Hobo UX100-023 data logger with its external sensor about 0.5 m from the TSs (test specimens).

3. Results

3.1. *Field observation*

3.1.1. *Transportation, storage, and packaging of the CLT panels*

The CLT panels were delivered either on a flatbed trailer (with panels lying on the sides) packaged in foil but otherwise exposed to the environment (prone to wind influence or physical damage) or in a dry freight trailer (panels mounted vertically on a stand) entirely protected from the outside environment. The latter is a more moisture safe choice for transport, but no excessive moisture content after transport with either option was recorded. However, in some cases the transport timing was not ideal, and the CLT panels had to be stored on site (i.e., the transport of the panels was not *just on time*). Among other factors, the distance of a

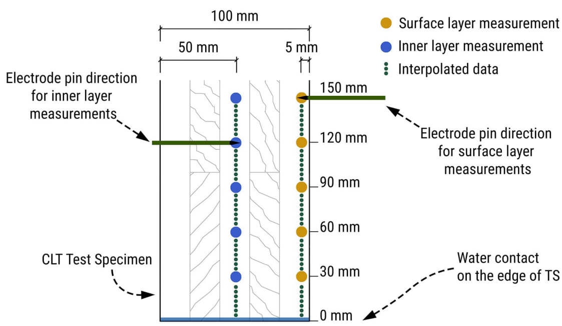

Fig. 4. Section cut from a CLT test specimen (TS) showing the measurement points and interpolated datapoints derived from the measurements.

building site and CLT factory could have influenced the timing of the transportation and installation works.

Field observations showed that if the CLT panels were stored on site, typical packaging did not prevent the wetting of the panels during interim storage (Fig. 5a). There were imperfections in the foil and water got into the package where it remained unnoticed (Fig. 5b). There were also damages (incisions, ripping, tearing) in the packaging foil of the installed panels (Fig. 5c), which in turn became entering points for precipitation. The opaque foils also inhibited the detection of wetting. Translucent protection foils facilitated faster response to occurred problems (Fig. 5d). In some cases the protective foils were installed on site, but such practice hindered the progress of other construction works and we documented incidents where the CLT panel was exposed to rain when the installation of the protection foils was still ongoing leading to moisture trapping under the foil (Fig. 5d).

3.1.2. CLT installation time and received precipitation amounts

Table 3 lists the cumulative precipitation amounts which the studied buildings experienced during the periods when the CLT panels were exposed to precipitation.

The installation of CLT panels in building A lasted for about 10 weeks and during this period there were frequent rain events (Fig. 6, building A). Many CLT details were continually exposed to precipitation after the initial installation until a full coverage weather protection tent was erected. The installation of CLT panels took three weeks in building B. Fortunately, this period coincided with a period of low rain amount (Fig. 6, building B). However, many of the wetting incidents covered in this article were documented during the three-week period. Moreover, it is probable that the wetting incidents happened over the course of the few days of heavy rain which occurred during the first half of the installation process (peak visible in Fig. 6, building B during September). The construction site of building B was not covered with a tent. Some CLT remained exposed to precipitation until the exterior envelope was entirely covered with insulation (polyisocyanurate boards with aluminium foil). There were frequent and heavy precipitation events during the 18-week period after the CLT installation (Fig. 6, building B) and several joints got repeatedly wet before the façade was finished. The installation of the CLT panels in building C lasted for five weeks and during this period there were several rainy days (Fig. 6, building C). Similarly to building B, the construction of building C continued without a full coverage weather protection.

The CLT installation periods were significantly shorter in the detached houses and consequently the precipitation amounts were smaller (Fig. 6, buildings D, E, F). The low precipitation amounts correlate with the low severity of wetting in these buildings. In building F, there was an extended period after the CLT installation when the construction works progressed slowly and unlike other detached houses the CLT was at least partially exposed to precipitation rather long.

3.2. Field measurements

3.2.1. Bottom edge of the CLT wall panel

The CLT wall panel bottom edge in the wall to foundation and wall to floor joints (Fig. 7a & Fig. 8a) proved to be one of the most critical areas. This was probably due to it being most exposed to wet conditions - most precipitation which landed on higher points flowed down the wall to this joint. The joint was also most susceptible to splashing water. The bottom edges of CLT panels had signs of water ingress in all the six observed buildings. A notable example of critical wetting occurred in building A, where rainwater flowed down on the wall panel exterior side (behind an opaque protection foil which probably had gaps or damages in it) and then under the end-grain edge of the panel (Fig. 7a). The floor panel protruded enough to facilitate water flow under the wall panel (Fig. 7b). The bottom part of the wall panel remained wet (MC > 25%) for over 6 months and prohibited the advancement of construction works.

The general principle of wetting (Fig. 7a) seems to have been the case

Fig. 5. Interim storage of CLT on-site (a) which proved to be inadequate and allowed water to enter the package (b). Problem detection was inhibited with opaque foils (a, b, c) but not with translucent foils (wall panels in photo d, however the roof panels were delivered without any protection and the on-site work to install the self-adhesive foil was time consuming and dangerous).

Table 3
Summary of the precipitation loads the studied buildings were exposed to.

	Cumulative precipitation amount (mm)					
Buildings	A	B	C	D	E	F
Usage type	Educational	Administrative	Healthcare	Detached houses		
During CLT installation	200	43	106	6	2	29
After CLT installation until all panels fully covered	75	292	77	8	33	200
TOTAL	**275**	**335**	**183**	**14**	**35**	**229**

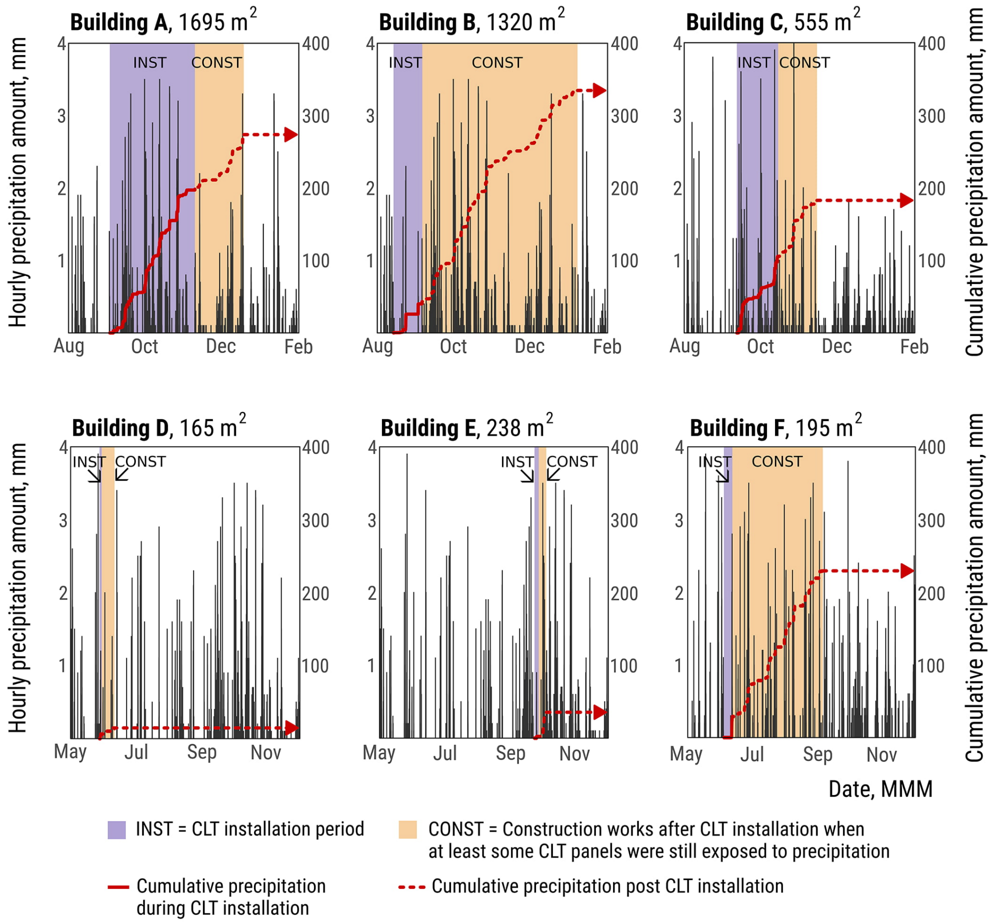

Fig. 6. Precipitation amounts during the construction of the observed buildings. A, B and C are non-residential buildings and D, E and F are detached houses.

in the foundation connection also where bitumen foil strips under the wall panels (Fig. 8) acted as the protruding surface which diverted the vertical downward water flow horizontally under the edges of the CLT wall panels.

It became evident that the bonding between the edges of the CLT panels and the bitumen foil was not ideal. Thin gaps and channels facilitated water flow under the panel.

Overall, MC measurements correlated with water stain marks (i.e., critical MC was not detected higher than 15 cm from the bottom edge). Thus, we concentrated on the monitoring of MC distribution and temporal kinetics at 30 mm from the bottom edges of the CLT wall panels on all floors. The moisture measurements showed that when the bottom of the CLT wall panel was exposed to free water (as described in Figs. 7a and 8a), the MC in the inner layers of the CLT increased well over 20% (with several points reaching fibre saturation) and remained at that level for months (Fig. 9). This occurred regardless of the protection foils installed vertically over the wall panels (Fig. 8c) or bitumen foil strips installed under the wall panels (Fig. 8b and c). The surface layers experienced a faster moisture dry-out.

In the case of building A, the wetting of the CLT wall panel bottom edges was detected during the weekly moisture safety round about three weeks after the installation of the specific panels. The MC had increased by the next inspection round and from that point onwards, regular MC measurements were made with attempts to cover the joint and apply

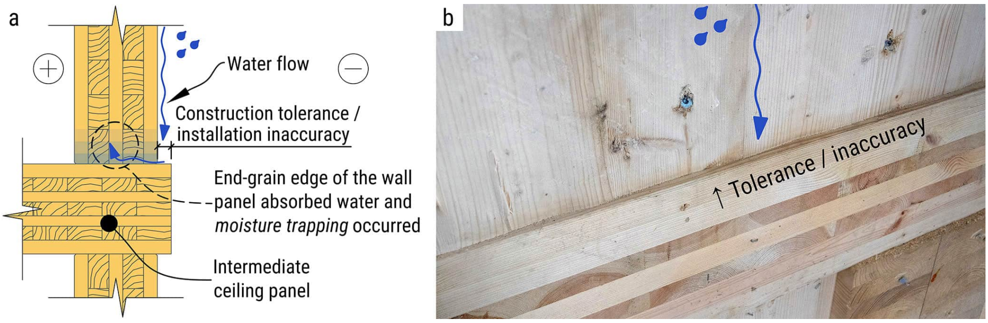

Fig. 7. CLT floor and wall panel connection joint (a) where the protruding floor panel (b) facilitated water ingress to the wall panel. Photo b is from building A.

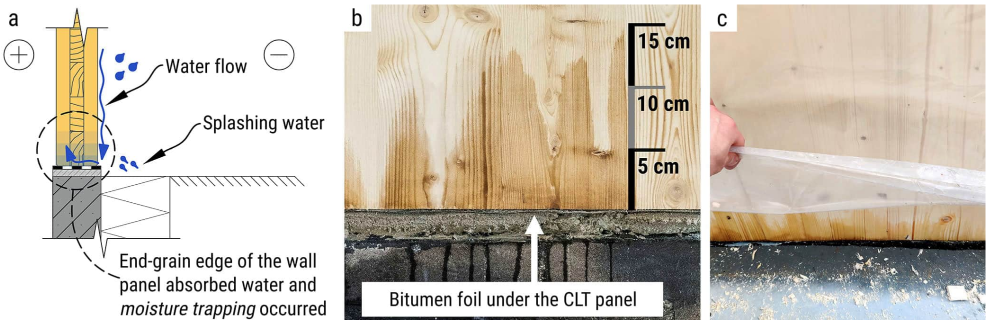

Fig. 8. CLT wall panel and foundation connection joint (a). The bottom edges of wall panels absorbed moisture despite bitumen strips under the CLT panels (b & c). Photo b = building B, photo c = building C.

local heating to dry the timber. However, the culprit of the wetting (the protruding edge of the intermediate ceiling panel, as described earlier in Fig. 7a) was unnoticed until a full coverage weather protection (a temporary tent) was erected and precipitation exposure was eliminated entirely. The wet area exhibited negligible moisture dry-out during the next five (winter) months (Fig. 9, building A) after which the general contractor started intensive mechanical drying (Fig. 10a) which proved to be effective. However, such wetting and subsequent drying resulted in large cracks in the CLT surface where the drying equipment was installed (Fig. 10b and c).

In building B the most critical wall panel edge wetting incidents occurred at the foundation connection where water penetrated the gap between the bitumen foil strip and CLT panels. There was no full coverage weather protection, but the 3-m-wide roof eaves and the progression of the insulation installation process lessened the water load on the walls. As soon as the windows were installed, portable air heaters and dryers were put to work and rooms were heated up to +15 °C. However, even after two and a half months in these conditions the MC (measured from the inside) was still over 20% in many points and reached up to 27% locally (Fig. 9, building B). Safe MC levels were achieved only after the building heating system was turned on.

In building C, similar wetting patterns as in buildings A and B were detected with MC reaching fibre saturation in several places at the CLT wall panel bottom connection. Casual measurements at higher points showed that MC seldom increased to critical levels at more than 100 mm from the bottom edge.

Buildings D and E were smaller detached houses where the installation of the CLT panels was a matter of days, and the insulation layer was installed shortly after. Nevertheless, numerous water stain marks were detected at the CLT wall panel bottom connection in building E. The stain marks were similar as in buildings B and C (Fig. 8), but MC over 20% was not detected (Fig. 9, building E) at the time of measurement (about a month after the start of the insulation installation). The CLT erection and following insulation layer installation took place during a short period with relatively low precipitation amounts (Fig. 6, building E), which could have contributed to a lower initial wetting amount. In building D only a few instances of water stain marks were detected at the wall panel bottom connection. Likewise to building E the duration of the CLT panel and insulation installation processes in building D was short and took place at a time of low precipitation amounts leading to an overall lower moisture load (Fig. 6, building D).

3.2.2. *Side edge of the floor panel*

In addition to water ingress to the wall panel bottom edge at the intermediate ceiling (floor) connection the wetting of the floor panel itself was detected in several studied buildings (Fig. 11). Loose hanging vertical foils did not provide sufficient protection against wetting. Casual measurements showed that compared to the wetting of the wall panel bottom edge, the side edge of the floor panel end dried out faster, however, not enough data is available for a confident statistic on this argument.

3.2.3. *Side edge of the roof panel*

Similarly to the intermediate ceiling (floor) panel the edges of the roof panels were exposed to precipitation in several studied buildings and temporary protection foils were not sufficient. Rainwater runoff was able to flow over the unprotected end-grain edges of the roof panels (Fig. 12). In some buildings the roof panels were installed at a slope which concentrated water flow to a single side of the building increasing the water load at that side. In the case of building A, the edges of the roof panels absorbed moisture beyond fibre saturation point. Unfortunately, this was discovered after the parapet wall was built. Thus, the moisture

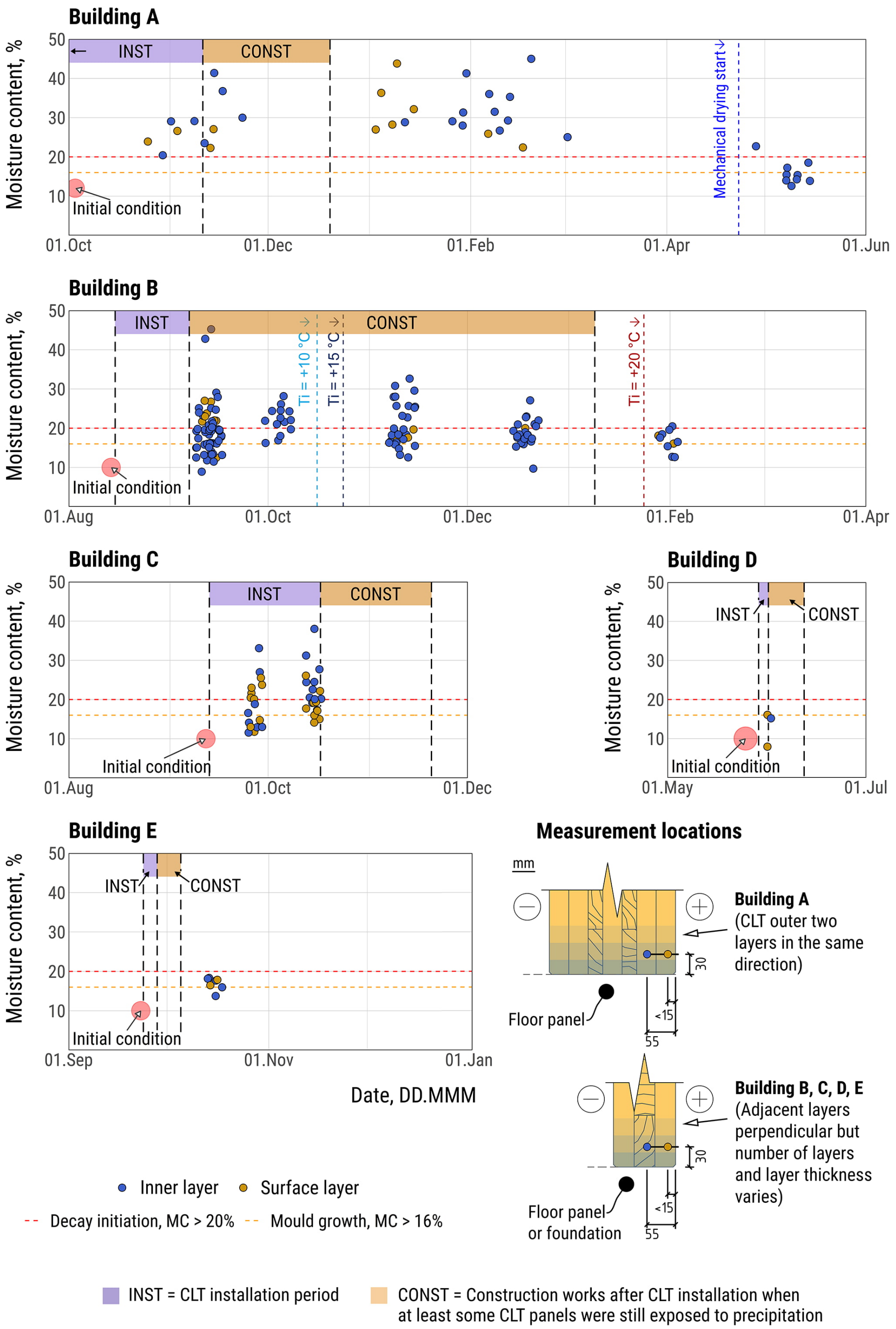

Fig. 9. Measured moisture content (MC) on the CLT wall panel bottom connection in five of the studied buildings. The initial condition circles mark the average range of CLT MC after leaving the factory (reported by the contractors).

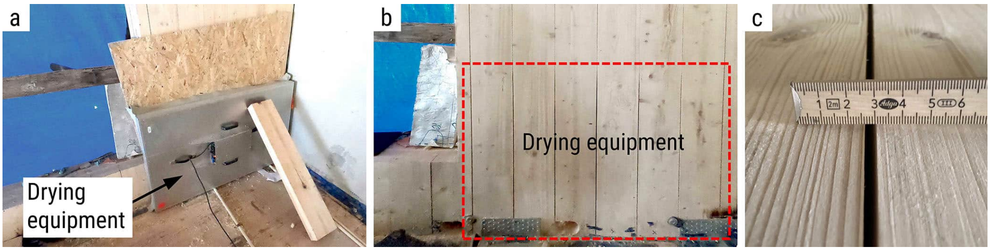

Fig. 10. Installed drying equipment (a) and large cracks visible (b, c) after moisture dry-out in building A.

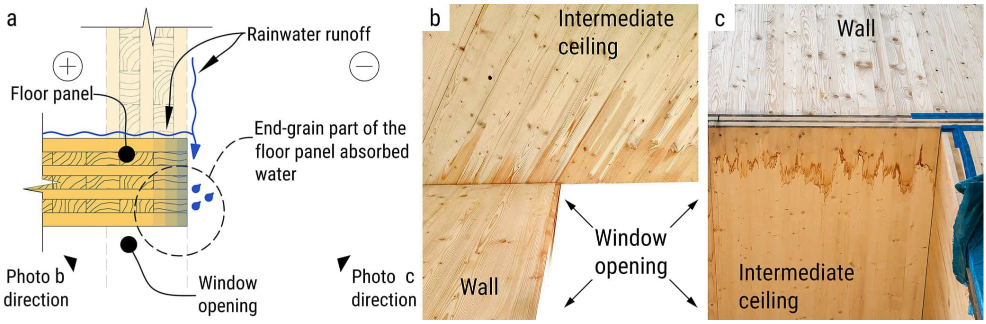

Fig. 11. CLT intermediate ceiling (floor) connection with a window opening (a), where frequent wetting occurred (b = building B, c = building F).

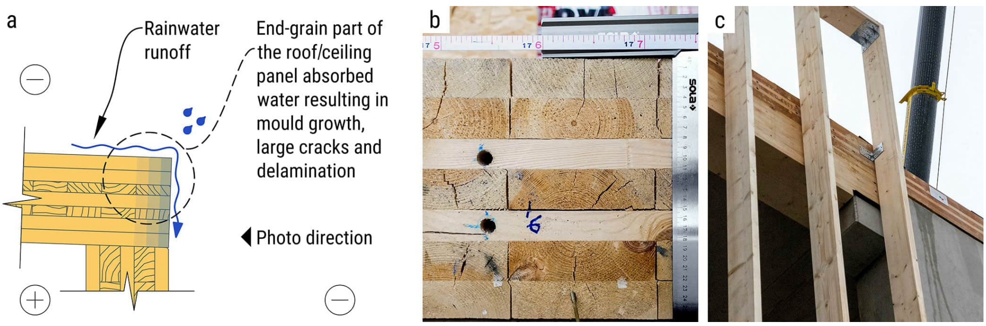

Fig. 12. CLT roof connection (a), where large cracks (b), delamination, and mould growth occurred after frequent wetting (c) and subsequent moisture dry-out. Photos of building A.

dry-out capability had been rather limited, and the MC remained elevated for long enough (Fig. 13) to facilitate microbial growth.

Fortunately, the ambient temperatures had been low (the construction took place during autumn and winter), but nevertheless an independent mycological examination was ordered by the general contractor. The examination [35] detected mould growth and blue stain fungi in different development stages. The parapet was disassembled, and local electrical heaters were used under a temporary cover to increase moisture dry-out. Subsequentially the edges of the CLT roof panel formed large cracks and delamination of the CLT layers occurred (Fig. 12b). This necessitated the use of additional diagonal screws to preserve the structural integrity of the wall to roof connection. This experience shows that the wetting of this joint is very critical.

3.2.4. *Wall window and roof skylight perimeter*

Window and skylight opening perimeter was also prone to wetting if not covered properly. The CLT end-grain edges were then fully exposed. In the case of windows, the bottom side of the opening became a horizontal plane for precipitation to land on (Fig. 14a). Without a protection covering the whole window or effectively sealing the end-grain edge, the bottom sill became an area which absorbed moisture beyond the fibre saturation point. Comparably to the wetting of the roof panel edges, the wetting of the skylight opening perimeters occured due to rainwater runoff flowing over the roof panel edges and through the skylight opening.

Both, the window and skylight opening perimeter were prone to delamination if excessive moisture ingress happened. Such occurrences were documented in buildings A and B (Fig. 14b and c). The suppliers of the CLT panels were different (originating from different countries) and thus the delamination was not considered to be the case of producer peculiarity, rather than being linked to excessive moisture ingress.

3.2.5. *Summary of the on-site findings*

Some type of end-grain wetting was present in every studied building

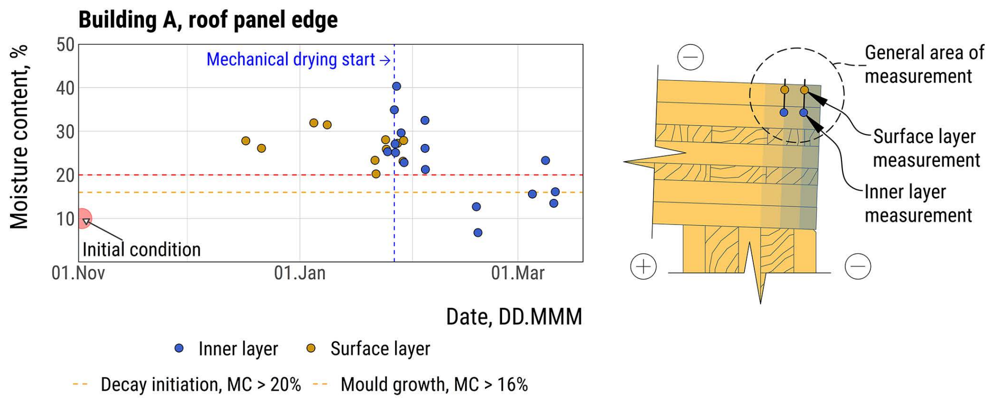

Fig. 13. Measured moisture content (MC) in the CLT roof panel edge in building A.

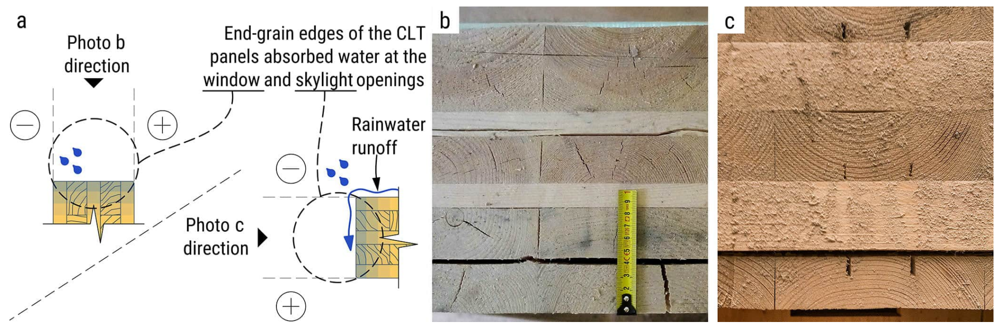

Fig. 14. Wall to window (b) and roof to skylight (c) connections (a), which experienced repeated wetting and where cracks and delamination occurred (b, c) after moisture dry-out (b = building A, c = building B).

Table 4
Overview of the on-site findings. Colours: wetting incident detected visually (wet, red) or not (dry, green). If not applicable or data not available (N/A), then grey.

Buildings	A	B	C	D	E	F
Bottom edge of CLT wall panel	Wet	Wet	Wet	Wet	Wet	Wet
Side edge of floor panel	Wet	Wet	N/A	Dry	N/A	Wet
Side edge of roof panel	Wet	Wet	Wet	N/A	N/A	Wet
Window or skylight perimeter	Wet	Wet	Wet	Dry	Dry	Wet

(Table 4). Larger buildings stood out with having examples of each type of CLT end-grain wetting addressed in this paper. Fewer incidents of CLT wetting in the detached houses D and E are explicable with their relatively short construction periods. In some cases, a specific type of wetting was not applicable – for example in the case of building D, there was no roof panel which could have got wet or in the case of buildings C and E there were no intermediate floor panels.

3.2.6. Laboratory measurements and moisture distribution in CLT end grain edge

The results of the seven-day wetting period of the laboratory test showed that MC increased during the first three days and then plateaued at ≈ 30% in the surface layer and at ≈ 25% in the inner (middle) CLT layer at the 30 mm mark from the water level.

At 60 mm and more from the water level there was only a slight tendency of increasing MC in the inner layer. The average MC (of all the test specimens) in the inner layer at 60 mm from the water level did not reach 15% after seven days of continuous water contact. In the surface layer there was a general tendency of MC decreasing at higher measurement points. The equilibrium MC corresponding to the laboratory conditions (average temperature +21.6 °C, average RH 29%) was ≈6% (calculated with equation 4-5 given in Ref. [9]) and thus the decrease of MC on the surface level was expected. The overall average MC at 60 mm from the water level in the surface layer did not exceed 20% MC.

From the measurement results moisture distribution diagrams were put together at distinct phases of the test. In Fig. 15 there are charts with average MC values from all twelve TSs throughout the seven-day water contact period and a moisture distribution diagram corresponding to the measurement results from the last day of the wetting period. MC in the inner layer did not increase over 15% at 60 mm or more from the water contact surface. However, MC was substantially higher nearer to the water level and was over 25% (i.e., probably at fibre saturation) at the 30 mm mark.

In Fig. 16 there are moisture distribution diagrams describing the situation after the two-week drying period. The TSs were divided into four groups (Table 2) by the drying conditions (indoor and outdoor environment in combination of uninhibited moisture dry-out and moisture trapping conditions). Moisture dry-out was most effective in indoor environment when the wet edges of the TSs were in direct contact with indoor air (equilibrium MC ≈ 6%) (Fig. 16). In the outside shelter, the equilibrium MC was ≈22% (average temperature +2.1 °C, average RH 92%) and thus the surface layer of all the TSs which were put in outside conditions experienced an increase in MC. The moisture dry-out was negligible in the inner layer for all the TSs in outside environment. Moisture dry-out in the inner layer was also hindered by the added CLT

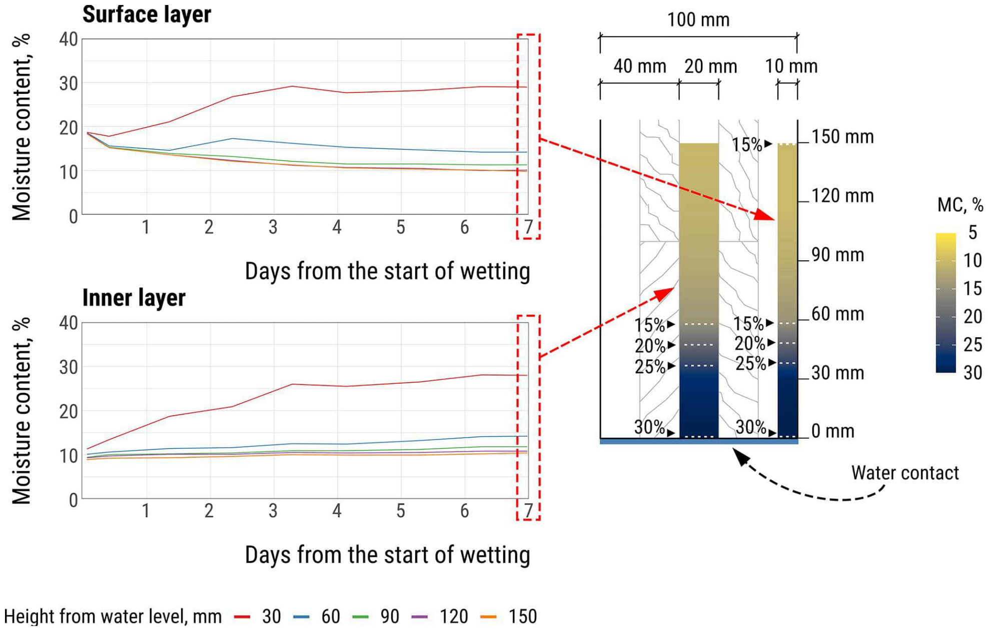

Fig. 15. Average measured moisture content in the CLT test specimen surface and inner layers (left) during the 7-day water contact period and a moisture distribution diagram interpolated from the datapoints of the last measurement.

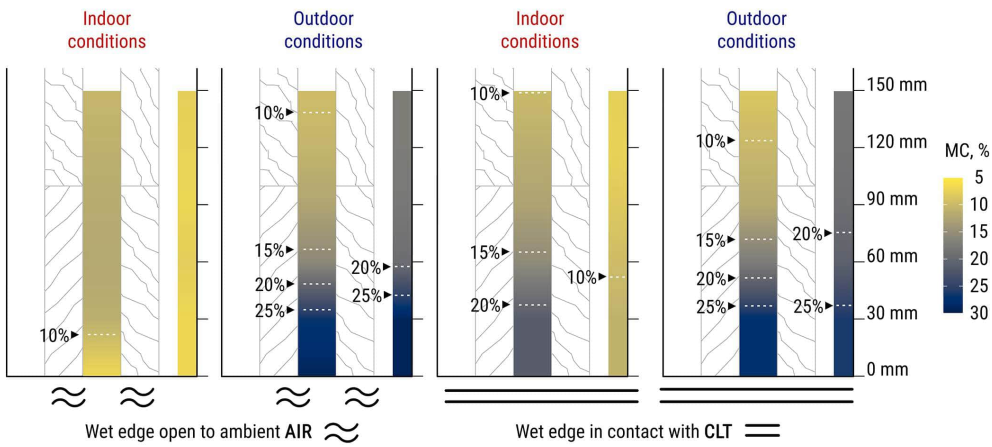

Fig. 16. Moisture distribution diagrams interpolated from the measured data after two weeks of drying.

detail in both indoor and outdoor environment. The MC in the bottom 30 mm was over 20% and 25% respectively (Fig. 16) when the conditions were unfavourable. After the two-week drying period in the indoor conditions the MC in the inner layer at 30 mm from the bottom in the TSs with moisture trapping conditions was on an average 10.3% higher than in the TSs with open edges (21.5% vs 11.2% correspondingly). For the TSs left to dry in the outside shelter the corresponding difference in MC was negligible and high in both cases due to the unfavourable ambient conditions.

The blue ink which was added to water in the wetting stage illustrated moisture transport well on the CLT surface and reflected the electrical resistance-based MC measurement adequately. It also demonstrated the heterogenic properties of wood (Fig. 17). Larger water stain marks did not rise above 130 mm in any test specimens during the seven-day wetting period, but there were a few instances where faint stain lines were visible higher up in the cracks and ply joints. Overall, the stain marks on the TSs correlated with the visual data gathered from on-site observations.

4. Discussion

A fast construction or installation process is often regarded by contractors as a (sole) way to avoid critical levels of CLT moisture content during the construction period. However, it is not clearly defined what a

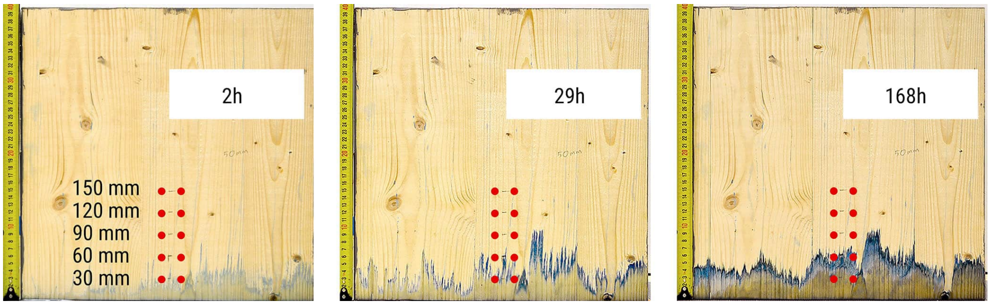

Fig. 17. Photos of TS № 20 over the course of the wetting stage at 2, 29 and 168 h. Blue ink was added to the water which left visible stain marks on the wood surface. Red dots mark the MC measurement points at different height from the bottom of test specimen. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fast-enough process is. Tengberg and Hagentoft [29] presented an anticipated construction time schedule for a CLT building with 18 apartments where the total time from transportation to the completion of facades was 15 weeks for the short schedule and 30 weeks for the long schedule. While the CLT surface area or the floor area of the case study building was not clearly specified, it can be estimated that the general volume of construction works would be similar to the non-residential buildings A and B in our study which above ground floor area was 1695 m^2 and 1320 m^2 respectively and to a lesser amount similar to the building C which had an above ground floor area of 555 m^2. The total construction time with CLT panels exposed to precipitation was 15, 21 and 9 weeks respectively in our studied non-residential buildings. The total duration of the precipitation open period was relatively short for building A because a temporary weather protection tent was erected. Otherwise, the period the construction was exposed to precipitation would have been much longer. Nevertheless, there were several wetting incidents, with severe consequences. The installation time of the CLT panels was significantly shorter for the detached houses, but we still detected signs of moisture ingress, albeit the MC levels had decreased by the time of our visits. There is a correlation between the severity of wetting incidents and the cumulative precipitation amount which in turn is related to the construction time (Table 5). However, it is not clear which time period could be regarded safe or short enough. As the example of the building B illustrates – many severe wetting incidents probably happened over the course of just a few days (intensive rain event visible in Fig. 6 for building B in early September) and not only the installation time, but also the period after the CLT installation is crucial and wetting due to precipitation could happen until all CLT details are covered with additional insulation and façade materials.

When detached houses are constructed, it could be plausible to choose a dry period of a few days to install the CLT elements, but a full coverage weather protection or specific local weather protection must be put to use immediately after the installation. Such a strategy is however not plausible with larger buildings. The study indicates that the installation period would probably be long enough for the CLT to get into contact with bulk water (caused by precipitation). This finding is in correlation with the conclusions presented by Tengberg and Hagentoft [29] and the results further emphasise that when CLT structures are exposed to precipitation there is a high probability of high moisture content and moisture uptake especially from the end-grain edges. It is thus sensible to protect the CLT details from precipitation throughout the entire construction process.

The results indicate that it is very important to protect the end-grain edges of CLT panels in addition to surface protection. In several studied buildings the CLT faces were protected with temporary protection foils or permanent self-adhering membranes. However, the end-grain edges were mostly unprotected and unfortunately the risk of moisture uptake from these edges realised in all the six studied buildings. The surface protection measures were not functional in protecting the end-grain edges. The most critical areas to end-grain wetting were the bottom edges of vertical panels, but damages related to excessive wetting such as delamination occurred also elsewhere. The ensuing risk from the initial wetting is even higher given that the results showed persistent high moisture content (≈30%) deep in the CLT panels which well exceeds the threshold level for biodegradation. Olsson [7] found microbial growth in CLT buildings under construction when the wood surface MC was at least 19%. The risk of microbial growth between an interior drywall and the load bearing CLT or even decay of the CLT is very high if such wetting goes unnoticed [6]. This also emphasises the need of on-site moisture management. A moisture safety plan and regular moisture inspection rounds were present only in building A, where also many wetting incidents were reported. It is debatable whether all these would have been noticed if the construction process were managed in the way of business-*as*-usual. Nevertheless, It became evident that regular moisture safety rounds were useful regardless of the protection methods implemented.

Liisma et al. [36] did a polygon test with CLT elements and reported that when measuring with 80 mm long electrode pins (that is including the moisture in deeper layers) from the end-grain edges of horizontally placed panels the precipitation exposed CLT details took over a month to dry below 17% MC. However, the authors of this research did not specify in which conditions the drying took place. Our study suggests vastly longer drying times and moisture stagnation in actual construction details, especially when the ambient air does not provide good drying conditions. Schmidt et al. [24] argued that end-grain wetting (of horizontal panels) was primarily an issue when moisture trapping conditions occurred and indicated that areas near exposed end-grain dried relatively quickly. However, our study revealed that end-grain wetting could still be a problem even when the wet end-grain edge of the CLT panel was exposed to the ambient air. We detected several post-wetting delamination incidents specifically in the areas exposed to air (e.g., at window or skylight perimeters). Schmidt et al. [24] indicated that moisture retention was present in the half-lap joint which exhibited

Table 5
Summary of the on-site study. Relation of wetting incidents and precipitation amounts. Colours: wetting incident detected (yes, red) or not (no, green).

Buildings	A	B	C	D	E	F
Above ground floor area, m^2	1695	1320	555	165	238	195
Surface protection foils used	Yes	Yes	Yes	No	No	No
Total precipitation exposed time, weeks	15	21	9	2	2	13
Total precipitation amount (mm)	**275**	**335**	**183**	**14**	**35**	**229**
Critical end-grain wetting	**Yes**	**Yes**	**Yes**	**No**	**No**	**Yes**
Some end-grain wetting	Yes	Yes	Yes	Yes	Yes	Yes

moisture trapping conditions. During our field study we detected many wet end-grain edges specifically in joints where moisture trapping conditions were present and similarly the MC remained high even after lengthy periods without additional water contact. The laboratory test confirmed that even after two weeks in warm and dry indoor environment MC remained over 21% in the bottom part of the wetted CLT wall panel if the panel was installed against another CLT detail.

Kalbe, Kukk, and Kalamees [25] presented a concept of mitigation practices to avoid wetting of CLT when installed without full coverage weather protection (such as a temporary tent) and a part of it was using liquid applied membrane coating on the end-grain edges of CLT panels. The usage of such methods could perhaps have prevented the high MC levels reported in our study, but further investigation of suitable protection methods is necessary. It was however evident that a rubber band or a similar solution was not functional in protecting the timber from end grain moisture uptake.

The laboratory test confirmed the findings from the on-site measurements and indicated that moisture dry-out from a wetted CLT end-grain is negligible when the ambient conditions are not favourable even when the wet surface is exposed to air. The average outdoor temperature from September to December in the Estonian moisture reference year [37] for mould calculations is 2.9 °C (SD = 7.6 °C) and the respective average RH is 90% (SD = 8.3%) and for the period from January to the end of April the respective averages are 1.5 °C (SD = 5.9 °C) and 81% RH (SD = 17.1%). These values are comparable to the outdoor conditions in our test and thus we deduce that in Estonia (or in regions with a similar climate) it is not feasible to wait for moisture to dry out from the CLT if end-grain moisture wicking has occurred. This is well in correlation with the on-site measurements where in many cases the moisture dry-out did not happen before additional heating or mechanical drying was applied. In addition, regarding to the photos taken of the test specimens during the laboratory test, it is also visible that moisture migration on the very surface of the CLT is faster than in deeper sections of the CLT and stain marks are visible within hours from the start of the water contact. Although, the absorbed water amount could be small in the first hours and timely moisture dry-out could be possible if the water contact remains short, there could be consequences to the aesthetics of the panel even with the short-term water contact. The analysis of water migration on the extreme surface layers is delicate and the methods used in the current study are quite limited for further analysis.

Laboratory measurements with the test specimens which exhibited moisture trapping conditions (CLT wall to floor connection mock-up, Fig. 3c) indicated a very slow moisture dry-out both in the outdoor shelter and in warm and dry indoor environment. The two-week drying period was perhaps too short, but nevertheless indicated the limitedness of the moisture dry-out capability of CLT connection joints. Furthermore, a two-week halt in construction works to dry the wet joints could lead to unnecessary expenses and delays, but the laboratory test indicated that even this period in combination with a good drying capacity would not be enough to dry the inner layers to safe MC levels. Applying mechanical drying and air heaters to speed up the moisture dry-out could lead to excessive crack formation as was shown in the case of building A (Fig. 10). This in turn can significantly weaken the airtightness of the building envelope [38]. Future research is needed to provide information about the maximum allowable MC at which point the crack formation is still within acceptable limits, and whether the increased crack formation due to wetting has any effect on the air tightness of the structure.

A limiting factor of the laboratory study is that both the surface and inside layer MC measurements were taken in the lamellas with the same grain direction, but for a comprehensive analysis it would have been useful if MC measurements would had been taken in the layer perpendicular to the bottom side also. Comparison of the MC measurements from one building to another in the field study was somewhat hindered due to the difference in CLT panel composition among the studied buildings.

Although the end-grain capillary water absorption of CLT has been somewhat overlooked, there are papers concerning the capillary moisture uptake of ordinary wood. Research which has specifically focused on the moisture distribution in end-grain wood has comprised more accurate measurement methods such as computer tomography scanning [39,40]. Sandberg and Salin [39] put Norway spruce specimens in 5-mm-deep water for end-grain sorption. Their results show that after seven days of water contact the highest MC was a few millimetres into the wood and that on an average the MC levelled out to the initial values at around 60 mm from the water contact surface. Our laboratory test results correlate with this quite well, although the tested specimens were rather different. Our measurements did not differentiate heartwood and sapwood as the more specific studies do. Johansson and Kifetew [40] illustrated the differences and their measurements showed that after a nine day wetting the MC in the pine sapwood did not increase higher than 150 mm from the water level, whereas in the heartwood the largest increase in MC was up to around 25 mm and then decreased rapidly.

The results indicate that although the end-grain moisture uptake is crucial, the problem remains localised. This is important to keep in mind when planning moisture measurements, but also might help with planning the works to remedy moisture damages.

5. Conclusion

The construction process of six CLT buildings, both larger non-residential buildings and smaller detached houses was studied from the moisture safety perspective and a complementary laboratory test was carried out to analyse the end-grain moisture uptake of vertical CLT panels. The findings corroborate with other research in that moisture ingress during the construction period is very difficult or impossible to avoid in CLT buildings when constructed without local or full coverage weather protection. There was some wetting of the end-grain joints in each of the studied buildings. In four buildings (out of six) there were either moisture related damages (such as delamination or mould growth) or the measured MC remained high for months (over 20% MC up to six months and over 25% MC up to four months).

The study shows that if CLT is exposed for a long time (i.e. during a typical installation and subsequent construction period), there is sufficient potential for precipitation and thus moisture ingress. It is not feasible to rely on a fast construction process, i.e., current CLT construction methods are not fast enough to erect and fully cover and seal each CLT surface and joint of a multi-storey building in a matter of a few days. The shortest precipitation exposed time was two weeks for the detached houses and nine weeks for the larger non-residential houses. For the 1320 m^2 administrative building the precipitation exposed time reached 21 weeks. The total precipitation amounts in the studied buildings ranged between 14 mm and 335 mm but was over 180 mm in all the non-residential buildings. End-grain wetting was also detected in the detached house with only 14 mm of total precipitation. Even short-term wetting could cause problems due to staining of the CLT or when moisture stagnation in the CLT connection joints occurs.

Unfortunately, it became apparent that typical CLT transport packaging might not protect the panels from wetting during intermittent storage and the packaging might also inhibit the detection of wetting. Nevertheless, covering the CLT panels in packaging foil is necessary to protect the CLT faces, but there is room for improvement.

The end-grain joints are highly critical as they wick moisture and often there are moisture trapping conditions involved which inhibit the moisture dry-out. There were instances where excessive moisture (MC > 25%) did not dry out even months after. Moisture dry-out was only possible via additional help from air dryers and heating. However, this led to larger cracks in the faces of CLT panels. In other areas where end-grain wetting occurred but the surface was exposed to ambient air, the delamination of CLT boards was detected.

The laboratory test confirmed the findings from the field study. MC plateaued on about 25% in the inner (middle) CLT layer at 30 mm from the water level after three days with water contact. Water contact was stopped after one week and by that time MC had not increased over 15% at 60 mm or more from the water level in the inner CLT layer, which implies that if end-grain wetting is of interest, then MC measurements should be done in the close proximity of the edges of CLT panels. After the two-week drying period, it became apparent that when vertical CLT panels wick moisture from the bottom edge and if the moisture dry-out conditions are unfavourable (low temperature or the end-grain edge is against another CLT panel), the moisture dry-out is negligible. However, there was a good drying potential when the end-grain edge was exposed to warm and dry air. As the on-site study showed excessive cracking when drying with warm air, it is up to future research to determine safe maximum MC levels regarding crack formation.

The present study clearly demonstrated that the CLT end-grain edges must be protected from moisture and further research is necessary to provide time and cost-effective methods for a comprehensive CLT moisture management when full coverage weather protection is not used.

CRediT authorship contribution statement

Kristo Kalbe: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Targo Kalamees:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Villu Kukk:** Writing – review & editing, Investigation. **Aime Ruus:** Writing – review & editing, Investigation. **Alvar Annuk:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has received funding from the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE (grant No. 2014-2020.4.01.15-0016) funded by the European Regional Development Fund, by the Estonian Research Council (grant No. PRG483), Moisture safety of interior insulation, constructional moisture and thermally efficient building envelope, and by the European Commission through the H2020 project Finest Twins (grant No. 856602). Arcwood by Peetri Puit OÜ is acknowledged for the delivery of the CLT panels for the laboratory study.

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PUBLICATION III

Kalbe, K., Pärn, R., Ruus, A., & Kalamees, T. (2024). Enhancing CLT Construction – Hygrothermal Modelling, Novel Performance Criterion, and Strategies for End-Grain Moisture Safety. Journal of Building Engineering, 111411. https://doi.org/10.1016/j.jobe.2024.111411

Journal of Building Engineering 98 (2024) 111411

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Enhancing CLT construction – Hygrothermal modelling, novel performance criterion, and strategies for end-grain moisture safety

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ARTICLE INFO

Keywords:
Hygrothermal performance
Anisotropic material properties
Building simulation
Moisture management
Mould growth prevention
Wood building
Climate resilient building

ABSTRACT

This study validated a 2D dynamic anisotropic hygrothermal simulation model for Cross-Laminated Timber (CLT), focusing on vertical water uptake and moisture dry-out processes. The simulations, compared against experimental data, showed a root mean square deviation of ≤3.3 across all locations. Variations in material properties necessitated the use of multiple material definitions. Moisture storage and liquid conductivity function had a significant impact on the results. A new two-step moisture content (MC) performance criterion was developed: MC ≤ 16 % at 30 mm and MC ≤ 25 % at 10 mm from the end grain to prevent mould growth. Sensitivity analysis suggested that validating $MC_{30\ mm}$ is reasonable when $MC_{10\ mm}$ exceeds 19 %. The criterion was applied to analyse moisture management strategies for CLT end-grain moisture safety. Simulations with 30-year climate data indicated a slight decrease in successful outcomes in recent years. Strategic installation timing, particularly favouring the spring season due to its relatively drier conditions in Estonia, was found to be highly beneficial. CLT end-grain protection or full-coverage weather protection is recommended to ensure a high level of moisture safety, and long construction periods should be avoided even with full-coverage protection. Including moisture dry-out periods before covering CLT is advised. However, unassisted dry-out is feasible only during spring (up to four weeks). Additional equipment is necessary for timely moisture dry-out during other seasons, including summer, due to higher precipitation loads. The use of anisotropic 2D hygrothermal simulations proved to be practical in enhancing CLT resilience to moisture-induced damage.

1. Introduction

1.1. Moisture safety of CLT end-grain surfaces

Research regarding moisture safety of cross-laminated timber (CLT) has mainly concentrated on the hygrothermal performance of the plane surfaces of CLT panels and moisture transfer through these surfaces (such as the faces of CLT walls or floor panels). For example, Kukk et al. [1,2] conducted laboratory tests with CLT walls and applied hygrothermal modelling and stochastic analysis to develop design criteria for the faces of CLT wall panels, specifically the limiting moisture content (MC) for the internal and external surfaces of CLT wall panels. The researchers, however, did not include water uptake from the end-grain surfaces of CLT wall panels.

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https://doi.org/10.1016/j.jobe.2024.111411
Received 9 July 2024; Received in revised form 30 September 2024; Accepted 23 November 2024
Available online 26 November 2024

Some studies of CLT moisture safety have specifically excluded the effects of end-grain wetting by sealing these surfaces [3–6]. In a similar vein, CLT wall assemblies have also been studied, primarily focusing on hygrothermal performance of the panel centre areas [3, 5–17]. The research has contributed to advancements in moisture safety regarding CLT faces, with several moisture protection products becoming available – for instance, self-adhering membranes for CLT floor panels which effectively block liquid water ingress while exhibiting a relatively low vapour resistance [18,19].

However, moisture safety analysis focusing on the end-grain wetting is lacking. There are only a few studies where this topic has received attention. Those studies mostly concern floor panels, where among other areas of study end-grain surfaces were exposed to water run-off, but the results have still primarily focused on panel faces [12,13,20]. Schmidt et al. [20] measured MC in various locations of wetted panels, with measuring points approximately 20 cm from the unsealed end-grain edge and 10 cm from the half-lap connection. The results near the half-lap connection indicated a notable moisture gain and retention, even after 130 cumulative days of drying. The authors pointed out that high MC (approaching or exceeding the fibre saturation point) can be observed in a small area near the end-grain surfaces of CLT panels and that repeated wetting of end-grain joints, combined with moisture-trapping conditions, could lead to moisture accumulation in the panel. This implies that there is a high risk associated with end-grain wetting of CLT panels and that research should concentrate on the small area near the end-grain surfaces. End-grain wetting could also pose a problem in panel-to-panel joints where the connection is perpendicular. A long-term moisture monitoring study by Schmidt and Riggio [21] showed that MC in the lower locations of a CLT wall panel bottom connection generally reached higher values. Vertical plies exhibited higher MC and slower drying rates compared to horizontal plies. This indicates that anisotropy of moisture transfer in timber should also be taken into account. Kalbe et al. [22] investigated vertical moisture uptake of six CLT structures during the construction phase, discovering that high MC (over 25 %) could occur in CLT buildings during the construction process prior to commissioning. The study showed that if CLT panels are exposed to precipitation during a typical installation and subsequent construction period, there is sufficient potential for moisture ingress. The end-grain joints were identified as highly critical as they wick moisture due to longitudinal wood fibres exposed to bulk water. Moisture trapping conditions occurred often, and the surrounding climate conditions were not favourable for moisture dry-out during the construction period. Moisture content levels remained high for a long time, causing delamination and mould growth. This highlights that moisture safety of CLT end-grain surfaces is a critically important topic and that the area near the end-grain surfaces should receive greater attention in moisture safety analysis and planning. There are solutions proposed to improve moisture safety of CLT construction and avoid end-grain wetting [23] but the performance of the solutions needs to be assessed.

1.2. Challenges in hygrothermal simulations regarding CLT end-grain wetting and dry-out

Hygrothermal simulation can be a useful tool to assess moisture uptake, distribution and dry-out in the CLT panels. However, modelling of CLT end-grain joints poses some challenges. CLT comprises timber boards with perpendicular wood fibres in each layer so that during liquid water absorption from the bottom end-grain surface of the CLT panel, there will be A) layers where the water uptake occurs longitudinally and B) layers where it will occur either radially or tangentially (or commonly transverse). At the same time there will be moisture redistribution in and between the layers. Furthermore, moisture dry-out will occur on the side surfaces of the CLT towards the surrounding environment if the side faces remain unexposed to bulk water. This means that there will be simultaneous moisture transport in various directions through wood layers with different fibre direction. Likewise, there will be moisture transport in various directions in the same wood layer (e.g., water uptake along the grain in the outermost layer and simultaneously water vapour transport perpendicular to the grain from the surface of the same layer). Thus, the moisture transport model needs to vary the material properties depending on the moisture transport direction, i.e. the model must reflect anisotropic variation of the material properties.

Most studies regarding hygrothermal simulations of CLT moisture safety implement one-dimensional (1D) models. In 1D calculations made for assessing CLT wall assemblies [2,3,5–17], the entire panel is modelled as a single material block. This approach is suitable for assessing the moisture safety of panel centre areas but cannot be used for moisture uptake and redistribution modelling from the end-grain surfaces. 1D models also do not take into account the anisotropic properties of wood. In two-dimensional (2D) calculations [1], which can simulate moisture flow in multiple directions, the CLT block is still often modelled as one material dismissing the anisotropic nature of wood. There are fewer cases of differentiating the CLT layers as longitudinal or transverse with the respective material properties [24] and even fewer examples of simulating moisture transport in CLT by taking account of multiple characteristic directions of wood in a single representative elementary volume in a 2D model. Moreover, in case of contact with bulk water, there will be moisture transport in both below and above the fibre saturation point, leading to a complex set of conditions that needs to be accurately considered in a hygrothermal model.

Brandstätter et al. [25] implemented a novel hygrothermal simulation model developed by Autengruber et al. [26], which uses the finite element software *Abaqus* to solve the numerical problem. The model was adapted to incorporate moisture transport across all characteristic wood directions simultaneously. To validate the model the authors used the results of laboratory experiments by Kalbe et al. [22] encompassing vertical moisture uptake and MC distribution within CLT wall panels. Brandstätter et al. achieved a good agreement between the simulations and measurements, but further analysis of CLT end-grain moisture safety was not part of their research. This is a gap which the current work aims to fill while implementing the commercial software IBK Delphin [27] for the coupled heat, air and moisture transport modelling. Version 6 of Delphin allows one to include anisotropic variation of material properties. However, there are no definitions of anisotropic spruce or pine material in the Delphin database as of 2024 and custom files must be composed for the anisotropic transport model to work. The anisotropic material transport model itself is still experimental in Delphin and needs further validation.

1.3. Moisture content as performance criterion for moisture safety in CLT construction

Mould index as well as moisture content limits are often used as the performance criteria of moisture safety analyses. In the case of end-grain surfaces, water contact can raise the MC in their vicinity very quickly [28], well above the maximum allowable limit of 15 % at assembly required by the European standard for CLT [29] or the limits suggested by other researchers, e.g. 16 % proposed by Kukk et al. [2]. Moisture content of 16 % also corresponds to a relative humidity (RH) of approximately 80 % on the surface of wood [30] and this entails a high mould risk [31] if warm conditions last long enough. Although it is safest to keep the MC of CLT below this limit, it is in practice difficult to do so without sophisticated weather protection [22,32]. Ensuring this MC level near end-grain surfaces during CLT construction, especially when exposed to the elements, is practically impossible, even though it may not pose an immediate risk owing to conditions that are unfavourable to mould growth or due to timely moisture dry-out. This discrepancy: MC above suggested limits but without negative consequences, creates contention at construction sites, hindering efficient construction processes. One possibility would be to implement a mould index calculation to predict whether the developed conditions lead to mould growth or not. However, performing mould index calculations during a moisture safety inspection round is not practical, given the rapid pace of modern construction. For a better practical and operative usability on a construction site, it would be beneficial to have a MC-based performance criterion which considers the rapid water absorption of the CLT end-grain surfaces and subsequent moisture dry-out providing greater flexibility.

This study proposes a two-step MC limit or target for CLT end-grain moisture safety management. The idea of the two-step MC limit is that an elevated MC in the proximity of the end-grain surface is allowable if the MC is lower further away from the water contact surface and the excess moisture in the vicinity of the water contact surface can dry out and redistribute before mould growth starts. The novel two-step performance criterion is designed to provide greater flexibility and serve as a foundation for an adaptable strategy that can accommodate various circumstances arising during the construction process.

1.4. Moisture safety strategies for CLT construction

A common conjecture is that a short construction period could be a valid moisture safety strategy to avoid problems with excessive MC in CLT. However, this might not be the case considering end-grain surfaces. Other notable factors influencing moisture safety include the implementation of full-coverage weather protection such as a tent-like structure or the implementation of local protection measures such as water-blocking coatings on the end-grain surfaces and temporary protection foils on the CLT faces. The concept of CLT localised moisture protection measures have been discussed earlier by Kalbe et al. [23]. It is of interest to compare these methods and establish a baseline for further research which might include the optimisation of the vapour permeability or other parameters of the localised protection measures. A key determinant is also the season when the installation of CLT panels takes place or the construction of the CLT panels proceeds. The worthwhile question is whether seasonality has an effect, especially compared to more specific moisture management methods. If there is an effect, then can the start of CLT installation during a favourable season be considered as an adequate moisture management method? When these factors are combined, then a moisture management strategy can be formed, and varying outcomes become realised. This study aims to investigate these factors.

Time et al. [33] presented a moisture safety strategy for CLT buildings comprising of 1) construction scheduling (the installation of the CLT was scheduled for July and August, which the authors referred to as a typically drier period in Trondheim, Norway), 2) localised protective measures, including end-grain surface protection (all interfaces between wood and concrete were protected), 3) immediate action upon rain events to protect the structure and drain free water, 4) regular moisture measurement and 5) prevention of covering wet CLT panels (target MC < 15 %). The strategy presented by Time et al. [33] yielded acceptable results by every investigated indicator and the authors concluded that full-coverage weather protection could be substituted by a comprehensive moisture management strategy. Kodi et al. [34] investigated moisture safety strategies for a renovation project in Estonia, which involved prefabricated timber-frame additional insulation elements. They discussed whether localised protection measures, avoidance of installation during precipitation and mechanical drying of the attic space, which accidently got wet during the installation, would have avoided moisture damages, or if a full-coverage weather protection structure, such as a temporary roof, was necessary. The authors conclude that it indeed is possible to exclude the temporary tent, but a strict moisture safety plan and its careful implementation are essential. In a Norwegian CLT school building, the temporary tent was considered, but due to cost considerations it was omitted, and a moisture measurement-based moisture safety strategy was opted for [35]. It was presumed that through the constant monitoring it would be possible to detect moisture ingress and damage can be prevented. The sensors were placed on various locations to monitor specifically exposed areas, but it was unclear how close the sensors were to the end-grain surfaces of CLT panels. Nevertheless, several increases in MC were detected, which could have developed into more extensive moisture damage and were thus avoided, showing the usefulness of the selected strategy. A moisture measurement-based moisture safety strategy can also benefit from a more precise MC criterion. It is apparent that research and development of moisture safety strategies is an important matter.

1.5. Objectives of the research

This work aims to take a step forward in addressing the aforementioned issues and is guided by the following main objectives:

- validate the 2D hygrothermal model composed in IBK Delphin software, which utilizes an experimental anisotropic transport model (as of 2024), along with custom anisotropic spruce material files, for CLT vertical water uptake and drying processes; and demonstrate its application in fulfilling the following objectives;

- develop a novel MC-based two-step performance criterion for areas near CLT end-grain surfaces; and
- study the key process variables and moisture management strategies regarding CLT end-grain moisture safety while implementing the newly developed performance criterion.

2. Methods

2.1. Experiments

For a comprehensive validation of the hygrothermal simulation model, three experiment series were conducted. In each experiment, the end-grain surface of CLT or wood specimens was exposed to water by immersion.

The first experiment series provided moisture distribution data in CLT (gathered with electrical resistance-based MC measurements according to EN 13183–2 [36]) throughout wetting and subsequent drying periods under varying conditions. The results of this experiment have been discussed earlier by Kalbe et al. in Refs. [22,28] and have been used in a study by Brandstätter et al. [25], where the authors developed a novel hygrothermal simulation algorithm and used the experimental data to validate their model. The hygrothermal simulation model in the current work focuses on the CLT wall panel bottom connection and utilizes a subset of the measurement results considering similar conditions.

The second experiment series was conducted to study water absorption in timber boards with different grain directions without the influence of adjacent timber boards. This experiment constituted the basis for the preliminary selection of material parameters for the hygrothermal simulation model. Electrical resistance-based MC measurements were taken on wood boards separated from dry CLT panels.

The third experiment series was deemed necessary to achieve a more precise validation of the hygrothermal model within the overhygroscopic range of MC. A gravimetric MC measurement method according to EN 13183–1 [37] was utilised to determine MC near the end-grain surface of CLT.

2.1.1. Moisture distribution development in CLT from end-grain wetting: electrical resistance-based MC measurements (experiment 1)

The experiment consisted of two phases: a water uptake test for one week (wetting phase) and a moisture drying-out test over two weeks in both indoor and outdoor conditions. Five-ply spruce CLT test specimens (TSs) measuring 400 mm in length, 400 mm in height and 100 in thickness were used. The end-grain surfaces of the TSs were coated with a liquid plastic coating (IKO MS Detail), except for the bottom surface which was subjected to water contact. The side faces remained open to allow moisture dry-out through those faces. The TSs were conditioned in sheltered autumn outdoor climate conditions (t ≈ 2 °C, RH ≈ 90 %) for two weeks before the wetting phase, resulting in an initial MC of 10–12 % and up to 20 % on the outer surface of the TSs.

During the wetting phase, the untreated bottom end-grain surfaces of the TSs were in continuous water contact for one week. During the two-week drying phase, the TSs were divided into groups based on the surrounding climates (Table 1). Moisture trapping conditions were induced by affixing the TSs onto another CLT plate, mimicking a CLT wall-to-floor connection. Throughout the drying phase, none of the TSs came into contact with bulk water. The experimental setup imitated a situation where the bottom surface of a CLT wall panel is exposed to bulk water during the construction phase, and moisture dry-out occurs through the side faces.

The drying potential in the indoor conditions was fair, characterised by a water vapour pressure difference of approximately 1800 Pa between the surrounding air and the wet surfaces of the CLT TSs. Conversely, outdoor conditions offered only marginal drying potential, with a water vapour pressure difference of approximately 50 Pa.

Electrical resistance-based MC measurements were conducted following the guidelines of EN 13183–2 [36], utilising a Logica Holzmeister LG9 NG wood moisture meter with 60 mm Teflon-insulated pins featuring 10 mm uninsulated tips. The instrument's expanded uncertainty was 0.8 % for MC values ranging between 12 % and 22 %. MC was measured at two depths from the side faces (5 mm and 50 mm) and at five heights (30 mm, 60 mm, 90 mm, 120 mm, and 150 mm) from the water level. Measurements at the depth of 5 mm characterised MC in the surface layer of the CLT, while measurements at the depth of 50 mm represented conditions in the middle (3rd) layer of the 5-layer CLT. The wood grain direction was consistent in both layers, with the bottom end-grain surface exposed to free water. Electrode pins for surface and middle layer measurements were inserted from the opposite sides of the TSs, perpendicular to the measured layer's wood grain. The results, as previously discussed in Refs. [22,28], revealed minimal variation in MC development at 120 mm and 150 mm, both at the depths of 5 mm and 50 mm. Consequently, only the results from the heights of 30 mm, 60 mm, and 90 mm were utilised for validating the simulation model and preparing subsequent experiments. Blue ink (Parker Quink) was added to water to better visualise moisture transport in the CLT. Parker Quink has been deemed suitable for staining fungal structures in mycological studies [38] and was thus considered appropriate for the water uptake study as well. After completing all moisture measurements, the TSs were cut into half and the reach of the blue staining was analysed. A composite image was generated,

Table 1
Temperature (*t*) and relative humidity (RH) during the wetting phase (indoor) and drying phase (both indoor and outdoor), measured at 0.5 m from the CLT test specimens with a Hobo UX100-023 data logger.

	Indoor conditions	Outdoor conditions
t	21.6 °C ± 0.8 °C	2 °C ± 2.7 °C
RH	29 % ± 5 %	92 % ± 5 %

which involved stacking of the images from all TSs in the darken blending mode. This method allows integration of the darkest areas across all images, resulting in an image with the more stained regions emphasised.

2.1.2. Water absorption of timber in different grain directions (experiment 2)

In this experiment, 20 timber boards were extracted from the same batch of CLT panels as in the experiment described previously. Each board was covered with liquid plastic coating to prevent water vapour exchange with the surrounding environment, except for the surface in contact with water. For half of the boards, water uptake occurred in the longitudinal wood grain direction, while for the other half it took place in the transverse grain direction. Mass change of the specimens was measured at intervals of 1 h, 2 h, 5 h, 8 h, 24 h, and 48 h from the initiation of water contact. The experiment was conducted under isothermal conditions ($t \approx 22$ °C, RH ≈ 29 %). Water absorption coefficients (A-values) were determined as per EN ISO 15148:2003 [39] for the longitudinal and transverse direction separately. Gravimetric measurements were utilised for determining the A-values. Additional MC measurements were taken at 10 mm intervals from the water-contact surface, utilising the same electrical resistance-based moisture meter as in the experiment described previously. Electrical resistance-based moisture measurements were utilised to determine the MC distribution in timber boards for pre-selecting the material files in the simulations.

2.1.3. Moisture distribution development in CLT from end-grain wetting: gravimetric MC measurements (experiment 3)

The experiment was conducted based on the gravimetric MC measurement method (EN 13183–1 [37]) to thoroughly analyse moisture distribution within different layers of CLT, specifically near the end-grain surface where the MC quickly rises to a very high level exceeding the range of electrical resistance-based MC measurement devices.

The experiment involved CLT from the same batch as in the previous experiments, but the TSs were smaller, as the previous experiments showed that the areas most affected by moisture uptake are located up to about 60 mm from the water contact edge. Eighteen TSs were prepared by cutting them from a five-layer CLT panel with a thickness of 100 mm. Each TS measured 140 mm in length and 70 mm in height (Fig. 1, left). Before the experiment, the TSs had been in storage in indoor conditions ($t \approx 22$ °C, RH ≈ 29 %) for approximately four years. Flexible vapour barrier tape (Tectis Sitko Flex) was applied to the air-exposed edges of the TSs to prevent moisture transfer through these surfaces. The bottom edge and side faces of the TSs were intentionally left untreated similarly to the first experiment described in section 2.1.1. The experiment also consisted of two phases: an initial water uptake test for up to 72 h (wetting phase) followed by a moisture drying-out test for up to 336 h. During the wetting phase, the TSs were held in containers with water levels continuously controlled and maintained at about 1 mm–2 mm above the bottom surface of the TSs. Unlike in the first experiment, it was not possible to use the same TSs throughout the whole experiment due to the destructive nature of the gravimetric method. Thus, the MC values for each water contact duration were measured from individual TSs.

Weighing of the TSs was performed individually before and after the wetting phase, following water contact for 4 h, 8 h, 24 h, and 48 h (three TSs for each duration). Immediately after the wetting phase, the TSs were cut into seven sections with a target thickness of 7 mm using a bandsaw with a thickness of 0.5 mm. This interval was chosen because 5 mm steps made the samples too small, making it difficult to cut uniformly sized specimens, whereas thicker specimens would have had a negative impact on the measurement resolution. Subsequently, these sections were fractured by hand into ribbons, with each ribbon corresponding to a specific layer and timber board within the CLT structure. The thickness of the ribbons was measured with a MarCal 16 EWR digital calliper (error limit 0.03 mm, [40]). The ribbons were then transferred to a drying oven (Fig. 1, right), and once dried, their final weight was determined.

In addition, there were four TSs that were held in water contact for 72 h and were then transferred to stable laboratory conditions for drying ($t \approx 6$ °C, RH ≈ 65 %) in a moisture-trapping setting. The moisture trapping conditions were created by attaching the TSs tightly to a dry planed timber beam, which imitated a CLT wall to floor connection. During the drying phase, none of the TSs encountered bulk water. Table 2 summarises the test setup. The drying conditions were characterised by a water vapour pressure difference of approximately 520 Pa between the surrounding air and the wet surfaces of the TSs. This was chosen as a middle ground compared to the two climate conditions in the first experiment (Table 1).

Half of the TSs underwent one week of drying, while the other half underwent three weeks of drying. The dried TSs were sliced and

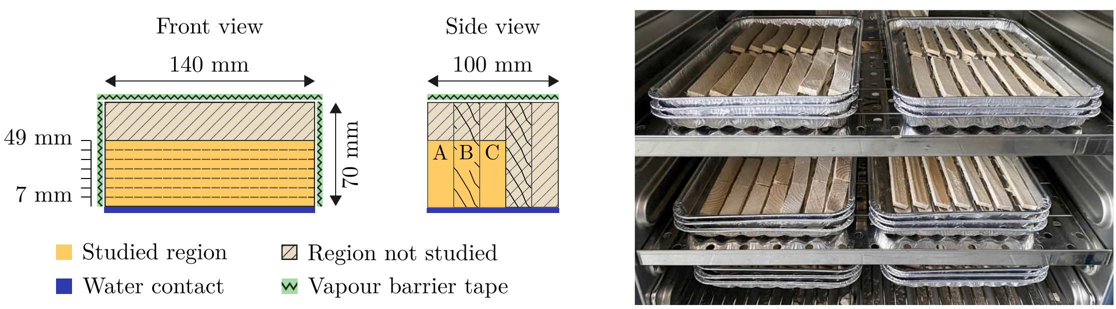


Fig. 1. CLT test specimen dimensions and cutting scheme for the gravimetric MC measurements (left); test specimen ribbons in the drying oven (right). The markings A, B and C correspond to the same markings in Fig. 5 (initial MC values used in the hygrothermal simulation). A is the outer (surface) longitudinal layer, B is the transverse layer, and C is the inner longitudinal layer.

Table 2
Test plan for experiment 3. Wetting and drying phase durations.

Number of TSs	Water contact duration (h)	Drying duration (h)	Comment
3	4	–	
3	8		
3	24		
3	48		
3	72		
2	72	168	Moisture trapping conditions during drying
2	72	504	

broken into smaller ribbons as in the case of the previously described wetted TSs (Fig. 1, right). The ribbons were then transferred to a drying oven. The oven used for drying all the timber ribbons was a Memmert UFB-500 manual-control mechanical convection oven with a setting accuracy of ±0.5 °C. Precise mass measurements were taken with a Kern PLJ 1200-3A precision balance featuring a weighing capacity of 1200 g, accuracy of 0.001 g, and precision of ±0.003 g [41].

2.2. Hygrothermal modelling

Analysis of CLT end-grain moisture performance was conducted using the hygrothermal modelling software IBK Delphin 6.1.6 [42, 43] which is suitable for applications in building sciences. Delphin has been validated several times [44]. A technical report from the software developers summarises its validation results using HAMSTAD Benchmarks 1–5, DIN EN ISO 10211 cases 1 and 2, DIN EN 15026, and the absorption-drying test. Delphin was validated for heat, moisture, and air transport in both 1D and 2D situations, with

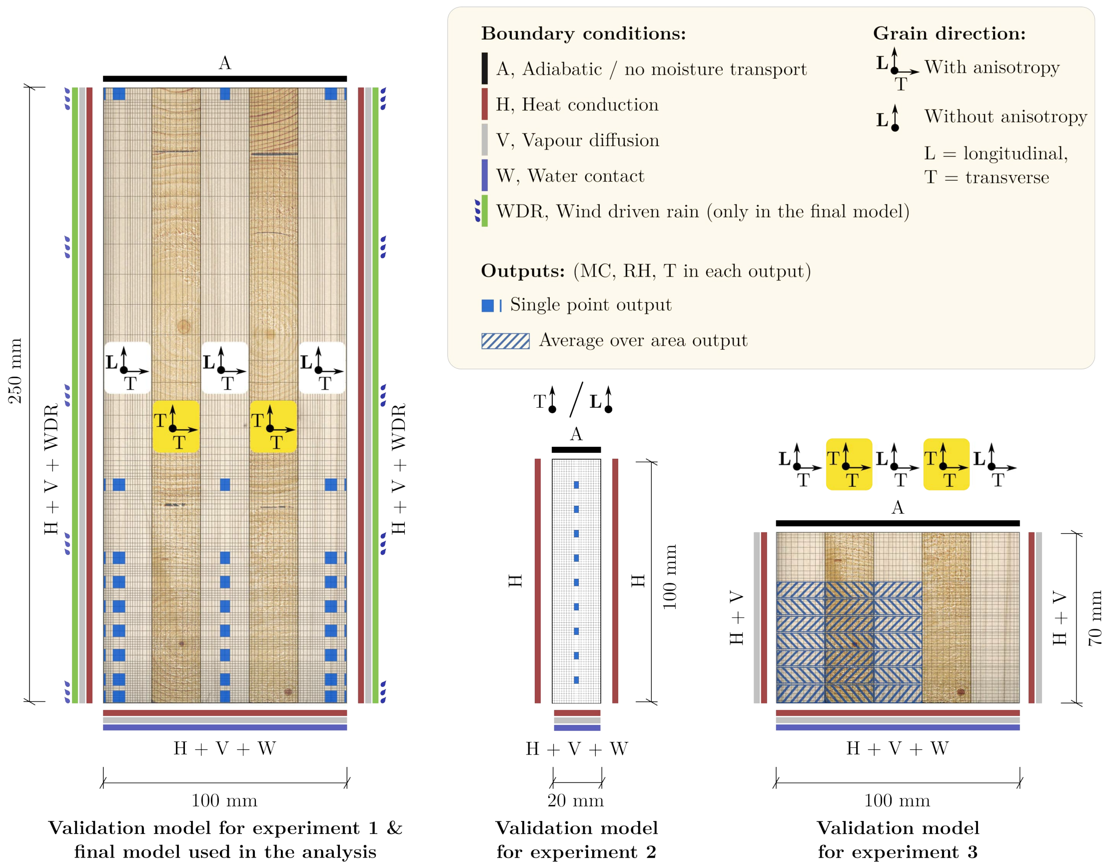


Fig. 2. Modelled CLT geometry for each experiment as well as for the final analysis (leftmost diagram). The illustration displays grain direction, boundary conditions, discretisation grid and output locations. For the description of the experiments, refer to sections 2.1.1 (experiment 1), 2.1.2 (experiment 2) and 2.1.3 (experiment 3).

all versions meeting the test case requirements [45]. Other authors, independent of the program developers, have validated Delphin models, including Kalbe et al. [46] who validated a 2D Delphin simulation for insulated sandwich panels which were exposed to high humidity and varying climate conditions in a laboratory setting. Wang et al. [24] validated a CLT hygrothermal simulation model generated in Delphin and highlighted the significance of differentiating liquid transport properties between the transverse and longitudinal directions. Starting from Delphin version 6, it is possible to take into account anisotropy of materials such as timber, where moisture transfer depends on the wood grain direction. While the functionality of anisotropic modelling with the Delphin software has been shown before [47], it is necessary to validate the model sufficiently before performing any analysis. Since timber properties can vary even across the same CLT panel, careful consideration is needed when selecting the material properties. Therefore, the model and the material properties were validated using the results of the three experiments described above.

2.2.1. Model basics and simulated geometry

Separate model geometries were developed (Fig. 2) to match each experiment as the test specimens in the experiments were different. The simulation files were configured to closely align with the experimental conditions. Scheduled water contact was used on the surfaces immersed in water. Water vapour transfer and heat exchange was simulated on the surfaces that were in contact with the ambient air and the corresponding measured temperature and relative humidity data were used as the boundary condition climate data. No moisture or heat transfer was assumed on the top surface in the models. Relevant outputs (MC, RH, temperature) were defined and set in the model exactly in the locations where actual electrical resistance-based measurements were taken or samples were cut during the experiments. The mean thickness of the samples employed for gravimetric measurements was used to define the output locations. Moisture trapping conditions were simulated by increasing the water vapour diffusion-equivalent air layer thickness up to 125 m on the bottom end-grain surface of the CLT wall panel, in order to mimic a CLT floor panel represented by the panels and timber beams affixed to the TSs in the corresponding experiments. Liquid water transfer towards such a CLT floor panel was neglected, as the auxiliary CLT panels in the experiments had a very low MC (<10 %) and thus the liquid conductivity of the dry panels was low. Excluding liquid water transfer towards the CLT floor panel also made sense in the analysis of end-grain protection strategies, because in today's practice CLT floor panels are frequently installed with waterproofing membranes which effectively block liquid water flow, but have a relatively low vapour resistance (e.g., Pro Clima Adhero 1000/3000 with an $S_d = 0.3$ m–0.8 m [19], or Siga Wetguard 200 SA with an $S_d = 2.5$ m–4.5 m [18]).

The model used for comparison with the results from the first experiment for moisture distribution development in CLT due to end-grain wetting (electrical resistance-based MC measurements) served as the basis for the final model utilised in the end-grain moisture safety analysis (leftmost diagram in Fig. 2). In this model, the bottom surface was configured to experience water contact in accordance with a schedule derived from the simulated actual yearly climate data. The schedule was modified to reflect the simulated moisture management practices (more on this in section 2.4). Additionally, wind driven rain was considered on the side surfaces of this model (account was taken of west and east winds, as this leads to the highest wind driven rain loads in Estonia).

2.2.2. Pre-selection and development of material definitions and validation of the hygrothermal simulation model

Careful consideration is necessary when selecting the material properties. In the Delphin database, the material files are

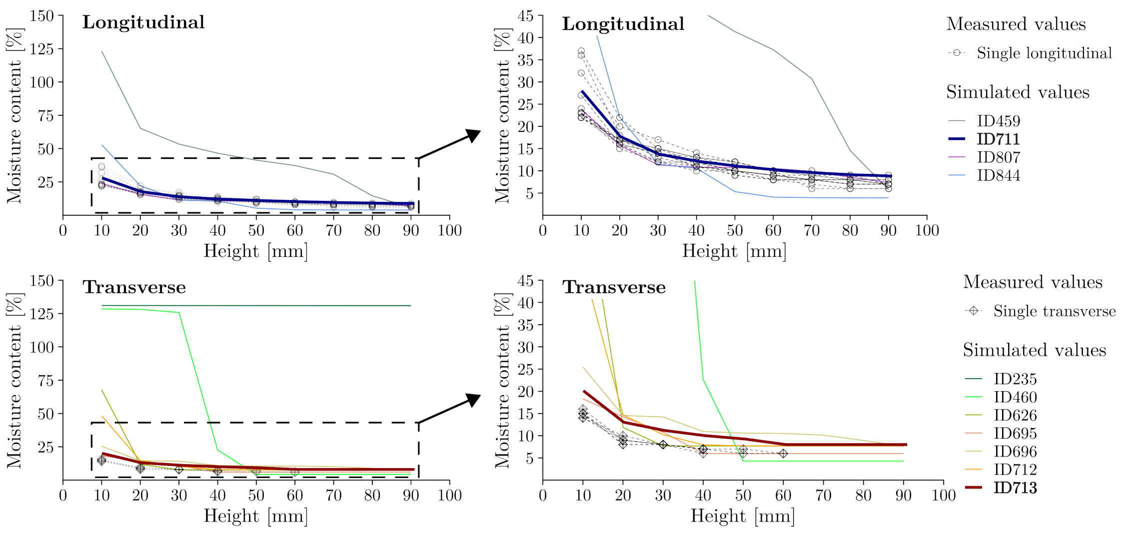


Fig. 3. Comparison of MC measurements from Experiment 2 with simulations using spruce material files in Delphin (ID*** codes refer to material file ID numbers in the Delphin database). The left charts show MC values on a 150 % scale, while the right charts zoom in on the dashed box sections from the left for better readability.

distinguished by unique identification (ID) number and there are five material files available for spruce for the longitudinal direction (ID459, ID697, ID711, ID807, ID844) and seven files for the transverse direction (ID235, ID460, ID626, ID695, ID696, ID717, ID713). In the database the file ID697 is replaced with ID807 and ID235 is replaced with ID460, but nevertheless were included in the initial testing and pre-selection.

The pre-selection of the material properties was done based on the water absorption measurements conducted with separated timber boards (experiment 2, see section 2.1.2). Some material definitions produced vastly different simulation results compared to the measurements (Fig. 3). Most materials from the built-in database exhibit a much greater moisture content – up to 130 % at the height of 10 mm from the water contact surface both in the longitudinal and transverse directions. The electrical resistance-based measurements showed a maximum MC of 37 % and 16 %, respectively. The accuracy of the electrical resistance-based measurements decreases at MC values above the fibre saturation point, but the difference of about 100 percentage points cannot be explained by the measurement method uncertainty alone, especially in the case of transverse grain direction.

Materials ID711 and ID807 showed a good correlation with the measurement data on longitudinal moisture transfer. The fit was less ideal for the transverse moisture transfer, but a reasonable agreement was achieved with the files ID695 and ID713 (Fig. 3).

In the Delphin database (version 6.1.6) there were no material files for spruce that account for anisotropy as of 2024. However, for the simulation model to consider different moisture flow directions within one representative elementary volume, the corresponding properties must be defined within a single material file. Thus, files of anisotropic spruce materials had to be compiled. While the moisture transport parameters of timber differ depending on the moisture flow direction relative to the timber fibre direction, the moisture storage function and storage base parameters remain isotropic and are not affected by the direction of moisture flow. This posed a challenge for the compilation of the files of anisotropic materials, as only one pair from the subset of suitable isotropic material files had the same moisture storage function and moisture storage base parameters – the materials ID711 and ID713. Combining other material files would have made it necessary to alter the storage parameters and moisture storage function, which would have introduced a further level of uncertainty. Thus, only one material file with anisotropic spruce material properties was possible to compile from the built-in material files (ID711 and ID713) from Delphin database (Table 3).

While the simulation conducted for preselection of the material properties yielded good results, it still did not take into account the material anisotropy or transient climate conditions. More comprehensive comparisons were thus necessary and were made on the basis of measurement data gathered from the experiments designed to assess moisture distribution in CLT with electrical resistance-based (experiment 1, section 2.1.1) and gravimetric MC measurements (experiment 3, section 2.1.3). It was presumed that some alteration of the material properties was necessary to achieve a good fit with the experimental data. First, the water absorption coefficients were modified based on the results of the second experiment, but this did not yield a better agreement in preliminary testing (specifically, it did not improve agreement with the data on MC development over time). Instead, it was found that altering the liquid conductivity and moisture storage had a greater impact.

Wang et al. [24] have also emphasised that the moisture storage function at the capillary range and the saturation water content of the CLT has a substantial impact on the accuracy of the hygrothermal model. Brandstätter et al. [25] showed in their analysis of simulated CLT water uptake that the mass transfer coefficient of free water is the main contributor to the intensity of moisture uptake, and that the effect of glue lines is smaller than the role of the investigated mass transfer coefficients. Therefore, the focus of optimisation in this work was set at the liquid water conductivity function.

The goal of the material definition optimisation process was to have three files for the anisotropic spruce material – one that produces the best fit for the measurement data as a whole, i.e. a close correlation with the mean of the measurement results, another that yields results in agreement with measurements with the lowest values, and finally a material file which generates an outcome corresponding to the highest measured values. This approach was chosen because the measurement results of the first experiment exhibited a wide variation, as discussed in Refs. [22,28]. A similar method was implemented by Brandstätter et al. [25] in their sensitivity analysis. Optimisation was done iteratively, until a satisfactory fit was found. An attempt was made not to exceed the range of values for the material functions defined in the built-in Delphin database of material definitions. For an optimised fit, it was necessary to increase the liquid water conductivity for volumetric moisture contents lower than 0.4 m^3/m^3 but decrease for higher moisture content levels. The results of the validation are presented in section 3.1, while the liquid conductivity, vapour permeability and moisture retention functions of the final selected and optimised material files are presented here in Fig. 4.

Table 3
Moisture transport and storage base parameters of the reference material files ID711 and ID713 in Delphin database.

	Longitudinal (ID711)	Transverse (ID713)	Unit
Bulk density of dry material	393.703		kg/m^3
Specific heat capacity of dry material	1843		J/(kg·K)
Open porosity	0.737531		m^3/m^3
Effective saturation content (long process)	0.72809		m^3/m^3
Capillary saturation content (short process)	0.655		m^3/m^3
Hygroscopic sorption value at 80 % RH	0.0598372		m^3/m^3
Thermal conductivity	0.151167	0.105583	W/(m·K)
Water absorption coefficient	0.012024	0.00526733	$kg/(m^2 \cdot s^{0.5})$
Water vapour diffusion resistance factor	4.57501	487.724	–
Liquid water conductivity at effective saturation	2.00481×10^{-10} Altered files = 1×10^{-11}	9.22366×10^{-10} Altered files = 1×10^{-11}	s

Root mean square error (RMSE) and mean bias error (MBE) were calculated to provide a quantitative indication of the fit of the simulation results with the experimental data. RMSE provides a measure of the average magnitude of the errors in the simulation outcome as compared to the measured values. A lower RMSE indicates a closer agreement of the simulation results with the experimental data, suggesting a better fit. However, RMSE penalises large errors due to squaring of the errors. Therefore, error calculations also included MBE, which gives equal weight to all errors and additionally provides information about the direction of the errors. MBE indicates whether the simulation tends to consistently over- or underestimate compared to the measurements. The two indicators were calculated on the basis of the experiment on moisture distribution development in CLT (experiment 1, electrical resistance-based MC measurements), as this experiment served as the primary basis for validating the hygrothermal simulation model. The statistical indicators were determined as follows:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n} (s_t - m_t)^2}{n}}$$

$$MBE = \frac{\sum_{t=1}^{n} (s_t - m_t)}{n}$$

Here, n is the number of measurements, s_t represents the simulated data, while m_t refers to the measured data at time point t. The measured data m_t comprise averaged measurement results from the TSs exposed to the given climate conditions.

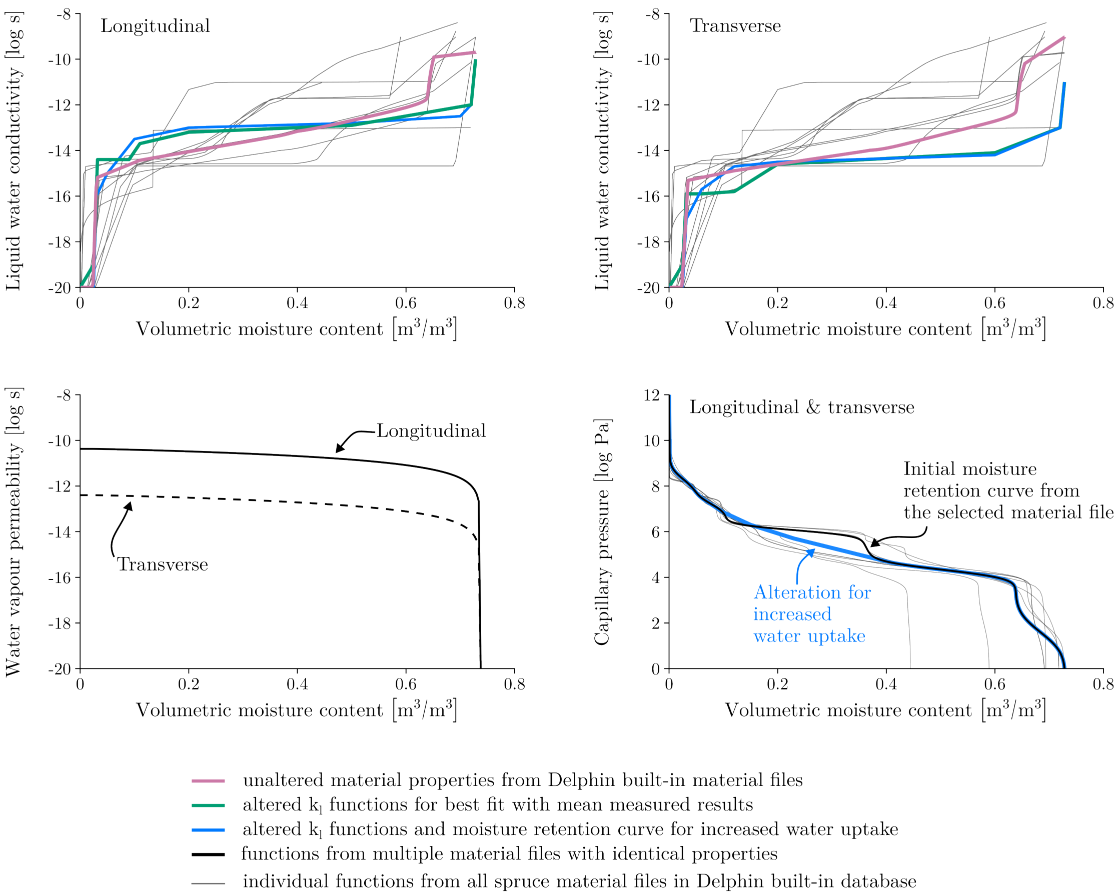


Fig. 4. Material functions from the selected and optimised material files.

2.3. Performance criterion development

The underlying performance criterion used in this work was mould growth initiation, calculated according to the improved Finnish mould growth model (originally referred to as the VTT mould model) [48,49]. The output of the model is an index (M) on a seven-grade scale: 0 – no growth (clear surface), 1 – growth seen with a microscope (growth is beginning), 2 – clear growth seen with a microscope (mould colonies have formed), 3 – growth seen with the naked eye, 4 – clear growth seen with the naked eye (>10 % coverage detectable visually), 5 – rich growth seen with the naked eye (>50 % coverage detectable visually), 6 – very rich growth (~100 % coverage). For input, the model considers exposure time, temperature, relative humidity (RH) and drying periods. The Finnish mould growth model has proved to be reliable and accurate in predicting mould growth when using wood surface RH as an input [50], particularly when contaminators are present [51], which is common on a construction site. However, calculation of M requires input data in the form of a time series. For better practical and operative usability on a construction site, a two-step MC limit is proposed in this work.

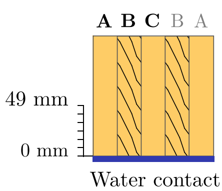
For the development of the two-step MC limit, measured MC distribution values (data gathered by gravimetric MC measurements, experiment 3, see section 2.1.3) were used as the starting MC in the hygrothermal simulation model (section 2.2.1). The simulation generated temperature and RH time series from the surface of the CLT panel as an output throughout the simulation period. The obtained results were subsequently utilised as input parameters in the Finnish mould growth model. The initial MC values that did not result in conditions yielding an $M > 1$ were deemed safe for use. These values are then recommended as practical MC limits when managing end-grain wetting.

Although the measured MC distribution values used in the simulations encompassed the entire CLT test specimen, only two areas were chosen as reference points for the performance criterion (the two-step MC limit). The first area was between 7 mm and 14 mm (midpoint ≈ 10 mm) and the second area between 28 mm and 35 mm (midpoint ≈ 31 mm) from the water contact surface. The two steps (MC investigation locations) were derived from the measurement locations used in experiment 3 (section 2.1.3), where they were selected as a compromise between measurement resolution and physical constraints of the measurement method. For simplicity, the height values are hereinafter referred to as 10 mm and 30 mm, respectively. These height values can also be readily utilised for on-site MC measurements.

To identify the limiting MC values, a series of mould index calculations were done in the hygrothermal model. The aim was to determine which MC values could be considered safe at the time when CLT panels are no longer exposed to precipitation and are beginning to be covered with additional structure layers during the construction period. Mould index value of 1 (initial stages of local growth) was set as the upper limit value. This is considered to be a suitable limit to minimise the risk resulting from mould growth on surfaces which are in contact with the indoor air ("green traffic light" [52]). Four sets of initial MC values (Fig. 5, mean results of the gravimetric MC measurements described in section 2.1.3) were used in the hygrothermal model. Experimental data were deemed to provide more accurate information on MC distribution than hypothetical values.

The general geometry and boundary conditions of the hygrothermal model used for the performance criterion development are described in section 2.2.1 and on the leftmost diagram in Fig. 2. In addition, a 200 mm thick insulation layer with thermal conductivity $\lambda = 0.028$ W/(m·K) and water vapour diffusion resistance factor $\mu = 100$ was added to the left (exterior) side of the CLT geometry to increase criticality. This produced a vapour diffusion resistance equivalent to that of 20 m of stagnant air on the CLT external surface, providing a higher risk scenario where moisture dry-out towards the outdoor environment is limited. On the interior side, two variations were made that involved an additional vapour diffusion resistance equivalent to that of 0.3 m or 1.0 m of stagnant air, respectively. An equivalent air layer thickness of 0.3 m corresponds to two gypsum boards with a total thickness of about 25 mm, which is a common solution in CLT construction. Kukk et al. have also used $S_d = 0.3$ m as an equivalent to the resistance of a water vapour permeable interior layer in CLT hygrothermal calculations [2]. One meter of stagnant air represents a situation where additional layers (e.g., timber finishing boards, paints, etc.) might be added to the gypsum boards, making the interior layer less water vapour permeable and thus increasing the risk of moisture build-up. However, both variants of the additional vapour diffusion resistance on the interior side of the CLT panel can be considered vapour permeable and not moisture trapping. Thus, the developed two-step MC criterion only applies for situations where at least the interior surface of the CLT panel is relatively open for moisture dry-out. For the bottom end-grain surface, moisture trapping conditions were modelled as described in section 2.2.1.

All things considered, the model described a situation where a CLT wall would have been covered with insulation and vapour open



Moisture content [%]

Height [mm]	4 h			8 h			24 h			48 h		
	A	B	C	A	B	C	A	B	C	A	B	C
42–49	8	8	8	9	9	9	10	9	11	15	13	13
35–42	8	8	8	10	9	9	11	9	11	16	13	14
28–35	9	8	8	10	9	10	12	10	13	18	14	16
21–28	10	8	9	11	9	12	15	11	15	22	15	20
14–21	12	8	10	14	10	14	19	11	19	31	18	28
7–14	19	9	14	23	10	21	28	12	26	51	19	48
0–7	67	19	62	68	22	78	96	24	85	131	33	120

Fig. 5. Initial MC used in the hygrothermal simulation model for determining the performance criterion. The MC values are the measured mean from experiment 3 (section 2.1.3). The height values show the boundaries (cut planes) of the measured layers.

interior finishing layers while the MC in the bottom part was still elevated from past wetting incidents and the bottom surface was in moisture trapping conditions. As described by Kalbe et al. [22] moisture trapping conditions occur often near CLT end-grain surfaces and MC in these areas could remain high even after lengthy periods without additional water contact.

Estonian Moisture Reference Year (MRY) for mould growth analysis [53] was used as the climatic dataset in the simulations for the performance criterion development. The simulations started in July and lasted for two months. This is a reference period that produces the highest mould risk during the MRY and corresponds to the time frame for completing interior finishes. For the indoor environment, a temperature shift of −5 °C from the standard indoor temperature setpoint (21 °C) was applied in order to describe the indoor environment during the construction period more realistically and provide a less intense moisture dry-out. Moisture excess during the construction period can vary depending on the moisture-intensity of the interior finishing works (e.g., concrete pouring and plastering can be moisture-intensive). The simulations were performed with both low and high humidity load. Table 4 summarises the hygrothermal boundary conditions used in the model. The calculations were made with the three material files described in section 2.2.2.

The performance criterion thresholds were defined as the values of initial MC at which the mould index M would remain below 1 on the surface of the CLT throughout the simulation. A mould sensitivity class 2 (corresponding to planed pine) and a mould decline factor of 0.25 (moderate decline, corresponding to planed pine) were used in the mould index calculations.

2.4. Analysis of CLT wall panel end-grain moisture safety

Long-term hygrothermal simulations were conducted to analyse which moisture safety strategies and process factors most influence the success of CLT construction regarding moisture safety of the end-grain surfaces of CLT wall panels. Climate data representing a period of 30 years were used as opposed to a test reference year. While the MRY is appropriate for analysis of mould growth risk, its precipitation data are too arbitrary and cannot be used to assess for example which season presents a higher or lower risk stemming from rain exposure.

The focus was on key construction process variables affecting CLT end-grain wetting and dry-out. The variables can be categorised into three groups: 1) variables influenced by the building size and type (expected CLT installation duration and post-installation period when the CLT panels are still exposed to the elements), 2) variables controlled by CLT producers as well as by the design team (i.e., localised moisture protection methods such as CLT wall face protection and CLT end-grain surface protection), and 3) variables mainly controlled by the general contractors (implementation of full-coverage weather protection, efforts to reduce water load on horizontal surfaces, and to some extent also the length of the post-installation period before addition of the next layers). Additionally, the CLT installation start season impacts the outcome, and although it might be possible to choose (or plan ahead) the start season at the time of design, it is often subject to external factors, especially in public procurement situations. Thus, this variable is mostly considered to be a factor that introduces randomness which is not under the direct control of any particular actor. This categorisation, derived from observations published by Kalbe et al. [22] and also made by the authors of this study, isn't rigid but offers an insight into the factors at play. A summary of the factors and their variable values is presented in Table 5. Each variable value was combined with all the other variable values and thus a total of 864 individual combinations were compiled. Each individual combination was simulated with each year from the 30-year climate data period and with each of the three material files described in section 2.2.2. This produced a total of 77 760 individual simulations. Variability of the material files and years contributes to the randomness, providing a basis for the probability calculations.

The combination setup began by setting the simulation time periods, defined as the sum of the installation duration and the post-installation period. The simulation was scheduled to end at the moment when the CLT panels would begin to be covered with additional layers. If no localised moisture protection methods nor full-coverage weather protection were used, the CLT structure in the model (as described in section 2.2.1 and on the leftmost diagram in Fig. 2) was left exposed to wind driven rain on the side faces and water contact on the bottom end-grain surface throughout the entire simulation period.

If CLT side face protection was applied, the wind driven rain was excluded from the model. This effectively meant that the side face protection was ideal without any water leaks. Any additional vapour resistance was neglected. The observations of the authors indicate that typically the protection foil is cut open from the bottom of CLT panels at the time of installation and the space between the foil and the CLT panel becomes ventilated. Moreover, if the protection foil is considered as ideal and no ventilation is assumed, the additional vapour resistance would hinder the influence of outside air which would skew the result towards drier conditions due to the low initial MC of the CLT. Furthermore, the application of the protection foil can vary and the foil could have imperfections and damages which produce both water leaks (as described by Kalbe et al. [22]) and holes for ventilation. Inclusion of these effects would have expanded the number of studied parameters exponentially and would have made the analysis unnecessarily complicated and more time consuming. Thus, it was decided to exclude the effect of (arbitrary) additional vapour resistance of the protection foil and no changes were made to the vapour transfer component on the side faces regardless of the presence of the protection foil.

Table 4
Ambient air temperature (t), relative humidity (RH) and indoor moisture excess ($\Delta\nu$) in the hygrothermal simulation model for the performance criterion analysis.

	Outdoor	Indoor construction site – low humidity load	Indoor construction site – high humidity load
t	15.6 °C ± 4.4 °C	17.8 °C ± 1.0 °C	
RH	77.5 % ± 17.3 %	70.4 % ± 9.5 %	87.6 % ± 10.4 %
$\Delta\nu$	–	0.7 g/m^3 ± 1.5 g/m^3	3.3 g/m^3 ± 1.7 g/m^3

Table 5
Variables of the analysed CLT moisture protection process safety measures.

Process factor	Variable value			
Expected CLT installation duration	1 week	4 weeks		16 weeks
Expected duration from CLT installation until addition of next structure layers	1 week	4 weeks		16 weeks
CLT wall face protection (applied prior to installation)	Yes (ideal rain protection)		No side face protection	
CLT end-grain surface protection (applied prior to installation)	Yes (ideal waterproofing)		No end-grain protection	
Full-coverage weather protection (FWP) implementation	FWP before installation	FWP after installation		FWP not implemented
Horizontal surface water drainage implementation	Rainwater drainage and prevention of puddle formation after rain		Absence of activities which enhance drainage	
Predicted start season of the CLT installation	Spring	Summer	Autumn	Winter

If CLT end-grain protection was applied, water contact via the bottom end-grain surface of the CLT wall panel was excluded from the model. Effectively this meant that the end-grain protection was ideal without any water leaks. Marginal vapour transfer was assumed, considering outdoor climate conditions and a vapour resistance value of $S_d = 125$ m for the floor panel, regardless of the presence of CLT end-grain protection.

Both of these local protection methods were assumed to have been employed in the CLT factory, i.e. they were implemented in the hygrothermal model from the beginning of the simulation. In case of utilising both the side face protection foil and end-grain protection, both the wind driven rain on the side faces and water contact via the bottom end-grain surface were excluded. This resulted in a model without liquid water ingress into the CLT, leaving only the effect of air humidity.

Full-coverage weather protection (FWP) was simulated in the same manner as in the case where both local protection methods were employed. However, for the case of FWP being erected after CLT installation, the wind driven rain and the bottom edge water contact were excluded only after the end of the installation period.

Implementation of horizontal surface water drainage can be seen as another measure that can form part of methodical moisture safety management by the construction site team. This aspect was included in the analysis, in order to compare the effectiveness of limiting the water contact duration with the impact of the more absolute protection measures described earlier. This provided information on whether limiting water contact can be an efficient measure in conjunction with a short installation period.

For the case with enhanced rainwater drainage and prevention of puddle formation (i.e. active moisture management by horizontal surface drainage), the start of the water contact was delayed in the model until the cumulative precipitation amount reached 2 mm. It was assumed that skilled and well-equipped construction workers can cover the construction on time in case of light rain, but moderate rainfall (≥2 mm [54,55]) may produce leaks that might overwhelm even a well-prepared team. The end of water contact in this case was defined as the last hour of the recorded precipitation period regardless of the rain amount. The assumption was that the construction team can promptly dry the structure and nearby surfaces after a rain event. For simplification purposes, no account was taken of the time and weekday when making this assumption.

If horizontal surface drainage management was not applied, the water contact start was taken to be the moment when the cumulative rain amount reached 0.5 mm, which corresponds to a moderate drizzle [54]. Cumulative precipitation below 0.5 mm was defined as a light drizzle which produces negligible runoff and does not result in accumulation of water under the CLT wall panel. The end of water contact was defined as the last hour of the recorded precipitation period, if the cumulative precipitation amounted to less than 2 mm. For precipitation amounts larger than 2 mm, it was assumed that a water puddle could form around the structure, extending the water contact duration. Thus the end of the water contact for the unmanaged variant was specified to be delayed by 6 h based on the experimental data of [28], according to which the water uptake rate of a CLT panel is highest roughly up to 6 h after the start of uptake. Preliminary modelling also showed negligible effect of a longer time lag.

The 30-year climate data (1991–2020) from Tallinn, Estonia was chosen for the analysis. The climate data was recorded by the

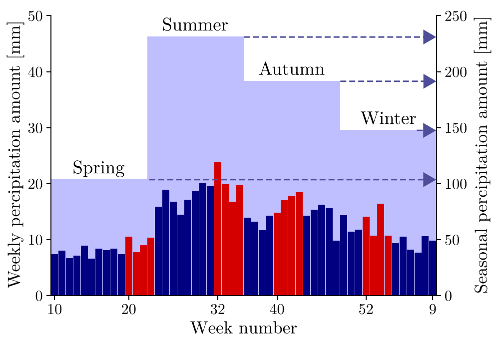


Fig. 6. Weekly and seasonal rain amounts in Tallinn, Estonia for the years 1991–2020. Red columns mark the chosen critical weeks for each season in terms of precipitation amount. The first week of each critical period served as the simulation starting point for the corresponding season. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Estonian Weather Service at the Tallinn-Harku meteorological station (N 59°23′53″, E 24°36′10″ [56]. Located in the northern part of the temperate climate zone, Tallinn is characterised by rainy summers and cold, snowy winters (Köppen climate classification Dfb). The utilised climate data included the outdoor air temperature, relative humidity, hourly rain amounts, wind velocity and direction. Solar radiation was excluded, as shading can occur in building sites (e.g. due to nearby buildings) and areas in solar shade are more critical. The start of the simulation for each season was chosen based on which consecutive four weeks had the highest statistical cumulative precipitation amount and at the same time included the week with the highest statistical precipitation amount. The simulation start weeks were thus week 20 for spring, week 32 for summer, week 40 for autumn, and week 52 for winter (Fig. 6). The simulation covered durations from 2 to 32 weeks, based on combinations of the expected CLT installation time (1–16 weeks) and the period until the addition of subsequent structural layers (another 1–16 weeks), as outlined in Table 5. Thus, the simulated periods ranged from two weeks per season to spans covering up to three seasons (e.g., starting in winter and ending in summer for the 32-week durations).

An outcome was considered successful when the mould index remained below 1 throughout the entire simulation period and simultaneously the MC remained below the limits specified in section 3.2 ($MC_{10\ mm} \leq 25$ % and $MC_{30\ mm} \leq 16$ %).

3. Results and discussion

First, the results of the simulation model validation are presented. Based on the validated simulation models, the results of the performance criterion development are then discussed. Next a detailed analysis of CLT end-grain moisture safety, including anticipated moisture dry-out times for the analysed scenarios is presented. This is accompanied by a sensitivity analysis of the performance criterion. Lastly, the interannual variability of CLT moisture safety and its correlation with climatic factors is reported.

3.1. Hygrothermal model validation

Initially, the simulation results were compared with the results of the electrical resistance-based measurements from the tests for moisture distribution development in CLT subjected to end-grain wetting (experiment 1, section 2.1.1). Since the measurement results display a large variation, three different material files were used to describe the entire range of the measurement results. This proved to be an adequate method, especially for the location nearest to the end-grain surface experiencing water contact.

In Fig. 7, measured results are compared with simulated results (for both isotropic and anisotropic transport models) at M_{30} indoor (30 mm from water contact in the middle layer of the specimens which dried indoors) and S_{30} outdoor (30 mm from water contact in the surface layer of the specimens which dried outdoors). It is apparent that when the conditions are favourable for moisture dry-out (M_{30} indoor, 7–21 days in Fig. 7), then the model which considers isotropic material properties predicts considerably faster moisture dry-out than the measurement data suggests. The isotropic material transport model consistently predicts lower MC, with a final difference of −10 % MC to −3 % MC compared to measured values. Meanwhile, the anisotropic model shows a smaller difference, between −3 % MC and +3 % MC. The anisotropic transport model is also better at replicating the outlying measured values during periods of intensive moisture uptake. Replicating moisture uptake in the surface layer proves particularly difficult (S_{30} in Fig. 7). In the isotropic material transport model, even the results using the increased water uptake material file remain below the measured average during the wetting phase (0–7 days), despite aiming to surpass the average and approach the higher outliers. The other two files

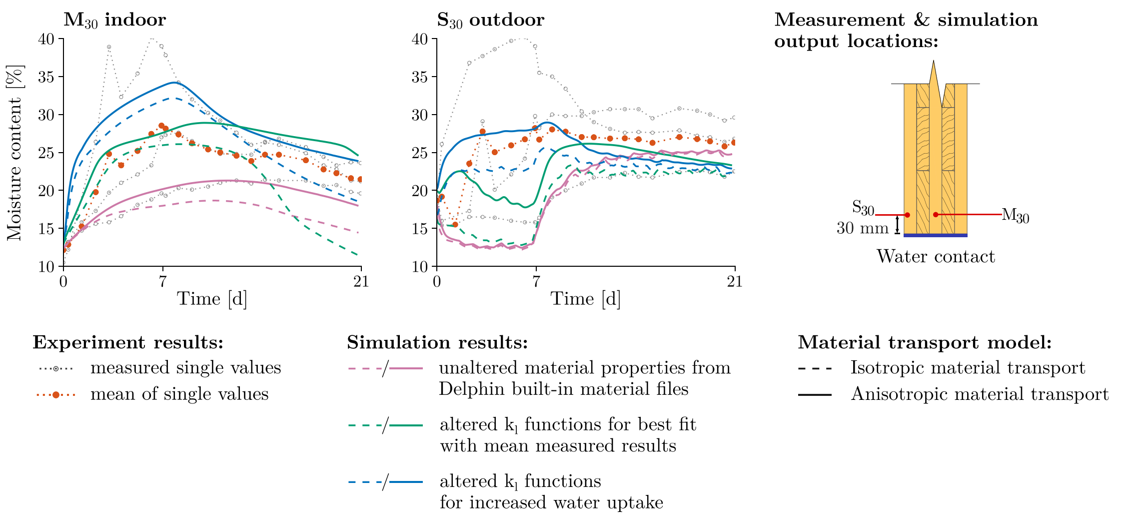


Fig. 7. Comparison of simulated values for the isotropic material transport model (dashed lines) and for the anisotropic material transport model (continous lines) with measured single values (dotted line & open circles) and the mean of measured values (closed circles).

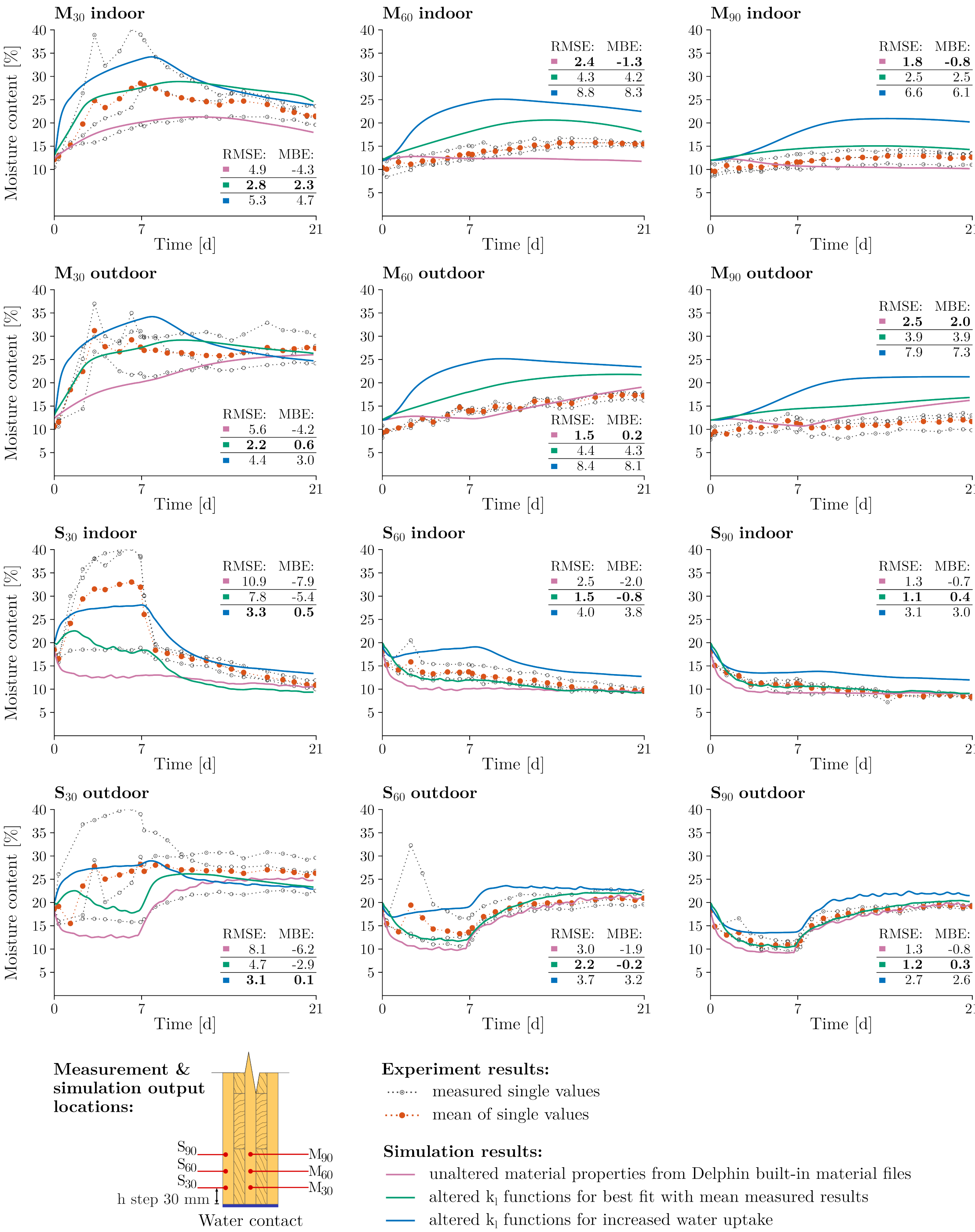


Fig. 8. Comparison of simulated moisture content values (continuous lines) with measured single values (open circles) and the mean of measured values (closed circles). Measurement data originates from experiment 1, section 2.1.1.

perform even worse, with results below the lowest measured values. The isotropic material model may be suitable for replicating 1D water uptake as shown in Fig. 7 (M_{30} indoor, 0–7 days; the middle timber layer behaves somewhat in a 1D manner in a CLT panel during the wetting phase). However, it becomes inadequate when multi-dimensional aspects start to dominate, such as when the moisture dry-out toward side faces becomes more prominent in the drying phase (M_{30} indoor, 7–21 days in Fig. 7). In these cases, or when multi-dimensional moisture redistribution and dry-out is already significant (e.g., surface layer results, S_{30} in Fig. 7), the anisotropic model proves more accurate. In the next comparisons, only the results from the better fitting anisotropic model are provided for clarity.

Fig. 8 compares the simulated moisture content (continuous lines) with measured single values (open circles) and the mean of measured values (closed circles) from experiment 1 (section 2.1.1). Simulation results are shown for three different anisotropic material files: 1) a file based on unaltered definitions from the Delphin database (magenta line), 2) an altered material file for the best fit (green line), and 3) an altered file for increased water uptake (blue line). Results are shown for the surface layer (*Si*) and middle layer (*Mi*) of the CLT panel at height *i* mm with statistical indicators RMSE and MBE included for each location.

The simulated values obtained from the middle layer at 30 mm from the water contact surface provide a good coverage of the range of measurement results in both indoor and outdoor drying conditions (M_{30} indoor and M_{30} outdoor in Fig. 8). The root mean square

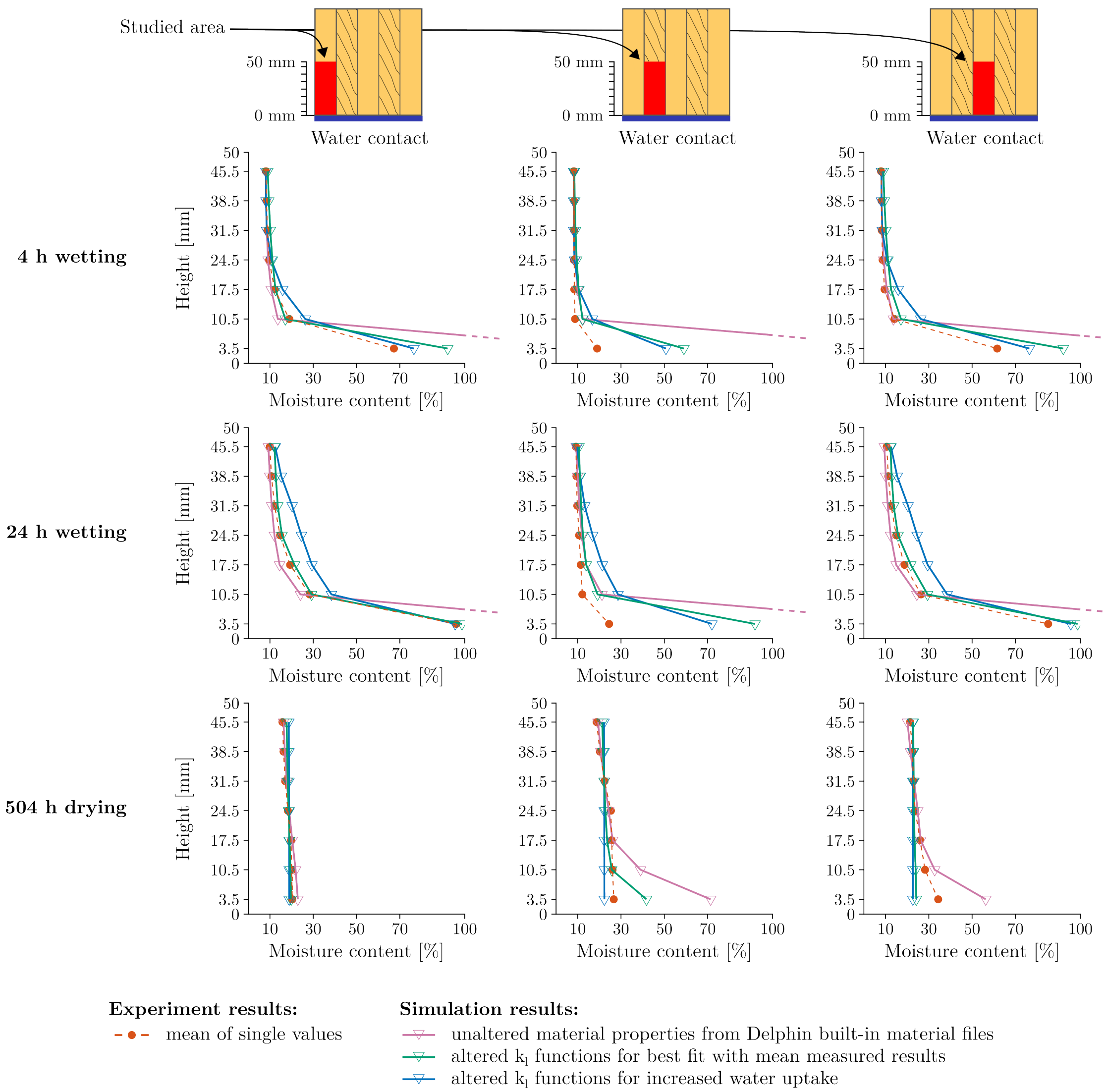


Fig. 9. Comparison of simulated results (open triangles and continuous lines) with the mean of measured values (closed circles and dashed lines). Measurement data originates from experiment 3, section 2.1.3.

error (RMSE) for the best fit model is between 2.2 and 2.8 while the mean bias error (MBE) is between 0.6 and 2.3, demonstrating a sufficient replication quality with little bias. This indicates a successful validation, considering that the uncertainty associated with the electrical resistance-based measurements at higher MC levels is of the same magnitude or higher.

For the results obtained at the height of 60 mm and 90 mm from the water contact surface in the middle layer (M_{60} and M_{90} in Fig. 8), good correlation is seen with the unaltered material file (RMSE between 1.5 and 2.5, MBE between −1.3 and 2.0), but both files with altered material definitions lead to an overestimation of moisture transfer in areas further away from the water contact (RMSE up to 8.8 and MBE up to 8.3). It was found that without altering the moisture storage function, specifically in the range of capillary pressure of approximately -10^6 Pa to -10^5 Pa corresponding to approximately 99.3–99.9 % RH, it was not possible to simultaneously achieve a good correlation with the observed extensive water uptake near the end-grain edges (M_{30}) and limited water uptake at the higher measurement points (M_{60} and M_{90}) with the given material files. Additional testing revealed that the moisture storage function is highly sensitive to alterations, which can produce vastly different results, but that analysis falls outside of the scope of the current article. Nevertheless, these observations are in line with the findings of Wang et al. [24], who also detected a significant impact of the moisture storage function.

The built-in material definitions in the Delphin database have quite a large variation in the storage functions (fine lines on the bottom right in Fig. 4) and substantial validation is necessary when dealing with simulations that take account of overhygroscopic moisture flow. Other material definitions produced even larger errors, as was already demonstrated during the pre-selection of the material files (Fig. 3).

Simulation results from the surface layer at the heights of 60 mm and 90 mm correlate very closely with measurement results (S_{60} and S_{90} in Fig. 8). However, simulated values for the surface layer at the point nearest to the water contact (S_{30} in Fig. 8) differ the most from the measurement results. The unaltered material file from the Delphin database produces the largest negative bias (MBE = −7.9 for indoor drying conditions and MBE = −6.2 for outdoor drying conditions), while the result obtained with the material file optimised for increased water uptake correlates well with the mean of the measurements (RMSE = 3.1–3.3 and MBE = 0.1–0.5).

Overall, the results are similar to what Brandstätter et al. [25] observed. Delphin (when used with the selected and developed material files) seems to simulate the initial intensive water uptake more accurately in the middle layer than the model developed by Brandstätter et al. [25], but less so in the surface layer at the point nearest to the water contact surface. Brandstätter and colleagues achieved an RMSE in the range of 1.0–4.0 with the same measurement dataset for their simulations.

The efficacy of the method of validating such simulation models with electrical resistance-based MC measurements is limited due to increased uncertainty of the measurements in the overhygroscopic range of MC in the CLT in the vicinity of the water contact surface. Therefore, the simulation results were also compared to the gravimetric MC measurement results (section 2.1.3). The comparison results are provided in Fig. 9, with simulated values shown as open triangles and continuous lines, and mean measured values as closed circles and dashed lines. Simulation results are again given for the three different anisotropic material files: 1) unaltered definitions from the Delphin database (magenta triangles and lines), 2) altered material file for the best fit (green triangles and lines), and 3) altered file for increased water uptake (blue triangles and lines). In this comparison, the altered material files produced a markedly better fit with the mean of the measured values than the initial unaltered material file (Fig. 9). The unaltered material file caused the MC to reach markedly high values (>100 %) in the areas closest to the water contact, even though none of the gravimetric measurements showed such high MC levels. The difference was largest among the results obtained from the transverse layer. According to the gravimetric measurements, MC in this layer remained below 30 % even in the areas closest to the water contact (average for the area between 0 mm and 7 mm from the water contact surface). This was also verified by generating a composite image of the TSs from the first experiment, where minimal staining was visible in the transverse layers (Fig. 10). To avoid compressing the scale and impairing readability, these results are represented by the dashed portion of the magenta line in Fig. 9. By the end of the dry-out phase the correlation improved, especially with the altered material files. The unaltered material file resulted in a more extensive moisture retention and thus longer dry-out times.

Klõšeiko et al. [57] have performed a capillary condensation redistribution (CCR) test and attempted to replicate the outcome with simulations using the Delphin hygrothermal modelling tool. Among other materials, the authors of that study tested spruce specimens and also found it challenging to reproduce the values obtained in the experiments. However, the results by Klõšeiko et al. mainly pertain to non-isothermal conditions that induce redistribution of capillary condensation, which is not the case with the experiments described here.

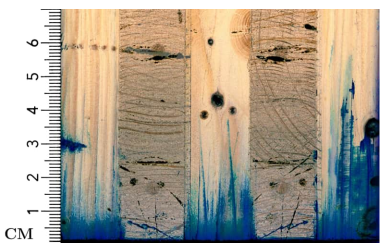


Fig. 10. Composite image of all TSs after water contact from the first experiment. Transverse layers show very little staining while the longitudinal layers exhibit significant water adsorption.

The water absorption coefficient (A-value) was determined separately for the longitudinal and transverse grain direction based on the second experiment (section 2.1.2). The measured values were 0.0138 kg/($m^2 \cdot s^{0.5}$) for the longitudinal direction and 0.0023 kg/($m^2 \cdot s^{0.5}$) for the transverse direction. The respective values in the material files from the Delphin database were 0.012 kg/($m^2 \cdot s^{0.5}$) and 0.0053 kg/($m^2 \cdot s^{0.5}$). While the longitudinal value in the selected material file from the Delphin database is 13 % higher than the measured value, the transverse value is more than twice as high. In the Delphin database there is only one transverse spruce material file that has a lower A-value (0.0024 kg/($m^2 \cdot s^{0.5}$)) than the selected material, and this value coincides well with the measured value. However, simulation results with this material file (ID626) indicate poorer correlation in the pre-selection exercise (Fig. 3). Wang et al. [24] validated a CLT hygrothermal simulation model generated in Delphin, and in their study the A-values were 0.012 kg/($m^2 \cdot s^{0.5}$) for the longitudinal direction and 0.0025 kg/($m^2 \cdot s^{0.5}$) for the transverse direction. All of the values presented above are well within the range of measured A-values for softwoods [30], but the results suggest that using the A-value as the sole basis for selecting a material file is not sufficient and that further validation is required.

While the simulations done in this study show some discrepancies as compared to the experimental data, the correlation was deemed sufficient to allow the corresponding models to be used in the CLT end-grain moisture safety analysis. It is possible to simulate both intensive water uptake and extended moisture retention. The risk associated with each moisture-related property depends on other factors such as the duration and frequency of precipitation (water contact) impacting the moisture dry-out potential. Therefore, all three selected and developed material files were used in further analysis.

3.2. Performance criterion development

Simulations for development of performance criterion were aimed at determining which initial MC distribution would result in the mould index M remaining below 1. It may be argued whether $M < 1$ is an appropriate criterion, but our position is that if the interior surface of the CLT panel can be exposed to the indoor air, it is reasonable to avoid condition $M > 1$. Other researchers concur that mould should not be allowed, even if it could be removed, because it is virtually impossible to check all connections and hidden areas [12]. Tengberg and Hagentoft [16] and Kukk et al. [1] have also opted for the $M < 1$ limit.

The calculations indicate that if the end-grain surface of CLT is exposed to water, the calculated maximum M on the inner face of CLT remains below 1 for scenarios where the initial moisture content of the CLT panel corresponds to that resulting from a maximum of 24 h of continuous water contact (Fig. 11). This was true for each simulated combination of humidity load and interior surface diffusion resistance (S_d 0.3 m–1 m) and with each material file. The mould index exceeded 1 in the case where the initial MC distribution was set at the level recorded after 48 h of wetting. In this case the mould index showed a tendency to increase in time for each ambient air and interior surface cover combination, except for the variant with low additional vapour resistance and low humidity load. The most critical material file with regard to mould growth was the one compiled on the basis of the unaltered files from the

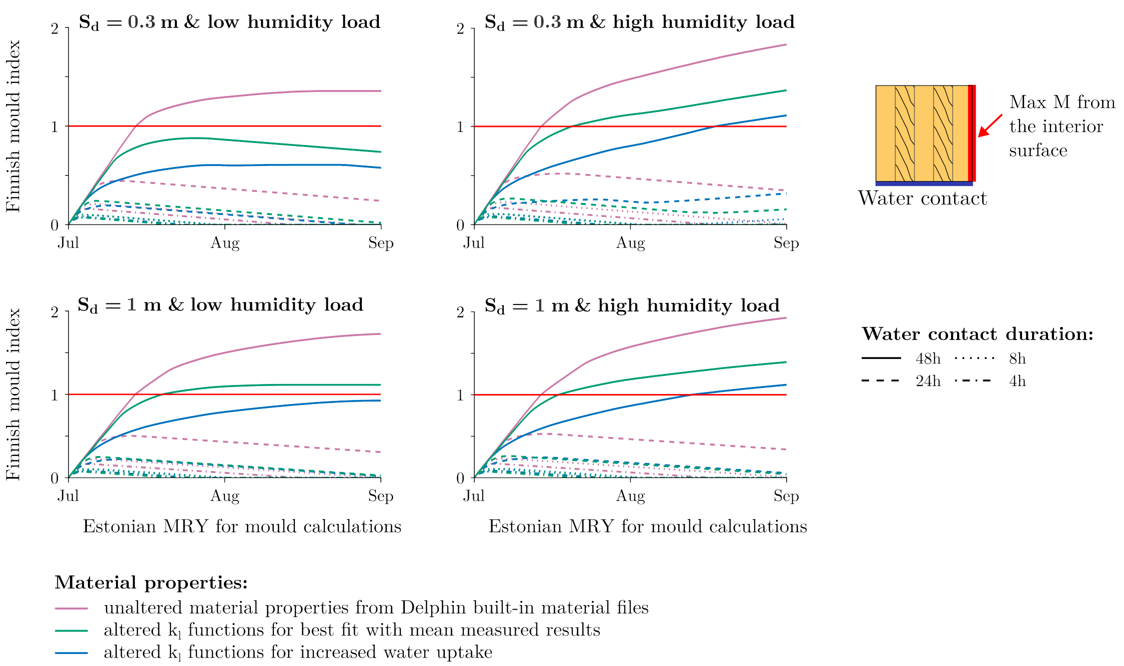


Fig. 11. Results of mould index calculations for performance criterion depending on additional water vapour resistance (S_d) of the interior surface and on indoor moisture load.

Delphin database. This is probably due to the longer moisture dry-out time when using this material file, as was demonstrated in the validation of the model (Fig. 9). The material definitions which were optimised for increased water uptake led to a faster moisture dry-out and thus resulted in a slower mould growth. Nonetheless, if the initial moisture content was high enough and there was a higher indoor humidity load and/or an increased vapour resistance of the interior surface of the CLT (up to $S_d = 1$ m), the increased dry-out rate did not lead to prevention of mould growth. Thus, the MC distribution derived from the 24-h wetting was set as the basis for defining the two-step MC performance criterion. Olsson et al. [58] also concluded after their laboratory studies that surfaces which were exposed to one day of wetting and then given the opportunity for open drying did not give rise to mould growth.

At the height of 30 mm from the water contact surface, the average starting MC which did not result in a mould index greater than 1, was up to 13 % in the longitudinal layers and 10 % in the transverse layers (refer to Fig. 5 for the comprehensive initial MC distribution). In their study on the hygrothermal criteria of CLT surfaces, Kukk et al. [2] concluded that for both the interior and the exterior surface, the initial MC should not exceed 16 % if mould growth is to be avoided. They also stated that if the interior surface is covered with vapour permeable interior finishing, the requirements can be more lenient. Since the MC limit at 30 mm can be linked with the requirements for the overall surface, it is reasonable to set the limit at 30 mm from the end-grain edge to be 16 % as a performance criterion. Furthermore, the European standard establishing the requirements for CLT (EN 16351:2021 [29]) states that at assembly, the moisture content of each timber board comprising the CLT shall be between 6 % and 15 %. It would not be logical to set the MC limit for the construction period lower than the standard limit for the production stage. However, since the initial moisture content at that height level was set to be lower in calculations based on the measured data, an additional simulation was performed to assess whether increasing the initial moisture content to 16 % in areas previously set to have an initial moisture content between 10 % and 15 % would alter the outcome. The results indicated little change, with the maximum mould index remaining just below 1 even under the most critical environmental conditions. Thus, using 16 % as the upper MC limit at 30 mm from the water contact surface inside the outermost longitudinal ply was considered safe.

For the area at 10 mm from the water contact surface, the initial MC in the models where M did not exceed 1 was up to 28 % in the longitudinal layers and 12 % in the transverse layers. While the average MC of the bottom-most slice of the longitudinal layer was 28 %, it is probable that wood cell walls nearer to the water contact surface were saturated with water. Although the definition of wood fibre saturation point (FSP) is somewhat unclear [59], in practical terms it is generally considered to be around 30 % [30]. This level of MC implies a rather high risk in terms of biodegradation – the minimum MC conducive to the growth of wood decay fungi is also generally considered to be at the FSP, that is to say near 30 % [60]. Brischke et al. have shown that loss of mass due to fungal decay in Norway spruce can also occur at a level below the FSP in a high RH environment [61]. However, in environments where RH was up to 93 % and the calculated initial MC was approximately 25 % there was negligible mass loss and the wood MC also remained below the FSP (which they calculated to be 30.3 %) after a 16-week inoculation period. This provides the basis for setting the threshold MC in the bottom-most layer at 25 % for the two-step MC limit. For practical implementation, the moisture content limit should be verifiable using an electrical resistance-based moisture content measurement device. Consequently, the limit should fall within the measurement range to ensure sufficient accuracy. Generally, electrical resistance-based measurement devices are most accurate up to the FSP, although it also depends on the specific device. Some authors consider the useable upper limit of an electrical resistance based moisture

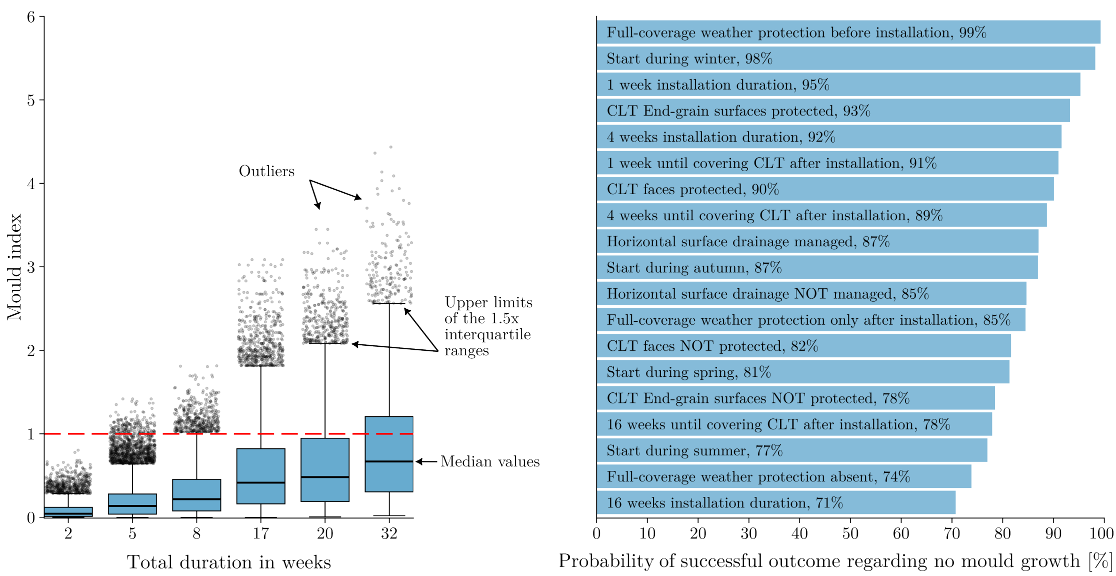


Fig. 12. Maximum mould index for all simulated combinations (left) and the probability of maximum M remaining below 1 during the CLT installation period and the post-installation period until covering the CLT with additional material layers (right).

meter to be 25 % [32]. It was thus deemed reasonable to set the performance criterion for the height of 10 mm from the end-grain surface at 25 % as opposed to the 28 % derived from the calculations. This difference can also be considered as a useful safety margin.

In summary, the target MC (performance criterion) for the CLT end-grain moisture safety analysis in this study were initially established as being 16 % MC at 30 mm and 25 % MC at 10 mm from the water contact surface in the CLT panel's longitudinal layers (with regard to the water uptake direction) when the panels are no longer exposed to precipitation and are about to be covered by additional structural layers. The target MC criterion is intended to only apply for situations where at least the interior surface of the CLT panel is relatively open for moisture dry-out.

3.3. Analysis of CLT wall panel end-grain moisture safety

The development of mould index was analysed throughout the entire simulation period covering the CLT installation duration and the post-installation period. In less fortunate circumstances, mould growth started during the construction period (before the CLT would have been covered with additional material layers). Approximately 14 % of the studied combinations ($n = 77\ 760$) yielded a mould index larger than 1 ($M > 1$) when calculated on the basis of temperature and relative humidity on the surface of the CLT panel at 10 mm or 30 mm from the water contact level (the highest M value at those heights was taken into account). It was discovered that in the cases where the mould index exceeded 1 at both the 10 mm and the 30 mm height level, the features common to the cases were absence of end-grain protection (76 % of the observations where $M > 1$) and absence of face protection (65 %). The longest installation duration (16 weeks) was also well represented, accounting for 69 % of the cases with $M > 1$, while the share of such cases with a 16-week post-installation period was 52 %.

Overall, the longer the total duration, the higher was the risk of mould growth, regardless of other factors (Fig. 12, left). The median value of M remained below 1 for all durations, but for the combinations with a total duration (installation duration + post-installation period) of 32 weeks, the third quartile of the mean M value of each observation was over 1. There were outlier instances with $M > 1$ in all the combinations except for the variant with a total duration of 2 weeks. In some outlying cases (2 % of all instances) the maximum mould index exceeded 2. This occurred when the total duration was longer than 17 weeks.

None of the cases where M exceeded 2 had full-coverage weather protection implemented before CLT installation and only 4 % of those cases featured end-grain protection. M exceeded 2 in 25 % of the cases where CLT face protection was applied, and all these cases had the end-grain surfaces unprotected.

The results of the mould index calculations indicate that implementing full-coverage weather protection prior to installing CLT elements, for instance in the form of a tent-like structure, largely reduces the likelihood of mould formation, resulting in a 99 % probability of prevention of mould growth during the CLT installation stage and the subsequent construction period preceding the covering of the CLT panels with additional layers (Fig. 12, right). This option is closely followed by CLT installation during winter (98 %) and performing a quick, 1-week installation (95 %). These three options are thus the safest ones as regards mould growth during the CLT construction period when the CLT panels are not yet covered with additional layers. The factor producing the lowest probability of preventing mould growth was the 16-week installation period. An in-situ research done at construction sites in Sweden (with monitoring periods of 2–5 months) [62] showed that 75 % of the CLT specimens exposed to external weather conditions experienced mould growth, but none of the specimens under a weather protection structure did, which demonstrates the validity of the outcomes of the current study. The researchers also applied mould prediction models (MRD and MOGLI) based on measured temperature and RH, but the calculations predicted mould growth in only one case. This could have been due to using air RH as an input, as opposed to RH on the surface of the specimens, which was used for input in the current study. Previous research has indicated that using wood surface RH as input is more accurate for mould growth analysis [50].

Mould growth is a complex process influenced by a number of factors including the type of substrate (which in this case is planed timber), humidity, temperature, and exposure time. It is possible that despite a high level of humidity (i.e. high timber MC), mould growth does not start due to a low temperature (as would be the case when building during winter) or because the period with suitable conditions is too short. However, conditions may change due to the covering of the CLT panels with additional material layers or due to an increase in ambient temperature from heating. Therefore, monitoring (and calculating) mould growth up to the point where the CLT

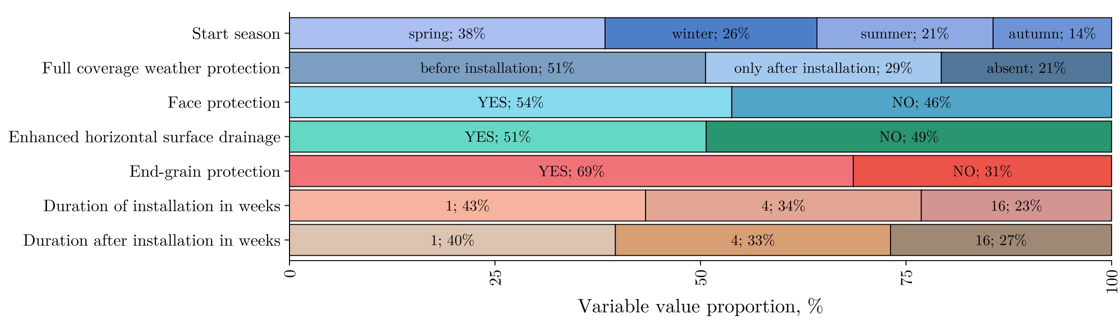


Fig. 13. Proportions of the values of different variables in the subset where both the mould index and the moisture content remained below the set limits ($M < 1$, $MC_{10\ mm} \leq 25$ % and $MC_{30\ mm} \leq 16$ %).

is covered is only one aspect of moisture safety assurance. Ensuring that the MC of the CLT is within safe limits before covering the panel is as important as making sure there is no mould growth. Here, the two-step MC limit (as defined in section 3.2) becomes relevant. To consider an outcome successful in terms of both limiting mould growth and meeting the MC target, the MC as recorded at the final hour of the simulation must have fallen within the specified limits: $MC_{10\ mm} \leq 25$ % and $MC_{30\ mm} \leq 16$ % (at 10 mm and 30 mm from the water contact surface, respectively), and the mould index must consistently remain below 1 throughout the simulated period encompassing both the CLT installation stage and the time until additional material layers are added to the CLT. It is expressed accordingly in Equation (1).

$$OK = \begin{cases} MC_{10\ mm} \leq 25\% \\ MC_{30\ mm} \leq 16\%, \\ M < 1 \text{ up to covering CLT} \end{cases} \quad \text{Equation 1}$$

Fig. 13 shows the extent to which each value of the employed variables is represented in the subset with only successful results (performance criterion from Equation (1)). The data show that the most effective measure is end-grain protection – 69 % of the successful combinations included CLT end-grain protection. Face protection as well as enhanced horizontal surface drainage seem to provide only a marginal advantage with regard to CLT end-grain moisture safety. Full-coverage weather protection (FWP) before CLT installation is more represented than the two other options for FWP. As for the installation start season, the most favourable period turns out to be spring, with autumn being the least favourable.

The probabilities of a successful end-result (i.e. when both M and MC targets are met) for all the studied variables are presented in Fig. 14. These values should be interpreted in such a way that the probability of success for the specified option is applicable when all other variables are unknown. When using the initial performance criterion (Equation (1)), the highest probability of success is achieved with installation starting in spring (58 %), followed by full-coverage weather protection (57 %) and CLT end-grain protection (52 %). If the only known factor is the duration of installation or post-installation period, the probability of success is between 38 % and 49 % for the duration of one or four weeks but drops to 26 % for the 16-week installation period.

Evidently, if other parameters are unknown, the start during a favourable season can be considered as effective as full-coverage weather protection. Of course, other variables can influence the outcome markedly, but the results indicate that choosing the installation season can be a valid moisture safety measure. On the other hand, they also show that if for example there is a delay in the procurement process, moisture safety could be compromised due to the change of construction start season, as start in autumn is the least favourable option with a success rate of only 22 %. The options of having no full-coverage weather protection (success rate 23 %) and no CLT end-grain surface protection (24 %) are also undesirable. Tengberg and Hagentoft [16] have previously also concluded that the season of construction has a significant effect on moisture safety of CLT buildings. However, for their chosen location (southern and south-central Sweden) and performance targets, the favourable seasons were summer and early autumn, while winter was less favourable. The targets used by Tengberg and Hagentoft [16] were similar to those in the current study: 1) MC < 18 % in the outer layer (0–20 mm) at the time of covering the surface, and 2) M < 1 on the surface of CLT. However, there were differences in the used material properties and in the way the employed simulation programs work. Tengberg and Hagentoft implemented the one-dimensional simulation program WUFI Pro and stated that they used the generic "Spruce radial" material from the WUFI database without considering material anisotropy or variations. The current study explicitly focuses on end-grain wetting of CLT, considers material anisotropy and variations, and uses combinations of a larger number of variables in the analysis. Due to water adsorption in the longitudinal wood grain direction and reduced moisture dry-out from the middle layers of CLT, the criticality of end-grain moisture

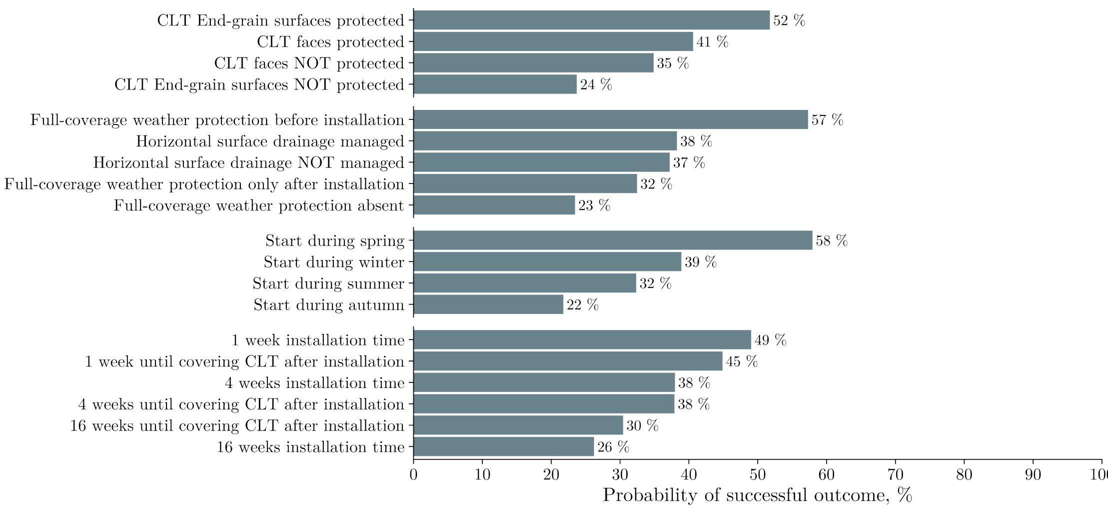


Fig. 14. Probability of a successful end-result (maximum M < 1 and $MC_{10\ mm} \leq 25$ %, $MC_{30\ mm} \leq 16$ %) for all the studied variables.

safety may differ from that of the CLT surface layers explaining the differences of the results compared to that of Tengberg and Hagentoft [16].

3.4. Sensitivity analysis of the performance criterion and further development

The results in the previous section indicate that the probability for a successful outcome overall is low. Further investigation shows that in many cases this is due to MC exceeding the $MC_{30\ mm} \leq 16$ % target even without wetting incidents i.e. due to hygroscopic moisture absorption from the ambient air which in turn is linked to longer exposure times to the outdoor air in case of longer installation and construction durations. It is also evident that the three different material file combinations behave differently in this regard. The material properties optimised for the best fit with the mean of the measurement results predict less moisture absorption and retention, leading to more results categorised as successful than with the two other material files. When looking at only the results where the $MC_{10\ mm} \leq 25$ % target is met, but the $MC_{30\ mm} \leq 16$ % target is not, it appears that the material file for the increased water uptake is overrepresented (43 % of the failed results), while the material file with the best fit to experimental data is least represented in the failed outcomes (24 %). While it is possible that in a CLT panel there are areas which absorb water vapour very well, it is not the case for the entire panel due to the heterogenic nature of wood and CLT being comprised of several timber boards. It is not known how the three options for the material properties are distributed in the timber stock in CLT production. In the current analysis they are treated as equal, which might lead to results that suggest worse performance. Furthermore, the MC target values were developed based on the critical MRY for mould growth calculations further biasing the outcomes towards poorer performance. Of the outcomes categorised as unsuccessful due to exceeding the $MC_{30\ mm} \leq 16$ % target, only 9 % had the mould index exceed 1 and less than 0.2 % had $M > 2$. To mitigate the stringent nature of the performance criterion, it is possible to increase the $MC_{30\ mm}$ target, while maintaining the $MC_{10\ mm}$ target at 25 %. This proposal is further corroborated by the higher target (18 %) used by Tengberg and Hagentoft [16], but also by the European standard EN 335:2013 “Durability of wood and wood-based products” [63], which states that an MC of more than 20 % is usually necessary for the development of fungi.

However, for better practical implementation, another solution would be to verify the $MC_{30\ mm}$ target compliance only if $MC_{10\ mm}$ exceeds a certain level, which indicates a possible end-grain wetting or a long enough exposure to humid air that elevated scrutiny is needed. Previous research has shown that it is unlikely that mould growth on CLT would occur solely because of air humidity [32,62,64]. Moreover, recent research has also indicated that for spruce and pine, a 75 % or even more than 80 % RH is too low for mould growth [65]. It is thus proposed that for validating the target MC at the higher measurement point a risk detection at the lower measurement point should precede. For example if $MC \geq 19$ % (as a middle ground of the 18 % used by Tengberg and Hagentoft [16] and 20 % limit of EN 335:2013) is detected at the 10 mm measurement point, then MC at 30 mm should also be validated. For the moisture retention curves used in the material files, the 19 % MC corresponds to approximately 86–87 % RH. Ryparová et al. [65] tested the initiation of mould growth on inoculated pine and spruce specimens at an RH of 75 %, 87 % and 95 % at a constant 22 °C. Mould growth was observed only at 87 % and 95 % RH, with microscopic signs appearing after a minimum of 7 days (19 days in transverse spruce) under highly favourable conditions. Furthermore, the results from experiment 3 show that in the longitudinal layers of CLT, 19 % MC is reached after 4 h of wetting from the end-grain and after 8 h MC is well over 19 % (Fig. 5). This implies that $MC < 19$ % is only attainable with short wetting periods, during which the calculated M remained low in the mould calculations for the performance criterion development (Fig. 11). Based on this, 19 % MC is deemed as a safe limit for the supplementary clause in the performance criterion. The performance criterion with the supplementary clause is expressed as follows in Equation (2).

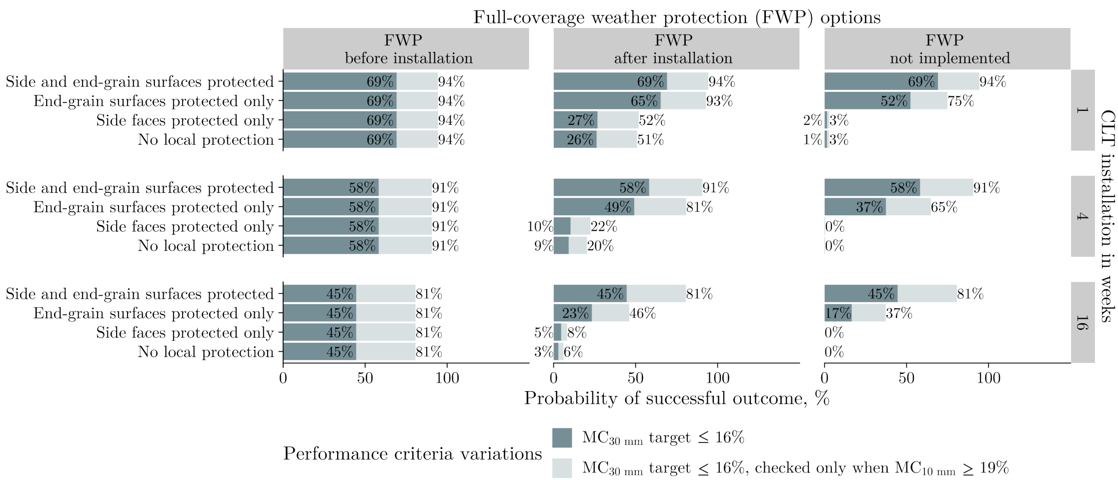


Fig. 15. Probability of a successful end-result (maximum $M < 1$ and $MC_{10\ mm} \leq 25$ %, $MC_{30\ mm} \leq$ varies) for different FWP and local protection measures and CLT installation period durations.

$$OK = \begin{cases} MC_{10\ mm} \leq 25\% \\ MC_{30\ mm} \leq 16\%, \quad \text{when } MC_{10\ mm} \geq 19\ \% \\ M < 1 \text{ up to covering CLT} \end{cases} \quad \text{Equation 2}$$

The results in Figs. 15 and 16 present the calculated success probabilities for both approaches for the $MC_{30\ mm}$ target, using the original target (Equation (1)) and the updated target with the supplementary clause, as shown in Equation (2). The $MC_{30\ mm}$ target with the supplementary clause (Equation (2)) substantially increases the number of results meeting the set targets (i.e. observations considered successful). For example, the probability of success rises to 94 % for the case of full-coverage weather protection implemented before the installation of CLT. The change in the probability of success is less prominent for the option of choosing spring as the start season (from 58 % to 68 % when applying the supplementary clause to $MC_{30\ mm}$ target). For other factors, the increase in the success rate is around 20–30 %.

Since the probabilities discussed above yielded only generalised information, as they were calculated considering all co-variations, the next step was to analyse combinations of certain selected subsets. Different protection strategies can be combined, and the results vary depending on the CLT installation duration, total construction duration and start season. Fig. 15 shows the results for combinations of different FWP options and localised protection methods, divided into blocks according to the CLT installation duration. The start season, time duration after installation, and horizontal surface drainage implementation level are included as sub-variables which function as factors of randomness.

With the original MC targets without the supplementary clause (Equation (1)), the probability of a successful outcome is reduced to below 50 % even for the cases where FWP is implemented before the installation of CLT panels, if the installation duration is 16 weeks (Fig. 15, bottom left). However, when the supplementary clause is used for the $MC_{30\ mm}$ 16 % target (Equation (2)), the probability for success remains over 90 % and falls to 81 % only for the longest 16-week installation duration, if FWP is implemented before CLT installation. With the supplementary clause, the results are more convincing, as FWP should only fail in rare, extreme cases of very high ambient RH.

If full-coverage weather protection (FWP) is erected only after the CLT installation (Fig. 15, centre column), the probability for success decreases greatly if the end-grain surface is not protected. This is true with both performance criteria variants. The reduction of the probability for success is especially evident when the installation duration is 4 weeks or more. In that case the probability of success is less than 10 % without local protection (considering the original performance criterion, Equation (1)). Adding side face protection in

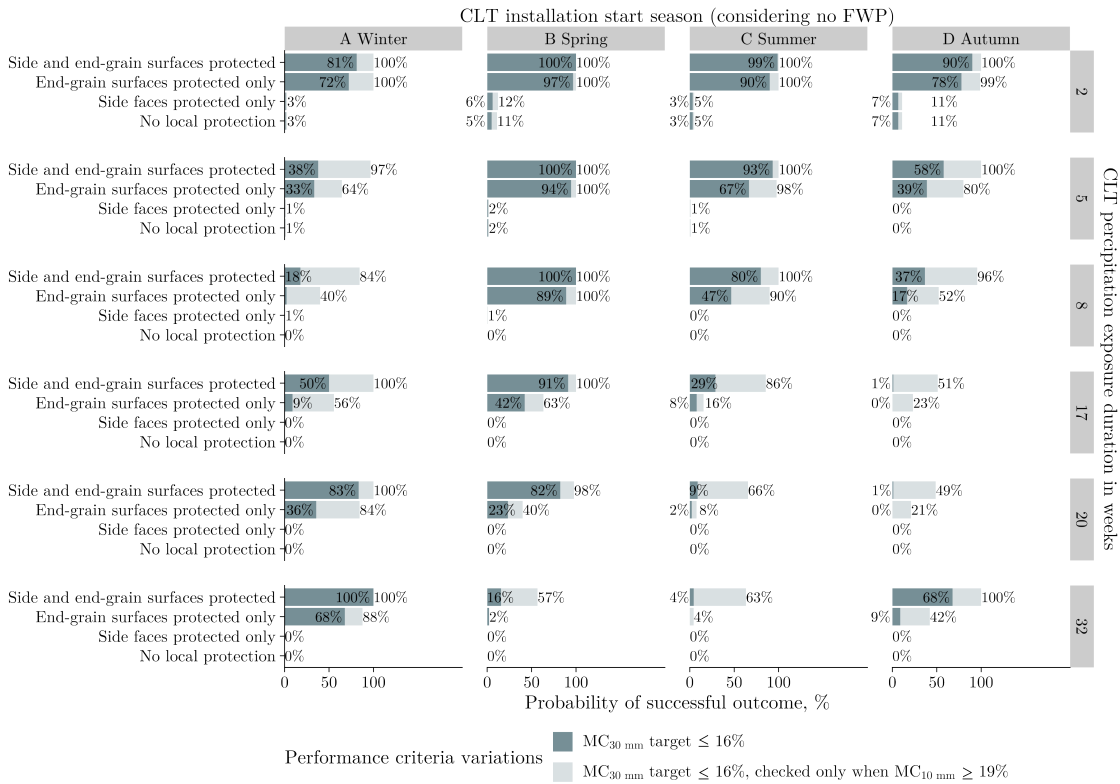


Fig. 16. Probability of a successful end-result (maximum $M < 1$ and $MC_{10\ mm} \leq 25$ %, $MC_{30\ mm} \leq$ varies) for the subset of combinations with no full-coverage weather protection (FWP).

conjunction with end-grain protection contributes marginally to the success rate for shorter installation durations but becomes clearly advantageous for longer installation durations. Side face protection without end-grain protection has negligible positive effect with regard to CLT end-grain moisture safety.

If FWP is not used (Fig. 15, right column), it is almost certain that the MC targets will be exceeded for the cases without end-grain protection, even when the installation duration is kept short. One of the hypotheses for this analysis was that a short installation duration might be enough to avoid end-grain wetting, but the calculations with the 30-year climate data show that even for an installation duration as short as one week, it is highly likely that there will be enough precipitation to cause excessive wetting. This is true regardless of the installation start season (Fig. 16) – the probability of success is negligible if neither FWP nor local protection measures are used (irrespective of the performance criterion selection). Nevertheless, starting in spring yields slightly better results. It can also be seen from Fig. 16 that when using the original performance criterion for $MC_{30\ mm}$ (Equation (1)), the probability of success diminishes rapidly with the increase in construction time when starting in summer, because the humid autumn season follows.

3.5. Anticipated moisture dry-out times for the analysed scenarios

Comparison of the effects of different levels of FWP implementation reveals that allocating time for moisture dry-out even without heating, i.e. in outdoor climate conditions (but without precipitation) is beneficial. To analyse the anticipated moisture dry-out times, the development of MC was examined for cases without any local moisture protection and no FWP during installation, but with FWP after installation. In these scenarios, the CLT panels became wet and then had the opportunity to dry out under an FWP cover. The simulated moisture dry-out times for these cases are presented in Table 6. The mean moisture dry-out time was calculated by averaging the dry-out times achieved with the three different material files used in the simulations. Table 6 also includes the minimum and maximum dry-out times (shown in parentheses) for each scenario, stemming from the material file variations.

For the area closer to the end-grain surface (10 mm), the limiting MC value has been set to 25 % (see section 3.2). If the CLT installation lasts for 1 week, the anticipated moisture dry-out time considering $MC_{10\ mm}$ is up to one week if the dry-out start season is spring or summer, up to two weeks if it starts in autumn and up to five weeks for a winter start. If the CLT installation duration is four weeks, the same general pattern applies, but the dry-out times are longer: in spring the moisture still dries out in approximately one week, but in summer it can take up to two weeks, and when the dry-out starts in autumn or winter, it can take from one to seven weeks to achieve the $MC_{10\ mm} \leq 25$ % target with the average being 5–6 weeks for the colder seasons (Table 6). In the case of the longest installation time of 16 weeks and thus very high initial MC, the average moisture dry-out time is at least two months for autumn and winter. This is in agreement with on-site observations of Kalbe et al. [22] which revealed that in buildings where the total time of exposure to precipitation was between 15 and 21 weeks and the onset season for moisture dry-out was autumn, the dry-out times were up to four months and in several cases the use of additional heating or drying equipment was necessary.

At 30 mm from the water contact surface, the MC should return to below 16 %, but in most cases, this seems unobtainable, except for when the moisture starts to dry out in spring (Table 6). The reason behind this is that during spring in Estonia, the mean relative humidity of the outdoor air is at its lowest (68 % for week 20, based on 30 years of climate data). However, it gradually increases throughout the summer and autumn, reaching 90 % on average by week 47. Thus, obtaining MC values below 16 % at 30 mm from the water contact surface is not particularly likely, except in spring. For further consideration, the dry-out times for $MC_{30\ mm}$ are given for three MC targets: 16 %, 18 % and 20 % respectively.

If the target MC at 30 mm height is set at 20 %, unassisted moisture dry-out becomes possible for the summer season as well. The average MC decreases to below 20 % in about one week and stabilises above 16 % if the CLT structure is exposed to the elements for one week and the dry-out starts in the summer season. If the structure is left exposed for four weeks, it takes two weeks for the $MC_{30\ mm}$ level to drop below 20 % followed by stabilisation at around 18 %, if the dry-out start season is summer. However, for the 16-week installation period, the MC stabilises at around 20 % after approximately three weeks of unassisted drying in the summer season. If the

Table 6
Mean moisture dry-out times in weeks until the specified target moisture content (MC*i*) at *i* mm from the water contact surface is achieved. The values in parentheses are the shortest and longest dry-out times for the different material files.

Drying start season	Installation duration in weeks	Time in weeks until target MC_i at the height *i* is achieved			
		$MC_{10\ mm} \leq 25$ %	$MC_{30\ mm} \leq 20$ %	$MC_{30\ mm} \leq 18$ %	$MC_{30\ mm} \leq 16$ %
Winter	1	**3** *(1–5)*	**7** *(5–8)*	**10**	**13** *(12–15)*
	4	**6** *(2–7)*	**8** *(7–8)*	**9** *(8–10)*	**12** *(11–13)*
	16	**8** *(4–9)*	**10** *(8–10)*	**12** *(10–12)*	**13**
Spring	1	**0,3** *(0,1–1)*	**0,6** *(0,1–0,2)*	**0,7** *(0,2–0,4)*	**1**
	4	**0,5** *(0,2–1)*	**0,9** *(0,1–0,3)*	**1** *(0,1–1)*	**3** *(1–4)*
	16	**1** *(0,3–2)*	**2** *(1–2)*	**3**	**4** *(3–6)*
Summer	1	**0,7** *(0,2–1)*	**1** *(0,1–1)*	**2** *(0,3–1)*	**> 16**
	4	**1** *(0,2–2)*	**2** *(1–2)*	**> 16**	
	16	**2** *(0,3–2)*	**3** *(2–3)*		
Autumn	1	**1** *(0,3–2)*	**2** *(1–2)*	**> 16**	**> 16**
	4	**5** *(1–7)*	**15** *(14–16)*		
	16	**10** *(4–13)*	**> 16**		

dry-out start season is winter, the MC remains higher than 20 % for at least two months, regardless of the initial MC. If the dry-out period starts in autumn, the 20 % target is attainable only if the installation duration is one week, while with longer installation periods that entail a higher initial MC, the MC remains well above 20 % for more than two months.

Researchers have observed fungal growth in CLT structures under construction when the MC of the wood surface reaches or exceeds 19 % [32] and thus the 20 % target is not advisable. The observed cases where the MC remained elevated for long periods are likely the same ones in which the mould index exceeded 1 or even 2 in the previous simulations (Fig. 12, left). It is evident that unassisted moisture dry-out is not a feasible moisture safety practice except if the dry-out starts in spring (i.e. during a period when the relative humidity of the outdoor air is at its lowest) or if it starts in summer after a period of precipitation exposure shorter than a month (in that case, $MC_{30\ mm} \leq 18$ % is attainable; see Table 6). During winter and autumn, the moisture dry-out potential is insufficient for the excess moisture to leave in a timely manner without assisted drying. Shirmohammadi and Faircloth [66] investigated fan drying on wetted CLT panels and showed promising results. The fan-dried sections achieved lower MC more quickly than ambient drying, however there was a larger MC distribution inside the CLT panel in case of fan drying. Future investigations of alternate drying methods could also be improved if the anisotropy of the material properties would be included in the hygrothermal models.

During the seasons with a lower moisture dry-out potential, there is a larger variation of dry-out times between cases with different material definitions. The materials which were optimised for increased water uptake exhibit shorter moisture dry-out times. It is possible that some areas of a CLT panel dry out quicker than others, but the opposite is also true. It is not feasible to perform moisture measurements with a very high spatial resolution, and therefore it is possible that areas requiring a longer dry-out during the construction period remain unidentified. It is hence sensible to base the moisture safety plan on at least the mean values presented in Table 6, or even on the maximum moisture dry-out times (shown in parentheses in Table 6) for a more conservative approach. If the moisture dry-out time exceeds what is feasible within the construction schedule, assisted moisture dry-out is recommended.

Table 7 provides a summary of the results for the most typical combinations. The post-installation full-coverage weather protection can be achieved through different methods capable of eliminating exposure to rainwater in an effective manner comparable to the use of a tent-like weather protection structure. A post-installation period of one week prior to covering the CLT with additional material layers is deemed reasonable, particularly if fast construction is a priority, but four weeks may also be acceptable if the construction schedule allows it. Since the CLT side surfaces are typically covered with protection foil, only the combinations with face protection are accounted for. The options related to the installation season and implementation of horizontal surface drainage have been allowed to vary. According to the presented results, if end-grain protection is used in combination with a short installation period followed by a one-week moisture dry-out period, the likelihood of success stands at 93 % if using the original target for $MC_{30\ mm}$ (Equation (1)). This would be a similar strategy which Time et al. [33] investigated. In their study, the strategy included installation during the driest period, the end-grain surfaces were protected and moisture dry-out was allowed before covering the structures. However, as our research shows, in the absence of end-grain protection, with the other variables left unchanged, the probability of success drops to 20 %. For the installation durations of four weeks and sixteen weeks, the probability of success is negligible without end-grain protection, but increases to 72 % and 43 %, respectively, with the inclusion of end-grain protection. Extending the post-installation period from one week to four weeks (while employing full-coverage weather protection) increases the probability of success for the variants without end-grain protection very slightly due to the improved moisture dry-out, but if the start season is unknown (i.e. the cases are distributed equally among all seasons), the success rate remains low for all cases with no end-grain protection. If the updated $MC_{30\ mm}$ target with the supplementary clause is used (Equation (2)), the number of cases yielding a successful outcome increase, but the likelihood of success in the absence of end-grain protection and with variables such as the start season left undefined still remains modest, even when using the shortest installation duration.

3.6. Analysis of interannual variability and correlation with climatic factors

Additionally, the interannual variability of success ratios and their correlation with climatic factors were analysed. There was quite a large variability in the share of successful results between different simulated years (Fig. 17, top left). The mean value was 38 % while the standard deviation was 5 percent points. Some outlying cases differed from the mean value more than 10 percent points. Over time, there is a trend towards a smaller share of successful results, but the correlation is weak. The correlation was also assessed using yearly mean temperature, mean relative humidity, and rainfall amounts (Fig. 17). A modest correlation was identified with the yearly rain amount and a stronger association was revealed with the mean outdoor air relative humidity.

3.7. Limitations of the study

The study has limitations in each of the focus areas that warrant discussion. First, the hygrothermal simulation model is validated only with measurements conducted on spruce. However, other wood species are also used in CLT manufacturing. Nevertheless, the work demonstrates the usefulness and accuracy of the 2D anisotropic hygrothermal simulation, which can serve as a basis for future work with other wood species.

Additionally, there is a large variability in the water uptake rate and extent, which the three different files for the anisotropic spruce material aimed to replicate. While the replication was sufficient, it is not known how these varying properties are distributed among a typical batch of timber boards that comprise CLT. For reliable distribution information, a separate comprehensive study is needed, although it would still have a great level of uncertainty deriving from the uncertainty of growth conditions of the timber. Currently, the analysis assumes equal distribution of the properties. Alternatively, including only the material file that leads to the most critical conditions could be used instead, as moisture damages occur first in areas where the material properties favour damage occurrence and

Table 7
Results for selected common moisture safety scenarios using both approaches for the $MC_{30\ mm}$ target (using the original target as in Equation (1) and using the updated target with the supplementary clause, as shown in Equation (2)).

Full-coverage weather protection	Face protection	Start season	Horizontal surface drainage implementation	Duration after installation in weeks	Duration of installation in weeks	End-grain protection	Probability of success (%)	
							$M < 1$ and $MC_{10\ mm} \leq 25\ \%$, $MC_{30\ mm} \leq 16\ \%$	$M < 1$ and $MC_{10\ mm} \leq 25\ \%$, $MC_{30\ mm} \leq 16\ \%$ checked only when $MC_{10\ mm} \geq 19\ \%$
After installation	Yes	Varies	Varies	1	1	yes	**93**	**100**
						no	**20**	**29**
					4	yes	**72**	**99**
						no	**3**	**6**
					16	yes	**43**	**84**
						no	**0**	**0**
				4	1	yes	**72**	**99**
						no	**27**	**51**
					4	yes	**59**	**95**
						no	**6**	**14**
					16	yes	**44**	**78**
						no	**0**	**0**

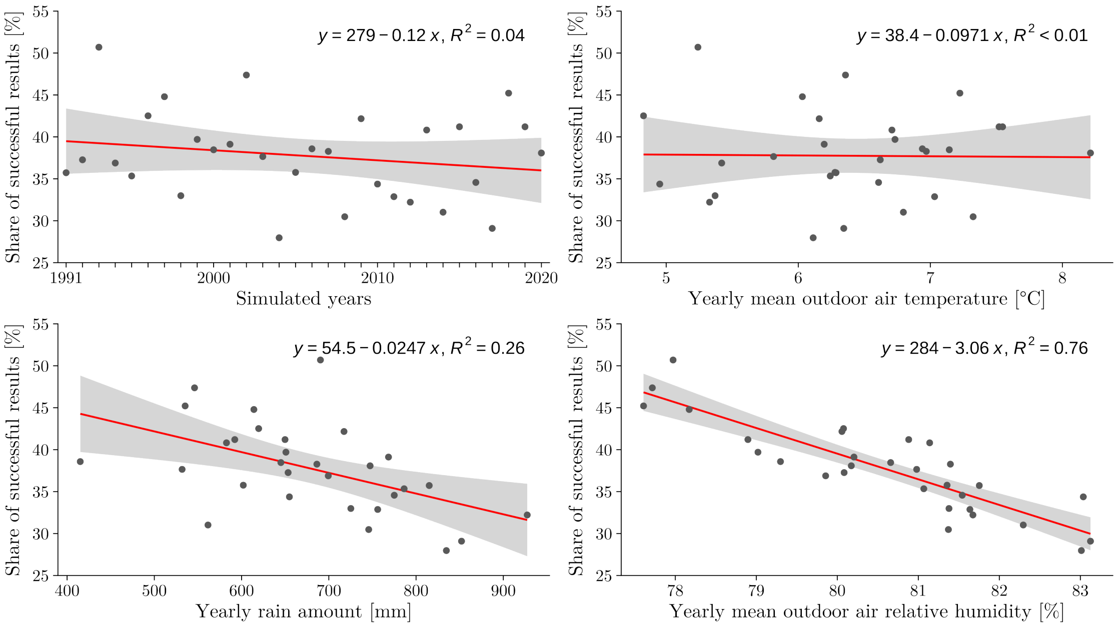


Fig. 17. Correlation of the share of successful results (y-axis) with simulated years (top left), yearly mean outdoor air temperature (top right), yearly rain amount (bottom left), and yearly mean outdoor air relative humidity (bottom right). The initial performance criterion was used to calculate the share of successful results here (Equation (1)).

it is sensible to aim for zero damages.

Since the validated model and developed material files were used as a basis for the other two focus areas of the work, limitations stemming from the input data for model validation also extend to those areas of focus as well. For the development of the novel two-step performance criterion, additional analysis could be useful in future studies. For instance, more incremental changes of initial moisture content or performing a broader, possibly stochastic analysis of various environmental conditions would help to further specify the performance criterion before its validation in situ. Also, different layer thicknesses of CLT exist and might affect the result. Future improvements in the performance criterion can include the influence of the panel layout.

Regarding the part of the study concerning process variables and moisture management strategies for CLT end-grain moisture safety, the results depend on the choice of climate data. Data for Tallinn, Estonia, characterized by cold winters and mild summers, with significant precipitation throughout the year, were used. Precipitation amounts in Tallinn peak during summer months and the relative humidity is lowest during spring. Calculations with multiple climate files are necessary for broader deductions. Introducing additional variables, such as variations in the vapour permeability of CLT face protection or end-grain surface protection, would have also introduced additional insights, but would have likewise substantially increased the number of simulations required. Therefore, such steps were viewed as appropriate for future studies.

4. Practical application

The validation of the hygrothermal simulation model, performance criterion development, and analysis of CLT end-grain wetting yield the following recommendations for simulations and practical moisture safety measures.

4.1. Recommendations for hygrothermal simulations considering liquid water transfer and anisotropic material properties in CLT

- simulations with many existing material definitions in Delphin (as of 2024) fail to reproduce experimental data (most lead to great overestimation of water uptake) and a careful selection or definition of material properties is necessary;
- material file selection based on water absorption coefficient (A-value) is not sufficient and a more comprehensive validation is required;
- large variations in water uptake intensity exist and the use of multiple material definitions might be warranted;
- the moisture storage function of a material definition in the overhygroscopic range greatly impacts the results;
- alterations of the liquid conductivity function might be necessary;
- the 2D hygrothermal model, which incorporates timber anisotropy, is more suitable for CLT moisture safety analysis, offering superior alignment with measured data than an isotropic material model.

4.2. Recommendations for practice

- implementation of CLT end-grain protection or full-coverage weather protection is recommended to assure a high level of moisture safety target;
- long construction periods should be avoided, even when full-coverage weather protection has been implemented, due to the risk of mould growth owing to humid outdoor air;
- scheduling the installation start of CLT to a dry period is highly beneficial (in Estonia's case, spring is recommended);
- inclusion of moisture dry-out periods before covering CLT in the moisture management plan for CLT buildings is recommended;
- moisture dry-out periods should consider the exposure time during installation and the season of the dry-out period;
- after an exposure time of four weeks, the moisture dry-out time is likely to be longer than one month if the dry-out starts during a colder and more humid season;
- shorter installation/exposure durations should be aimed (preferably less than a month);
- short term wetting of CLT end-grain surfaces might not pose an immediate risk, however if wetting occurs, efforts should be made to reduce the MC below 25 % at 10 mm from the end-grain surface in the longitudinal layer (with regard to the water uptake direction); MC should be below 16 % elsewhere (required to measure when MC at 10 mm is $\geq$ 19 %);
- unassisted dry-out is feasible only during a relatively dry season (e.g. spring in Estonia), at other times, additional equipment is warranted to ensure a timely moisture dry-out.

5. Conclusion

This study presented the validation of a 2D anisotropic simulation model for CLT vertical water uptake and moisture dry-out and demonstrated the applicability of the model by developing a moisture content-based two-step performance criterion for areas near CLT end-grain surfaces, and by implementing it in an analysis of moisture safety of CLT end-grain surfaces in various conditions.

IBK Delphin simulation software was used for the hygrothermal simulation models, including the seldom used modelling of anisotropic material properties. Only a few spruce material definitions in the Delphin database yielded results comparable to those obtained through measurements, with only one pair suitable for compiling the anisotropic material file. Two additional material definitions were developed to attain a better fit with measurements. The simulation results were compared to electrical resistance-based and gravimetric moisture content (MC) measurements. The simulation with optimised material files accurately replicated moisture distribution near the end-grain surface subjected to water contact, but it was necessary to use all three material files to cover the entire range of measured values. The overall performance of the model was deemed sufficient for further analysis, as the root mean square deviation ranged between 1.1 and 3.3 in the most optimal cases throughout all investigated locations.

Next, a novel two-step performance criterion for assessing moisture safety of CLT end-grain areas was developed, determining permissible MC distribution in the CLT wall panel in terms of mould growth in the case of water ingress via the end-grain surface. Mould index remained below 1 when the MC of CLT after 24 h of water contact was used as the initial MC in the simulations. The unaltered material definitions from the Delphin database yielded longer dry-out times and more extensive mould growth, whereas altered definitions optimised for increased water uptake resulted in faster dry-out rates. The performance criterion was established as $MC_{30\ mm} \leq 16$ % at 30 mm and $MC_{10\ mm} \leq 25$ % at 10 mm distance from the end grain i.e. water contact surface in the CLT panel's longitudinal layers with regard to the water uptake direction. Further development of the performance criterion indicated that it is reasonable to require the validation of $MC_{30\ mm}$ when $MC_{10\ mm}$ exceeds 19 % MC.

CLT wall panel end-grain surface moisture safety strategies were studied with climate data from Tallinn, Estonia, covering a 30-year period. The yearly variability was significant, however a slight tendency for a smaller share of successful results with more recent years was detectable. Both the installation duration and post-installation duration when the CLT panels were still exposed to precipitation had a noticeable influence on the results. The largest positive effect came from the utilisation of end-grain protection or starting the installation during spring. Utilisation of full-coverage weather protection was also influential. The outcome had a modest correlation with yearly rain amounts and a stronger correlation with outdoor air relative humidity.

Approximately 14 % of the simulated moisture safety scenarios resulted in a mould index greater than 1 during the time frame from the start of CLT installation until the time when the CLT panels would be covered with additional material layers. The scenarios where mould growth started were primarily characterised by a lack of end-grain and face protection. The median value of the mould index M remained below 1 for all studied durations, with a tendency to increase in case of longer construction periods. If CLT installation takes place under a full-coverage weather protection structure, then there is a very low likelihood (1 %) of mould growth developing on the CLT before it is covered by additional layers (assuming no accidental water leakages).

When considering both the two-step MC performance criterion and avoidance of mould growth, the single most effective measure was protecting the end-grain surfaces which represented 69 % of successful combinations. Side face protection and enhanced horizontal surface drainage provided marginal benefits, particularly when combined with longer installation durations.

Moisture dry-out periods should be incorporated into CLT moisture management, as even short installation durations entail a low success rate if no end grain protection is implemented and moisture dry-out becomes necessary to avoid high levels of built-in humidity. There is also a consequential seasonal impact: spring is the most favourable season for installation, while autumn is the worst (considering Estonian climate). Choosing the installation season can be a valid moisture safety measure and should also be incorporated into CLT moisture management. On the other hand, if for example there is a delay in the procurement process, moisture safety could be compromised due to the postponement of construction start resulting in a change of the start season. Autumn and winter the dry-out periods are considerably longer, requiring the use of assisted drying. If factors such as the start season for CLT installation are unknown, it is not advisable to install CLT without end-grain surface protection.

CRediT authorship contribution statement

Kristo Kalbe: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Roland Pärn:** Investigation. **Aime Ruus:** Writing – review & editing, Investigation. **Targo Kalamees:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used GPT-4o, a large language model developed by OpenAI, in order to improve the readability and conciseness of certain sections of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been supported by the Estonian Centre of Excellence in Energy Efficiency, ENER (grant TK230) funded by the Estonian Ministry of Education and Research, by the Estonian Research Council (grant no. PRG2732 "Climate Resilient Renovation to Achieve Future-proof Buildings"), by the European Commission through LIFE IP BUILDEST (LIFE20 IPC/EE/000010), and by the ERA-NET Cofund Action 'ForestValue" project WoodLCC (N° 773324). Arcwood by Peetri Puit OÜ is acknowledged for the delivery of the CLT panels for the laboratory study.

Data availability

Data will be made available on request.

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PUBLICATION IV

Kalbe, K. & Kalamees, T. (2025). Evaluating Moisture Safety Strategies in CLT Buildings – Predictions vs Actual Outcomes. Case Studies in Construction Materials, https://doi.org/10.2139/ssrn.5073613 (submitted on 17th December 2024, revision submitted on 12th March 2025, under review)

Evaluating moisture safety strategies in CLT buildings – predictions vs actual outcomes

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Abstract

This study evaluated moisture safety strategies and construction practices in two non-residential CLT buildings through predictive analyses and on-site observations. The measured moisture content (MC) ranged from 9%–18% in the first building (excluding the areas with damaged end-grain protection), 12%–18% in the first-floor panels of the second building (with end-grain protection), and up to 40% in its unprotected second-floor panels. Localised damage to end-grain protection and a poorly designed floor panel connection joint caused moisture issues in the first building where material replacement was necessary. In the second building elevated MC in the second-floor panels warranted mechanically aided moisture dry-out. Readiness to mitigate moisture problems was deemed necessary regardless of the protection method used against water ingress. Prolonged exposure to outdoor air, even when under temporary weather protection increased MC in the case of the first building, however the temporary weather protection proved effective in protecting against rain. Undamaged end-grain protection was also deemed effective. The predictive analyses of moisture safety strategies indicated that in 6 of 10 cases for the first building and in all cases for the first-floor panels of the second building a moisture safe outcome was expected. However, no moisture-safe outcomes were indicated for the second-floor panels of the second building. The results demonstrate the benefits of predictive analyses which likely could have prevented the selection of a solution without end-grain protection in the second-floor panels in the second building, as evidenced by measurable data. The outcomes rely on design and planning quality, so including specific moisture safety drawings and a moisture safety strategy analysis within the building design is recommended.

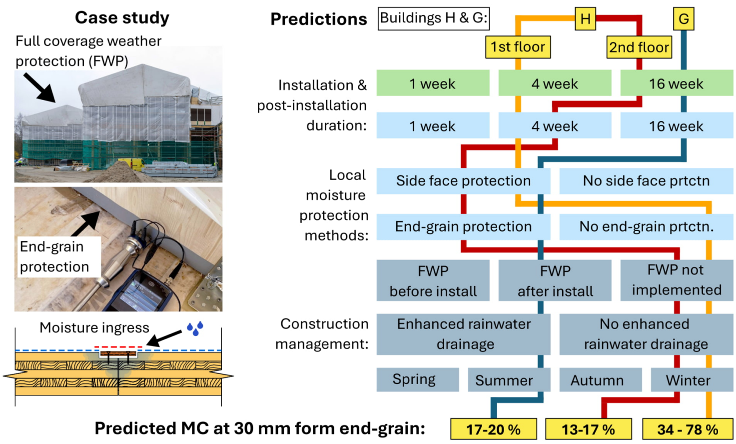
Keywords

Moisture risk mitigation; Moisture management; Timber building; Climate-resilient building; Durability

Highlights

- Prediction method aligned with the outcomes and has potential for use in practice.
- End-grain protection and a protective tent provide effective moisture safety for CLT.
- Prolonged air exposure, even under a protective tent, can increase MC in CLT.
- Moisture monitoring and mitigation readiness are important regardless of protection.
- Moisture safety relies on clear design and risk analysis; contractor expertise follows.

Graphical abstract



1. Introduction

The construction phase of cross-laminated timber (CLT) buildings can be challenging with respect to moisture safety. Although several studies have investigated the hygrothermal performance of timber-based building envelopes – using simulations [1–4], laboratory analyses [5–8], field measurements [9–11] or their combinations [12–14] – most focus on the use phase rather than construction. Nonetheless, findings point to the susceptibility of CLT to moisture issues during construction and the critical importance of moisture safety at this stage.

Olsson [15] analysed cross laminated timber buildings, constructed without weather protection, and showed that half of measuring points had mould growth and around a third had moderate or extensive growth. Liisma *et al.* [16] studied the construction of a CLT building without a temporary roof and showed that the moisture content of the uncovered horizontal CLT element exposed to the climate reached over 25 % after precipitation and the moisture content after prolonged direct exposure could reach up to 40 % in a week. Kalbe *et al.* [17] examined the construction of six CLT buildings and determined that, when built without weather protection, they are inevitably subjected to precipitation with moisture content levels potentially exceeding 25 % during the construction process before commissioning. The study highlighted that even a single rainfall event can cause critical moisture content in the end-grain areas of CLT panels, pointing to the potential importance of incorporating a full-coverage weather protection structure as part of a comprehensive CLT moisture safety strategy.

Timely enclosure to limit exposure to precipitation is also a key factor in managing moisture safety in CLT construction. Öberg and Wiege [18] analysed moisture influence on CLT building and concluded that short building time is essential, early planning to minimise building time is necessary, and some form of weather protection is required year-round. Furthermore, they noted that if expected rainfall exceeds 40 mm or construction lasts longer than a few weeks, a roof cover becomes essential. Time *et al.* [19] presented the moisture strategy employed during the construction of a CLT building in Trondheim, Norway. The building was constructed without the use of a temporary roof or a full-coverage weather protection structure, requiring alternative protective measures. The moisture safety strategy encompassed 1) scheduling the CLT installation for the typically drier months in Trondheim, Norway; 2) applying localized protection measures, including end-grain surface treatment; 3) promptly addressing rain events by safeguarding the structure; 4) conducting regular moisture measurements; and 5) avoiding the covering of wet CLT panels, with a target moisture content of less than 15 %. The authors found the moisture safety strategy to be effective. Based on this, they suggested that comprehensive on-site moisture safety measures could replace the need for a full-coverage weather protection structure. In an earlier publication, Kalbe *et al.* [20] discussed the concept of localised CLT moisture protection measures and recommended that construction design documentation, alongside the as-built solution, should incorporate drawings and detailed specifications for wetting mitigation strategies during the construction period. Schmidt and Riggio [21] documented the results of CLT moisture monitoring during construction and concluded that achieving a moisture-safe outcome requires preventative actions. These include design adjustments (e.g. avoiding details that trap moisture), fabrication enhancement (e.g. using localized coatings), and construction sequencing (e.g. limiting exposure and ensuring drying). These studies reinforce the critical need for a moisture safety strategy for each CLT building, whether it involves full-coverage weather protection, localized protection, or careful scheduling of installations.

Kodi *et al.* [22] reported on moisture damage, specifically mould growth, resulting from inadequate moisture safety during a renovation project in Estonia involving prefabricated timber panels. Alongside documenting the damages, the authors examined various moisture safety strategies that could have been implemented. They concluded that employing specific measures, such as maintaining a designated ventilation air change rate in the attic (where significant moisture ingress occurred during construction), could have prevented or mitigated the effects of the moisture ingress. This aligns with the broader consensus in the literature that emphasizes the importance of moisture control throughout the building process, as highlighted by Mjörnell *et al.* [23] who developed a method for including moisture safety in the building process, which later evolved to the Swedish industry standard ByggaF [24]. The method has different stages in the building process: planning, design, construction and operation. The method contains a number of routines, templates and checklists for clients to formulate moisture safety requirements and to monitor and document the measures implemented by various actors. Ten years after the development of the moisture safety method, the results of the CIB W040 study [25] show that one-third of construction projects were affected by moisture problems, even though practitioners implemented a variety of preventive measures at least for some time. Wang [26] has developed a guide for managing construction specifically in CLT buildings, taking a step further from the general guidelines of Mjörnell *et al.* [23]. The guide by Wang [26] covers the basics of wood and moisture, detailing a range of moisture safety measures from simple to advanced and spanning local detailing to whole-building protection strategies. Additionally, it offers recommendations for moisture drying and remediation. Alsmarker [27] also developed a guide for moisture-proofing CLT construction without the use of a full temporary shelter, providing practical solutions and general recommendations for managing moisture in such projects.

Although guidelines for CLT moisture safety are present, it remains equally critical to provide directions for selecting suitable moisture safety strategies. Kalbe *et al.* [28] analysed moisture safety strategies for CLT wall panel end-grain moisture safety. The study involved the hygrothermal modelling of a total of 77, 760 combinations, considering factors such as installation season and duration, outdoor climate, wood material properties, excess moisture drying out period, CLT face and end-grain surface protections, full-coverage weather protection, and horizontal surface water drainage. The study also introduced a two-step moisture content target to ensure the CLT panels remained within safe moisture thresholds before being covered with additional layers. The most effective measures for ensuring CLT end-grain moisture safety (i.e. meet the set moisture content targets) were end-grain protection and implementing full-coverage weather protection structure before the installation of CLT. End-grain protection was employed in 69 % of successful cases, while the implementation of a full-coverage weather protection structure before installation was present in 51 % of the successful cases. Longer installation durations increased the risk of developing mould growth during the construction period. Seasonal timing also played an important role – spring was the most favourable installation period for the Estonian climate, offering conditions that balanced drying potential and minimal risk of mould growth. The study developed a predictive framework for moisture safety strategy analysis, allowing practitioners to assess the outcomes of various measures and select those that provide the most efficient moisture safety strategy for a given project.

Applying theoretical concepts to practical scenarios is important in advancing research and practice. The objectives of this study is to evaluate the real-world performance of optimised moisture safety strategies and assess the extent to which actual outcomes align with predictions. The study also seeks to analyse the impact of including moisture safety into the procurement process. The hypotheses are as follows:

1. The moisture safety strategy predicted to result in poorer outcomes by the analysis method will indeed lead to worse conditions in practice, while the strategy predicted to perform better will yield superior results.
2. A combination of an experienced contractor and a well-designed moisture safety strategy can ensure a moisture-safe outcome.

To achieve the objectives and validate the hypothesis, this study evaluates the effectiveness of moisture safety measures and strategies in two non-residential CLT buildings in Estonia, which serve as case studies (Figure 1). The evaluation considers customer requirements, design documentation, and the practical implementation of moisture safety measures. Furthermore, the hygrothermal model and moisture safety prediction concept introduced by Kalbe *et al.* [28] are applied to these case studies to analyse the outcomes of the implemented moisture safety strategies. While previous studies have assessed the effectiveness of moisture safety strategies, research on predicting these outcomes remains limited. This study helps bridge that gap by further validating a prediction method. A well-validated approach enables the selection of appropriate moisture safety strategies for CLT construction, contributing to optimised moisture management.

2. Methods

2.1. Case study buildings, site observations, and moisture measurements

The construction process and timber moisture content were monitored, and the efficacy of moisture safety measures and the implementation of moisture safety strategies were analysed in two buildings, where most of the above-ground load-bearing structures and partition walls were made of CLT. The buildings, referred to as G and H (Figure 1), are situated in Tallinn, Estonia.

Figure 1 Case study buildings G (left) and H (right).

The building G, Pelgulinna State Upper Secondary School, won the main award and the popular favourite title at the best wooden building 2023 competition organized by the Estonian Forest and Wood Industries Association. It is also one of the largest wooden buildings in Estonia. 85 % of the load-bearing structures of the building are cross-laminated timber and glulam. The total volume of CLT in this building is 2530 m^3, and the volume of glulam is 270 m^3. The building H is the first kindergarten built from CLT panels as the main building material in Tallinn. This building is a pilot project for the Tallinn municipality, with future plans to construct kindergartens from wood, given the architectural flexibility, cost efficiency, and reduced environmental footprint of timber buildings. Table 1 presents the main characteristics of the case study buildings. In both buildings, the wood in CLT was untreated, and the edges of the lumber boards were not glued together. The CLT panels had been produced from Norway spruce lumber, with the outer layers oriented vertically (longitudinal wood grain parallel to the height of the building). As the practice of covering horizontal CLT (floor) panels with a waterproof membrane is common in Estonia, the study concentrated on the moisture safety of vertical CLT (wall) panels, where vertical water uptake has been shown to be highly problematic [17]. For example, previous research has suggested that there is a correlation between air leakages during the service phase in CLT wall panels and wetting incidents that occurred during construction [29].

Table 1. Characterisation of the case study buildings

Building, usage type	**G,** Upper secondary school	**H,** Day-care centre
Year finished	2023	2024
Floors above ground	4	2
Net floor area	8273 m^2	2427 m^2
Construction cost (wo. VAT)	25 M€ / 3022 €/m^2	9.43 M€ / 3885 €/m^2
Insulation system of CLT walls*	MW + vent. façade EPS + ETICS	MW + vent. façade
Insulation system of CLT roofs*	VB + MW + compact roof	VB + MW + compact roof
CLT thickness	110–200 mm (walls), 100–300 mm (floors & roof)	140–160 mm (walls), 200–300 mm (floor & roof)

* MW = mineral wool, EPS = expanded polystyrene insulation panels, VB = vapour barrier, ETICS = External Thermal Insulation Composite System.

Site visits included inspecting the CLT panels for moisture or damage, checking for free water, stains, shrinkage, or swelling. Photographs and videos were taken to identify the critical areas of moisture ingress. The moisture measurements were conducted using the Gann Hydromette CH 17 and Hydromette HT 65 wood moisture meters, following EN 13183–2 guidelines [30]. The 60 mm electrodes had Teflon-insulated pins with 10 mm uninsulated tips, allowing measurements at various depths. Moisture content was measured in the 40 mm thick surface layer (20–40 mm deep). Measurements were taken at various locations focusing on areas near the end-grain surfaces of the CLT panels. The procedure, based on the approach of previous investigations, included: 1) visual inspection for wet areas; 2) moisture content measurements in areas with suspicion of wetting; 3) moisture content measurements in nearby dry, structurally similar areas. The instruments were adjusted for usage with spruce wood and for the temperature of the measured wood. A reference test adapter, rated at 21.0% ± 0.5% at 20°C, was used for frequent accuracy checks. For European conifers, greater measuring errors are expected above 40% moisture content, according to the product specifications of the measurement instruments. Some authors equate moisture content values above 30% (approximately the fibre saturation point) to 30%. However, this study reported the measured values as they were, since only a few exceeded 30%, and the authors consider this information valuable. Readings above the fibre saturation point are less accurate, but they still indicate significantly wet wood. This information is important when discussing moisture dry-out, as the actual mass of water in the timber is certainly greater than a 30% value would suggest. Measurements were taken 30 mm from the end-grain surface, and occasionally at 10 mm (Figure 2). Measuring near knots, cracks or other irregularities was avoided. Air temperature and humidity were recorded with Hobo UX100-023 data loggers.

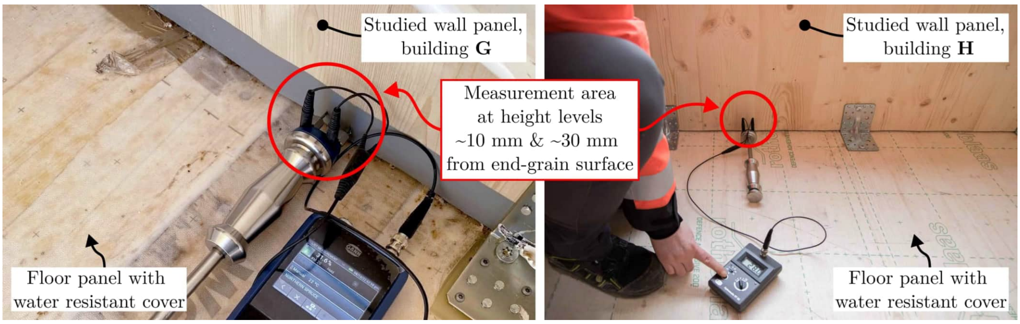


Figure 2 Moisture content was measured at approximately 30 mm and 10 mm from the end-grain surfaces of wall panel bottom sections with similar structural conditions during field measurements. The left photo is of the building G, and the right photo is of the building H.

2.2. *Moisture safety strategy analysis framework*

Moisture safety strategies were evaluated by first examining customer requirements and the design documentation of the case study buildings, and then analysing the practical measures applied on-site. Kalbe *et al.* [28] analysed CLT moisture safety strategies, focusing on key construction variables affecting CLT end-grain wetting and drying. The variables can be categorised into three groups:

1) building type and size: expected CLT installation duration and post-installation duration;
2) moisture safety design: localised moisture protection methods, such as CLT panel face and end-grain surface protection; and
3) construction management: implementation of full-coverage weather protection, efforts to reduce water load on horizontal surfaces, and the start season of CLT installation.

The moisture safety strategies of most CLT buildings are proposed to fit within the process variable framework introduced by Kalbe *et al.* [28]. The framework, combined with the hygrothermal modelling of all combinations derived from the process variables (Table 2) and a long-term climate data series, can be used to predict the outcomes of moisture safety strategies for the studied buildings. The choice of variables is supported by findings from previous research. For example, Kalbe *et al.* [17] demonstrated through six case study buildings that the duration of precipitation exposure – both during installation and after its completion until the addition of subsequent structural layers – determined whether critical end-grain wetting occurred. Liisma *et al.* [16] found that CLT protected with preliminary PE foils during construction exhibited lower moisture content, highlighting the importance of vertical protection foils for CLT wall panels and the potential benefits of end-grain protection, as also discussed by Kalbe *et al.* in [20] and [17]. Time *et al.* [19] proposed a moisture safety strategy that included localized protection measures such as end-grain surface treatment. They also emphasized that scheduling CLT installation during drier months and promptly addressing rain events could be beneficial, supporting the inclusion of seasonality in the framework analysis. The impact of seasonal variation on the moisture safety of timber structures has also been discussed by Pihelo and Kalamees [31]. Additionally, Tengberg and Bolmsvik [32] demonstrated that full-coverage weather protection structures effectively enhanced moisture safety. Collectively, these studies provide the foundation for the variables included in the moisture safety analysis framework.

Table 2. Variables of the analysed CLT moisture protection process safety measures.

<table>
<tr><th>Process factor type</th><th>Process factor</th><th colspan="4">Variable value</th></tr>
<tr><td rowspan="2">Building type and size</td><td>Expected CLT installation duration</td><td>1 week</td><td>4 weeks</td><td colspan="2">16 weeks</td></tr>
<tr><td>Expected duration from CLT installation until addition of next structure layers</td><td>1 week</td><td>4 weeks</td><td colspan="2">16 weeks</td></tr>
<tr><td rowspan="2">Moisture safety design</td><td>CLT wall face protection (applied prior to installation)</td><td colspan="2">Yes (ideal rain protection)</td><td colspan="2">No side face protection</td></tr>
<tr><td>CLT end-grain surface protection (applied prior to installation)</td><td colspan="2">Yes (ideal waterproofing)</td><td colspan="2">No end-grain protection</td></tr>
<tr><td rowspan="3">Construction management</td><td>Full-coverage weather protection (FWP) implementation</td><td>FWP before installation</td><td>FWP after installation</td><td colspan="2">FWP not implemented</td></tr>
<tr><td>Horizontal surface water drainage implementation</td><td colspan="2">Rainwater drainage and prevention of puddle formation after rain</td><td colspan="2">Absence of activities enhancing drainage</td></tr>
<tr><td>Predicted start season of the CLT installation</td><td>Spring</td><td>Summer</td><td>Autumn</td><td>Winter</td></tr>
</table>

2.3. *Weather data*

Weather data for analysing the actual conditions during the construction of the studied buildings was acquired from a nearby Tallinn-Harku meteorological station (N 59°23´53´´, E 24°36´10´´ [33]). The weather station was located 7 km from the building G and 4 km from the building H. Due to the high spatial and temporal variability of precipitation, the recorded rainfall at the meteorological station likely differed from that on the construction site. However, given the relatively flat topography of Estonia and the proximity of weather stations in the same climate zone, it is reasonable to assume a similar frequency and general intensity of precipitation over time, offering an indication of probable moisture load on the CLT.

For the analysis of the expected outcome of the moisture safety strategies, a 30-year climate data (1991 – 2020) from the same Tallinn-Harku meteorological station was used in the hygrothermal modelling. Temperature, relative humidity, hourly rainfall, wind speed and direction were included in the data, but solar radiation was excluded due to the potential shading on construction sites, which increases moisture risks.

2.4. Hygrothermal modelling & performance criterion

As a key element of the moisture safety strategy outcome prediction workflow, hygrothermal modelling was used to analyse CLT end-grain moisture performance. This analysis, performed with IBK Delphin 6.1.6 [34,35], was used to assess the expected success probability of the chosen moisture safety strategies. Kalbe *et al.* [28] conducted an extensive study validating the Delphin 6 anisotropic moisture transport method for CLT vertical water uptake and subsequent moisture dry-out simulations. The same experimental data as used by Kalbe *et al.* [28] was also used by Brandstätter *et al.* [36] for validating their hygrothermal simulation model developed in the finite element software *Abaqus*. The results achieved by Kalbe and Brandstätter were both credible and consistent, supporting effective cross-validation of the two software tools. Both researchers concluded that addressing timber property variations in CLT requires multiple material definitions to capture both intensive and moderate water uptake.

This study utilises the same model, geometry (Figure 4), input data, and material definitions (Table 3, Figure 3) as used by Kalbe *et al.* [28]. The details of the material properties and how the process variables were set up in the model are given in their previous work [28]. Table 3 presents the base parameters of the material properties used in the hygrothermal modelling, while Figure 3 presents the functions for liquid water conductivity, water vapour permeability, and the moisture retention curve.

Table 3. Moisture transport and storage base parameters of the spruce material files in the hygrothermal simulation software Delphin database that provided the best fit with measurement data in [28] and were therefore used in this study.

	Longitudinal	Transverse	Unit
Bulk density of dry material	393.703		kg/m^3
Specific heat capacity of dry material	1843		J/(kg·K)
Open porosity	0.737531		m^3/m^3
Effective saturation content (long process)	0.72809		m^3/m^3
Capillary saturation content (short process)	0.655		m^3/m^3
Hygroscopic sorption value at 80% RH	0.0598372		m^3/m^3
Thermal conductivity	0.151167	0.105583	W/(m·K)
Water absorption coefficient	0.012024	0.00526733	kg/(m^2·s$^{0.5}$)
Water vapour diffusion resistance factor	4.57501	487.724	-
Liquid water conductivity at effective saturation	2.00481×10^{-10}	9.22366×10^{-10}	s
Liquid water conductivity	1×10^{-11}	1×10^{-11}	s
at effective saturation for material files altered to achieve better fit with test data in [28]**.**			

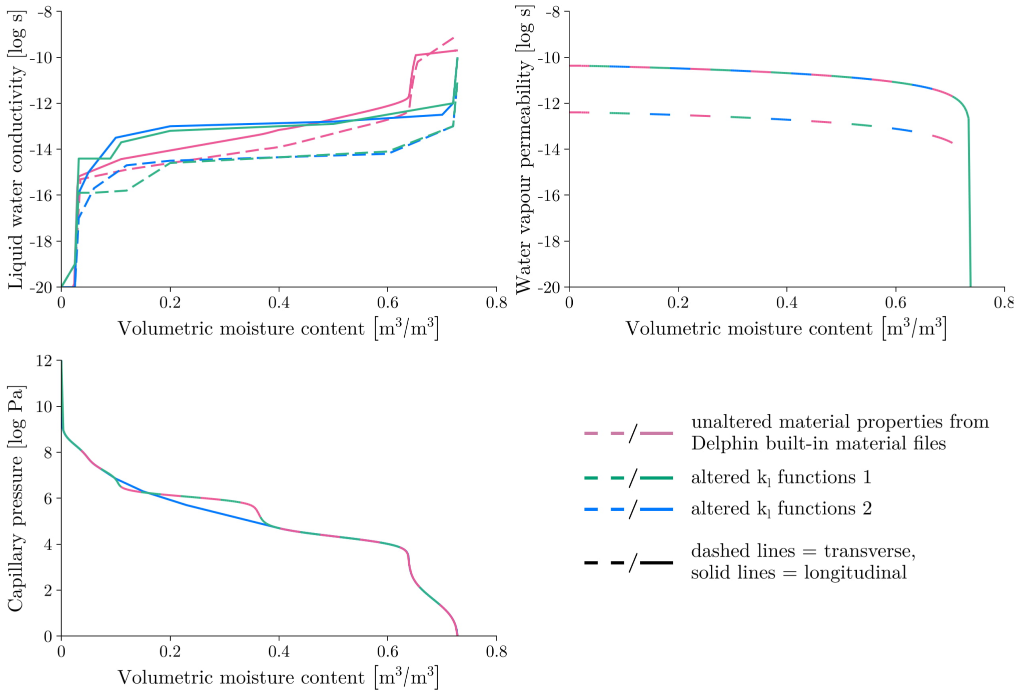


Figure 3 Material functions for the spruce material files used in hygrothermal modeling. Magenta lines represent unaltered properties from the software database, which fit measurement data for limited water uptake in Kalbe *et al.* [28]. Altered functions, derived from the same work, include altered function 1 (green), adjusted in [28] to best fit the average measurement data, and altered function 2 (blue), adjusted to represent increased water uptake. Solid lines show functions for the longitudinal direction; dashed lines show functions for the transverse direction. For more details on the validation of the material properties, see [28].

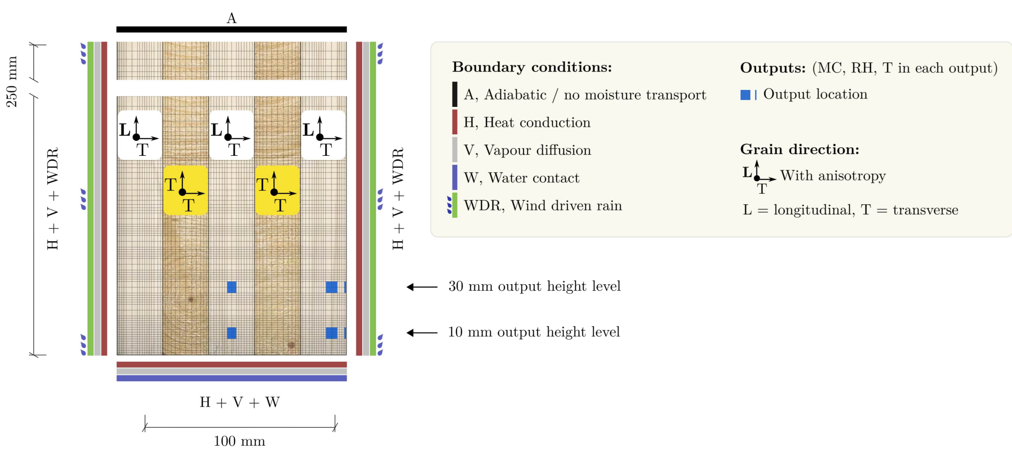


Figure 4 Modelled geometry for the analysis of the CLT end-grain moisture safety. The illustration displays grain direction, boundary conditions, discretisation grid and output locations. CLT layer thicknesses in the model were adjusted to reflect the actual built structure of the case study buildings for MC comparisons with measured values.

The moisture content in the CLT of the case study buildings was also simulated using the acquired weather data and recorded exposure times specific to each studied case. The CLT thickness in those simulation models was adjusted to represent the actual built structure (Table 1).

In their work, Kalbe *et al.* [28] also proposed a performance criterion focused on end-grain surface moisture safety in CLT construction. This is expressed in Equation 1, where $MC_{10\ mm}$ is the moisture content (MC) measured at 10 mm from the water contact surface and $MC_{30\ mm}$ is the moisture content measured at 30 mm from the water contact surface in the CLT panel's longitudinal layers (with regard to the water uptake direction) and M is the mould index in the Finnish mould growth model. The validation of moisture content at 30 mm can be omitted if moisture content at 10 mm is lower than 19 %.

Equation 1

$$OK = \begin{cases} MC_{10\ mm} \leq 25\ \% \\ MC_{30\ mm} \leq 16\ \%, \quad \text{when } MC_{10\ mm} \geq 19\ \% \\ M < 1 \quad\quad \text{up to covering CLT} \end{cases}$$

A total of 864 variable combinations, based on the process factors and values in Table 2, were simulated using 30 years of climate data and three material files for anisotropic spruce, resulting in 77, 760 simulations. From these, the sub-variants corresponding to the moisture safety strategies of the case study buildings (as shown in the tracks in Figure 7) were selected. This allowed for the calculation of the expected probability of success for the chosen moisture safety strategies. An outcome was considered successful when the criterion specified in Equation 1 was fulfilled. The details of the simulation model and development of the performance criterion are available in the previous work of Kalbe *et al.* [28].

3. Results

3.1. Moisture safety strategy analysis

3.1.1. The analysis of customer specifications and requirements

For the building G, the institutional client (Riigi Kinnisvara AS, the state real estate development and management company), an expert in property development and management, mandated the use of previously established technical requirements for non-residential buildings, which included moisture safety requirements [37]. The client required the preparation of a moisture safety plan and the appointment of a moisture expert. Additionally, the client of the building G mandated that timber moisture content must remain below 18 %, and that CLT must be installed under a full-coverage weather protection structure (a tent roof with side walls). However, the parties involved in the project agreed to change this during the construction and the full-coverage weather protection structure was only erected after the installation of the CLT.

The institutional customer of the building H is a local municipality (the capital city Tallinn), which has a lot of experience in ordering the design and construction of buildings. However, no specific moisture requirements were set, only laws, regulations, and general instructions such as the previously mentioned technical requirements for non-residential buildings by the state real estate development company [37] were referred to in the procurement. Detailed requirements for moisture safety, such as the maximum allowable timber moisture content, control methods, measurement frequency, worker training, and documentation, were not mandated in the procurement of the building H. The development of construction period moisture safety method was to be decided and adopted by the CLT producer and general contractor.

3.1.2. The analysis of the design documentation

The project documentation of the building G advised to install CLT under a full-coverage weather protection structure, or alternatively treat the bottom end-grain surfaces with a moisture-proof sealer, wrap panels in thermal film (Figure 5), and apply water resistant self-adhesive protective films to floor panels. As the designers specified the use of a full-coverage weather protection structure, they did not provide drawings for additional weather protection solutions. Moisture safety was partly covered in the architectural section of the project documentation. The moisture safety topic remained brief and general in the structural design section, which concentrated only on the load-bearing capacity of the building and overlooked moisture loads during construction. Moisture content limit values were provided inconsistently in the architectural design documentation, with some sections requiring <18 % and others <16 %. Additionally, a guideline was provided for the relative humidity limit (to prevent mould growth): <80 % (at air temperatures above +5°C), unless specified otherwise by the product manufacturer. The structural part of the project documentation set another conflicting limit for timber moisture content: <15 % but did not give a guideline for air RH limit. Overall, the moisture safety section in the project documentation for the building G was limited, though still more detailed than typical for Estonia.

Figure 5 Installation of the first CLT panels in building G. The CLT panels arrived wrapped in white plastic film.

The architectural section of the project documentation of the building H also covered the moisture safety topic in a general manner and did not specify any limiting moisture content or RH values. The structural section of the design documentation of the building H specified that the CLT panels should be covered with a weather-resistant packaging foil from the factory which should be kept on the panels during the installation process and until the building was rendered weatherproof. According to the structural design drawings for the building H, liquid waterproofing was required for the bottom end-grain surface of the first-floor CLT panels, but not for the second-floor panels. Additionally, the limiting value of the moisture content for the CLT panels was given as 15 %.

3.2. The analysis of applied and incidental moisture safety strategies with outcome prediction

Moisture was managed in both buildings with varying degree in thoroughness and moisture protection methods. For the builder of the building G, it was the third large CLT construction they erected, but for the builder and customer of the building H, it was only the first. In the building G, the CLT installation took approximately five weeks per block (the building was divided into three blocks, each of which was sequentially covered with a full-coverage weather protection structure). Ideally, the assembly of the full-coverage weather protection structure should be done in parallel with the installation of the CLT panels so that when the installation of a section is finished, it would become protected from precipitation immediately. But in this case, there was an approximately two-to-three-week period after the installation when the CLT panels were still exposed to precipitation and were then covered with the full-coverage weather protection structure (Figure 6).

Figure 6 Temporary full-coverage weather protection structure at different stages on the building G.

Figure 7 summarises the process variable framework proposed by Kalbe *et al.* [28], with the moisture safety strategies of the case study buildings superimposed on the chart. Each buildings' path on the chart reflects the combined influence of the building design, customer's specifications, design documentation and decisions made during the construction process. Within the moisture safety analysis framework, installation time was regarded as the entire period from the CLT installation start to the moment when each block of the building was fully covered with the full-coverage weather protection structure. The closest match for installation duration in the moisture safety analysis framework was thus 16 weeks for the building G, which best approximates the actual ca eight-week exposure time, adding a safety margin over the four-week choice. Following the installation period, the CLT panels were under the full-coverage weather protection structure, exposed to ambient air for eight to ten weeks, facilitating moisture dry-out until additional structure layers were added. Therefore, the sixteen-week option was suitable also for this step in the moisture safety analysis framework. A similar timeline was applicable to all the blocks of the building G.

The CLT installation in the building H took approximately eight or four weeks, depending on whether the start was counted from the installation start of the first or second floor's panels. Since different end-grain protection methods were used on the first and second floor, the outcomes for both should be analysed separately. This separation can also consider the different installation times for the two floors. Consequently, the installation duration was set at sixteen weeks for the first-floor panels and four weeks for the second-floor panels in the moisture safety analysis framework. After the installation, the CLT on both floors of the building H remained exposed for approximately a month until it was covered with insulation.

Protecting the side faces of CLT wall panels with packaging foil is well established in Estonia and was used in both buildings G and H. However, for the end-grain surface different methods were implemented: in the building G, a liquid applied water blocking coating was applied for all CLT wall panels, whereas in the building H an adhesive membrane was applied to the first-floor panels only, leaving those on the second floor unprotected. In the building G, a more thorough process was implemented for horizontal surface water drainage, as the client mandated the preparation of a moisture safety plan. The installation start season was summer for the CLT panels in the building G and winter for the building H.

Each path leads to an outcome which was calculated on the basis of the results of the hygrothermal simulation models. For the building G, the predicted probability of a moisture safe outcome was 6/10, despite the consideration of ideal side face and end-grain surface protection measures and implementing a full-coverage weather protection structure after the installation of the CLT panels. The main culprit for a somewhat less desirable prediction was the long period after the installation when the CLT panels were still exposed to outside air during autumn. Consequently, the predicted average moisture content at 10 and 30 mm from the end-grain surface was between 17 and 20 %. While the criterion in Equation 1 was met 6 times out of 10 (when considering the 30-year climate data for Tallinn, Estonia and three anisotropic spruce material files), there were, on average, 4 out of 10 instances where moisture content (MC) may exceed the set target ($MC_{30\ mm} \leq 16$ %, when $MC_{10\ mm} \geq 19$ %) due to hygroscopic moisture absorption from extended exposure to ambient air and thus a moisture safe outcome would not be guaranteed.

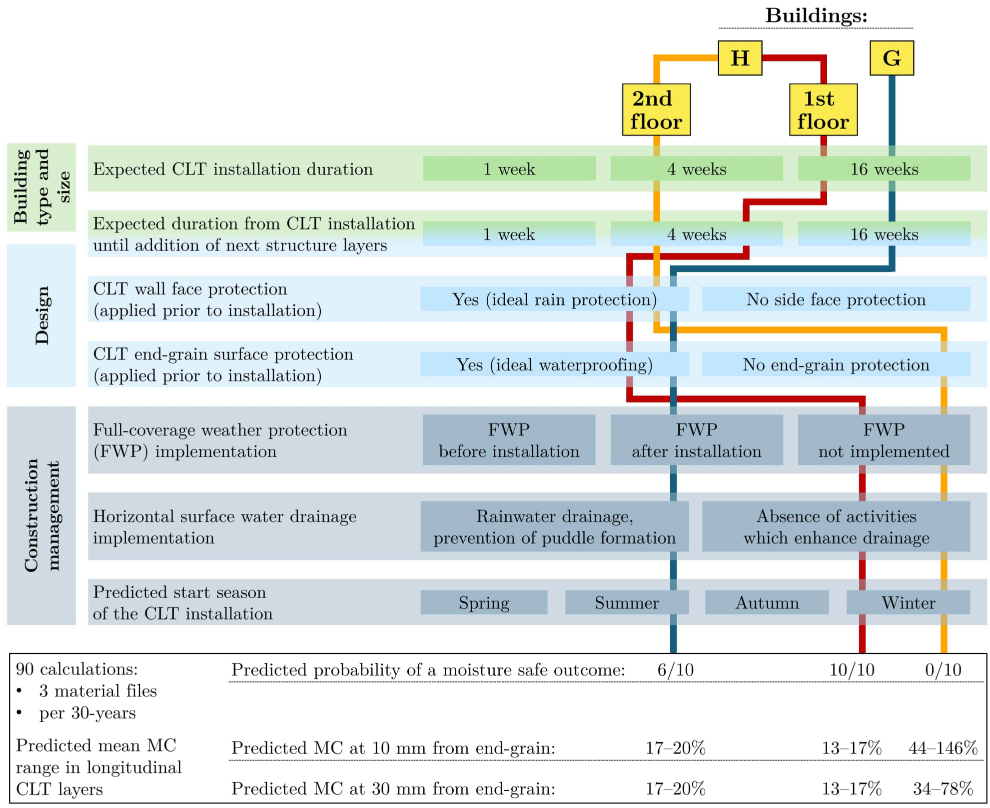


Figure 7 CLT moisture safety process variables with superimposed lines representing the moisture safety strategies of the studied buildings. The building H is divided into floor 1 and floor 2 due to differing end-grain surface protection of the CLT panels on each floor. The durations which the strategy paths pass are close to, though not identical, the actual construction timelines. MC = moisture content.

For the case of the first floor in the building H, the predicted probability of a moisture safe outcome was 10/10. In this case there were two main contributors to the better outlook compared to the building G: a shorter post-installation period and installation start during winter. However, for the second floor of the building H, a moisture-safe outcome was not anticipated, as the predicted moisture content in the bottom part of the wall panels reached 34 % to 146 %. This was due to the lack of end-grain surface protection leading the surface to be exposed to water contact repeatedly. Previous laboratory tests have shown [28] that 48 hours of continuous water contact can increase the moisture content in the bottom 7 mm of a CLT wall panel over 130 % which suggested that the predicted moisture content values could be realistic given the 8-week period which the CLT panel for the second floor of the building H was exposed to precipitation.

3.3. The actual outcome of the applied and incidental moisture safety strategies

The chosen strategy for the building G should have provided protection against wetting for both the CLT side faces and the bottom end-grain surfaces. A less-than-ideal outcome for moisture safety was predicted only due to the long period after the installation of the CLT when the panels were still exposed to outside air during autumn, but on average the expected moisture content in the wall panel bottom area should have ranged between 17 % and 20 %. Figure 8 presents the 24-hour moving averages of recorded temperature and relative humidity (RH) within the indoor area of the first block of the building G during construction, when the temporary full-coverage weather protection was already in place.

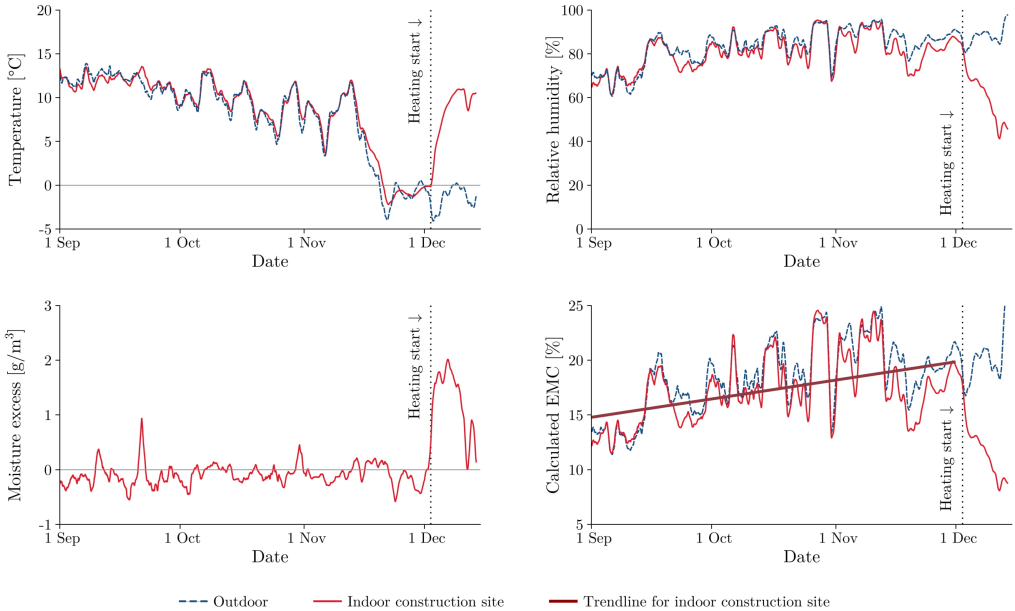


Figure 8 24-hour moving averages of temperature (t, top left) and relative humidity (RH, top right) measured in the indoor area of the first block of building G and outdoors in a shaded area on the construction site. Moisture excess (bottom left) and equilibrium moisture content (EMC, bottom right) for timber were calculated based on the recorded t and RH values.

The figure also includes the calculated moisture excess and the equilibrium moisture content (EMC) of timber (calculated from the temperature and RH data) in the indoor area at any given time during the measurement period. The data shows that conditions under the temporary full-coverage weather protection structure were similar to outdoor air conditions, with moisture excess remaining near zero until the openings were sealed and heating started. The trend for the calculated equilibrium moisture content of timber was upward, occasionally exceeding 20% and reaching nearly 25%. However, once heating started, the calculated equilibrium moisture content decreased rapidly, suggesting a good potential for moisture dry-out. Throughout the measurement period, the 24-hour moving average temperature never exceeded 15°C, even after heating was initiated, which was probably a good strategy for avoiding possible mould growth.

On-site measurements about a month after the installation started indicated values exceeding 21 % and even over 30 % (Figure 9, left). While the specific cause of higher than expected moisture content could not be identified, visual inspection revealed potential damage to the Riwega ELLE-Plan (S_d < 5 m) liquid-applied end-grain waterproofing membrane (Figure 9, middle). While many wet areas appeared visually undamaged, potential damage to the membrane on the surface under the panels could not be confirmed due to inaccessible panel undersides. Swelling and warping of timber in the CLT panels correlated with wet areas. (Figure 9, right). Nevertheless, the waterproofing membrane provided adequate moisture protection in most areas.

Figure 9 Moisture measurements (left), waterproofing membrane damage (middle), and timber swelling (right) in the building G.

The points where the liquid applied waterproofing membrane was damaged functioned similarly to end-grain zones without protection. Weather data from a nearby weather station indicated that during the period up to the assembly of the full-coverage weather protection structure, the building G received approximately 70 mm of rain (Figure 10, left), which was mostly diverted, but as the measurements indicated – some areas still got wet. Figure 11 shows the measured moisture content (point) values and simulated moisture content values (continuous lines) based on the actual climate data from each building's construction period and based on the main moisture protection strategy. In case of the building G, the calculations were also made for the hypothetical variant which excluded the end-grain surface protections, although, the main strategy assumed ideal end-grain protection. The measured values are also divided into two based on whether their first moisture content value was over 19 % or not. The measured moisture content values which exceeded 19 % were deemed to have been taken from the areas where a probable end-grain protection damage was present. Most measured values remained below the values simulated with an ideal end-grain protection. Both the simulated and measured results for the variant with a functioning end-grain protection reflected the tendency for moisture content increase over time which affirms the risk indicated by the moisture safety analysis framework (Figure 7). Fortunately, the long period under the full-coverage weather protection structure without additional wall assembly layers also provided time for moisture dry-out. The measured values from the areas with presumed end-grain protection damage correlated well with the simulation where no end-grain protection was assumed. Both of these indicated a moisture dry-out over time. A long period after the CLT installation when the panels were exposed to outside air had a dual effect: it caused an increase of moisture content in the panels, yet also allowed excess moisture dry-out from previous wetting incidents.

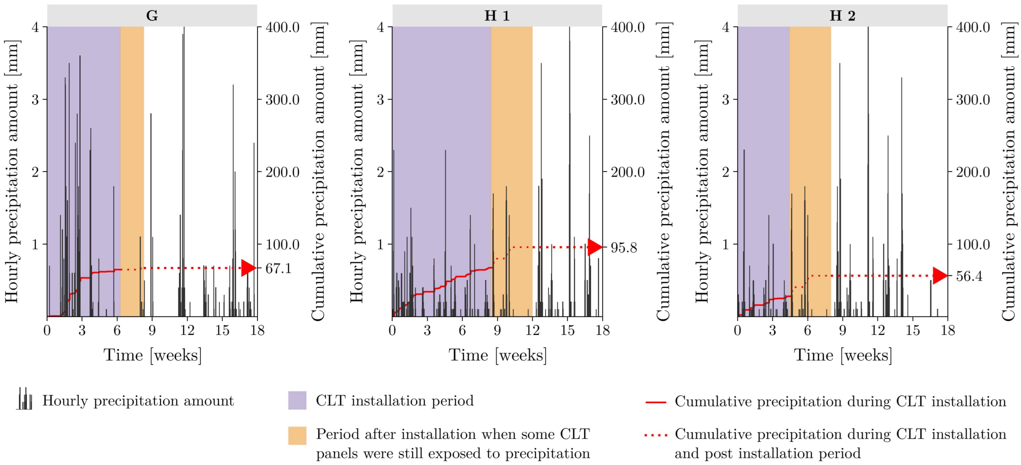


Figure 10 Precipitation amounts during the construction of the observed buildings. The time scale is provided relative to the installation start time.

In the case of the first floor in the building H, there were neither visual indications of end-grain moisture ingress or swelling of timber boards nor did the measurements indicate elevated moisture content (Figure 11, right chart, dark red points and lines). The selected moisture safety strategy was effective, and the fabric-based self-adhesive waterproofing membrane (Riwega VSK Micro, $S_d > 2$ m) on the bottom areas of the first-floor CLT panels performed well.

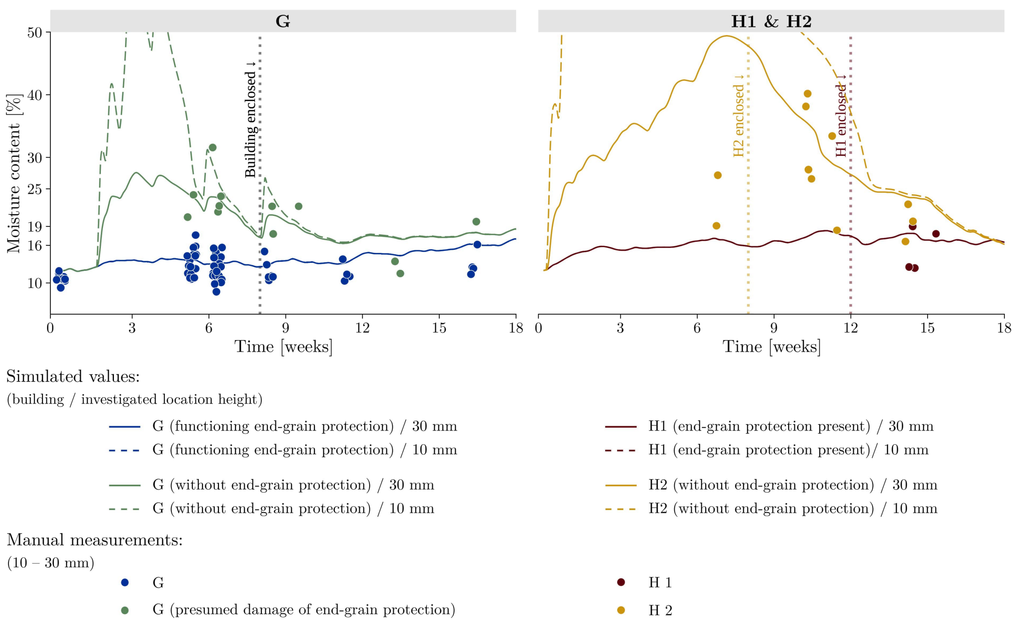


Figure 11 Measured and simulated moisture content of the external wall bottom areas of the studied buildings. The time scale is provided relative to the installation start time. The simulated moisture content is the average of the three material files used in the simulations.

No damages were identified in the fabric-based waterproofing membrane as opposed to the liquid applied membrane coating used in the building G. The approximately 100 mm of rain (Figure 10, middle chart H1) was effectively diverted.

For the second-floor panels in the building H, the moisture safety estimation method predicted a moisture unsafe outcome (0/10, Figure 7) due to the absent bottom end-grain surface protection. The simulation with the actual climate data also indicated very high moisture content reaching well over 30 % (Figure 11, right chart, yellow lines). This was confirmed by manual measurements (Figure 11, right chart, yellow points and Figure 12, top left). While the calculated cumulative precipitation amount for the second floor in the building H was the lowest of the studied buildings, the recorded moisture content measurements were nevertheless the highest. This can be linked to the absence of end-grain protection. In this case, the moisture safety estimation tool prediction was correct.

Visual findings also confirmed that the wet areas exhibited swelling (Figure 12, top middle). After the discovery of the wet CLT on the second floor, large air fans were brought on the site to accelerate the moisture dry-out (Figure 12, top right). Fortunately, the installation start was during winter and the main period when moisture was dried out was during spring, which is the period with the highest moisture dry-out potential in Estonia. The simulated moisture content showed a sufficient correlation with the measured values throughout the dry-out period (Figure 11, right chart) though it was slightly higher – likely because of increased air change from the fans. Safe moisture content was achieved at approximately 8 weeks after the building was enclosed. Furthermore, most walls were left exposed in the final interior, allowing for extended moisture dry-out periods without disrupting the construction schedule (Figure 12, bottom).

Figure 12 Moisture measurements (top left), timber swelling (top middle) and accelerated air drying (top right) in the building G. The bottom photos show the second floor interior before final completion and handover to the client.

4. Discussion

4.1. Prediction of moisture safety strategy outcomes

For the building G, the analysis framework predicted, using 30 years of climate data, that the extended period after installation during which the CLT remained exposed to outdoor air (though protected from precipitation) would lower the likelihood of a moisture-safe outcome. On-site measurements and the results of the hygrothermal simulation, using actual climate data from the construction period, confirmed an increasing trend in the moisture content of the CLT panels, supporting the prediction. However, if the end-grain waterproofing membrane had not been damaged, the actual result would have been largely, if not entirely, positive, especially when focusing on the moisture safety of the CLT wall panel bottom end-grain areas. This supports the analysis framework but also shows that the framework assumes ideal moisture protection, and when this protection fails, the actual outcome no longer aligns with the prediction. The moisture safety strategy analysis framework could include the risk assessment of other areas as well, such as the solutions used in a CLT floor panel joint, which was highly problematic in the building G. At this joint there was a groove, rather than a half-lap connection and the groove acted as a bowl where water accumulated. A plywood strip was secured into the groove which then also got wet and prohibited moisture dry-out. Unfortunately, the waterproofing membrane was not installed within the groove on the CLT floor panels. Protection was only added over the connection when the plywood strips were fitted, allowing water ingress beforehand. This caused elevated moisture content in the CLT and in the plywood strips (Figure 13), a condition that can be highly critical due to the moisture trapping nature of the connection joint. For instance, Austigard and Mattsson [38] reported decay up to 2 cm deep in a similar case, where plywood strips were installed over the CLT floor panel connection joint. In the case of the building G, the wet areas were identified early enough to prevent further damage.

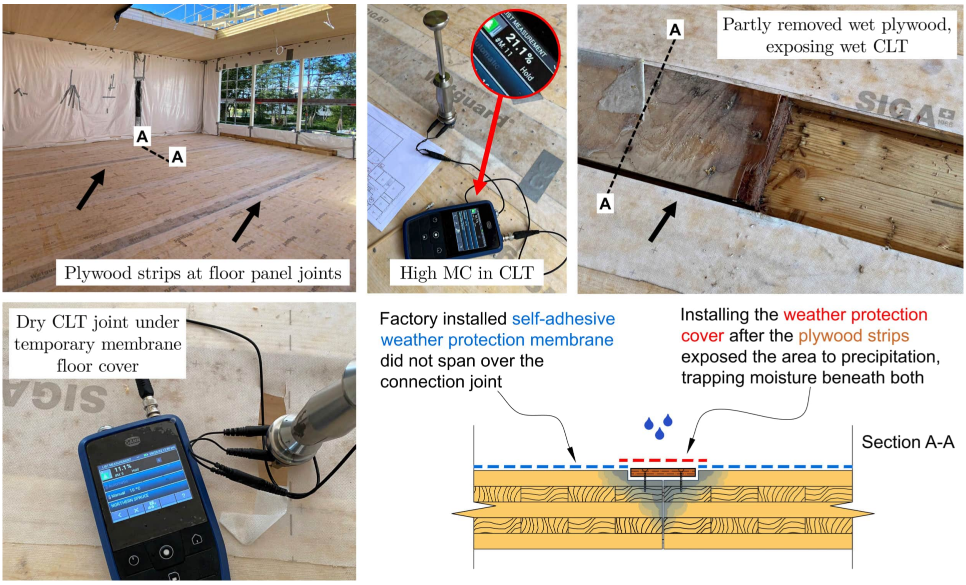


Figure 13 In building G, water infiltration at CLT floor joints raised moisture content above 20%. Initially, a plywood strip was installed before the weather protection membrane, but in a revised method the membrane was installed first, ensuring a dry connection.

All the wet plywood strips were replaced and the CLT was dried before installing new plywood strips. The installation method of the floor panels was adjusted after the issue was first detected. The waterproofing membrane was temporarily fixed over the groove of the floor panel connection joints and removed only once the area was protected from precipitation, enabling dry installation of the plywood strip. No additional damage was observed, which was fortunate, as In the building H a conventional half-lap connection was used, and such problems were not identified there. Isaksson and Thelandersson [39] have also showed that it is important to avoid water trapping details and limit wetting time to minimize moisture content in outdoor above ground applications [16].

For the building H, the predictions matched the actual outcomes, with the measured and simulated moisture content values aligning sufficiently. On the first floor, the fabric-based waterproofing at the bottom end-grain edges proved more effective than the thin liquid applied waterproofing membrane used in the building G. For the second floor of the building H, the moisture safety strategy analysis predicted a high-risk scenario with no chance of success (in terms of guaranteeing a moisture-safe outcome) and a very high moisture content. This proved to be the actual outcome. Had the interior finishing system been something other than exposed CLT and had the construction schedule allowed less time for moisture dry-out, the consequences would have been much more problematic. If the moisture safety strategy had been analysed in advance, a solution without end-grain protection might not have been selected. However, this remains speculative and lacks supporting evidence.

The pre-analysis of moisture safety strategies in advance could be beneficial and if if would be included in the early stages of moisture safety planning process. However, additional analysis of similar case studies is required to fully confirm the method's reliability and practical applicability.

Mjörnell *et al.* [23] specified that a risk analysis could be carried out in order to estimate the moisture safety as a part of the overall moisture safety planning process. We suggest that the risk analysis should address not only the moisture performance of the designed structures but also the chosen moisture safety strategies. The current moisture safety strategy analysis method could be useful here, offering potential to streamline decision-making.

4.2. Effectiveness of moisture safety measures

Regarding the effectiveness of moisture safety measures, local protection has demonstrated its benefits. Previous investigations into localised CLT moisture protection [20] have now been validated. For instance, the panels on the first floor of the building H remained free from moisture ingress despite the absence of a full-coverage weather protection structure, relying solely on local protection. It has been suggested that if expected rainfall exceeds 40 mm or construction lasts longer than a few weeks, a roof cover becomes essential [18] or that CLT construction should preferably have a complete weather protection. However, the results of this study show that with local protection measures and scheduling the installation of CLT for a favourable season can lead to a moisture safe outcome, even when installation times exceed a few weeks and the measured cumulative precipitation amounts exceed 40 mm. Nevertheless, despite their potential effectiveness, local protection measures are not infallible. In the case shown in Figure 13, the failure appears to be linked to the sequence of membrane installation over floor panel joints. In contrast, Figure 9 (middle) illustrates damage to a liquid-applied membrane coating, likely caused by mechanical impact. Further research on local moisture protection solutions for CLT is needed. Key areas of interest include understanding how, when, and why protection measures such as membranes or coatings fail, and whether moisture entering through failure points poses a significant risk. Additionally, it is crucial to assess how effectively these protection measures allow moisture to dry out. This highlights the advantages of full-coverage weather protection structures, which remains a more fail safe method.Tengberg and Bolmsvik [32] also showed that a full-coverage weather protection structure significantly reduces the risk of mould growth on CLT elements. But at the same time and somewhat counterintuitively, as demonstrated by the case of the building G and our calculations for it, prolonged exposure under a full-coverage weather protection structure can introduce risks. Extended exposure to outdoor air, even without contact with bulk water, can increase timber moisture content. This highlights the importance of rapid enclosure of CLT, irrespective of the use of an full-coverage weather protection structure. A rapid enclosure strategy, along with ensuring that wet CLT panels are not covered, was emphasised in [19]. Additionally, regular moisture content measurements remain essential even when wetting mitigation practices are in place, as evidenced by the case of the building G. To enhance monitoring, integrating systems like those described by Vestergaard Kellgren [40] into CLT construction would be beneficial, regardless of the chosen moisture safety strategy.

4.3. Moisture safety in the procurement process

The findings from the observations are somewhat inconclusive regarding the inclusion of moisture safety in the procurement process. Although, the inclusion of moisture safety was more prominent in the case of the building

G, there still was occasional excessive wetting (due to the occasional failure of the thin local protection membrane) and material needed to be replaced (in the case of the risky floor panel connection joint). In case of the building H, the initial solution for the first-floor panels yielded a moisture safe outcome, even though a specific moisture safety planning for the construction period was not mandated by the customer. Nevertheless, the solution that proved effective was specified during the design phase, indicating that, in a broader sense, moisture safety was incorporated into the design of the building H, which helped to reach good results with the first floor wall panels. Unfortunately, the same design did not include the moisture safety solution used for the first-floor panels in the second-floor panels. This shows the delicacy of moisture-safe design. It is clear that well thought out design and the accompanying drawings of moisture safety solutions in the design process of buildings are important.

While the general contractor for the building G was more experienced in CLT construction, the results do not show a clear correlation between experience and the outcome. Clearer connections with the outcomes stem from the moisture safety design. Neither of the case study buildings had a sophisticated moisture safety project, and the analysis of the construction processes suggests that both buildings would have benefited from a detailed moisture safety project, predictive analyses, and preliminary risk assessment. To date, more than 10 years have already passed since the construction of the first CLT building in Estonia [41,42], and 5 years have passed since the construction of the large public CLT building erected by the general contractor of one of the case study buildings [16]. Moisture safety practices have improved since, but as the case study indicates, there are still instances where excessive wetting occurs. More detailed moisture safety planning and preliminary analysis of the outcomes would likely improve the moisture safety of CLT structures. The general contractors of the studied case buildings demonstrated commendable overall performance; despite the presence of some moisture issues, which, while not entirely avoidable, show the challenges of achieving flawless construction practices and indicate the continuous need for further efforts to improve moisture safety.

4.4. Limitations of the study and future research

This study has certain limitations, particularly in the validation of the moisture safety strategy prediction method, as relying on only two buildings allows for unsystematic deviation. Further validation with additional case study buildings would be beneficial. Ongoing work aims to address this, as new CLT buildings are continuing to be built, and site observations are ongoing. Validation using data from other countries would also be valuable. However, this requires more than a simple comparison of moisture measurement results. A thorough site observation study – or at least an analysis of photographs, construction logbooks, and interviews with relevant stakeholders – is necessary to adequately explain potential discrepancies between predicted and actual outcomes. These requirements currently pose challenges to international validation.

An important limitation of the moisture safety strategy outcome prediction method arises from the selection of risk areas included in the analysis. This study focused solely on the bottom end-grain areas of wall panels, as they are the most vulnerable to moisture ingress, while horizontal panels were assumed to be protected by waterproofing membranes, a common practice. However, this case study also identified the floor panel connection joint as a critical risk area. Expanding the analysis to include additional risk points would increase complexity, which is why the current study remained focused on the primary risk area. Furthermore, on-site storage of CLT panels may influence moisture safety; however, additional data is required to incorporate this factor into the analysis. Many uncertainties arise, such as predicting potential damage to protective covers during storage, making it challenging to assess its impact reliably. Nevertheless, ongoing efforts aim to address these aspects. Additionally, consolidating the framework results into a concise spreadsheet or application is considered a valuable step for future development.

5. Recommendations for practice

The practical conclusions and recommendations for construction are:

- Detailed moisture protection solutions must be clearly specified during the design phase, as design quality seems to outweigh contractor expertise in ensuring moisture safety.
- Local protection can suffice without a full-coverage weather protection structure, but this carries higher risks and demands a responsive, adaptive moisture safety process. A preliminary risk assessment is advised when relying on local protection or considering the exclusion of protection measures.
- End-grain protection of CLT wall panels is effective, though local protection measures can fail or be damaged, warranting regular moisture monitoring. The swelling and warping of CLT can indicate excess moisture content even without water uptake marks on the surface of CLT.
- Delaying full-coverage weather protection after CLT installation creates a window for potential wetting incidents, as local protection can be damaged or incomplete.
- Installing CLT under a full-coverage weather protection structure ensures the highest moisture safety, however prolonged exposure to outside air, even under full-coverage weather protection, raises moisture content in CLT.
- Floor panel edges, particularly at cut-out grooves in panel-to-panel joints, should be moisture-protected similarly to wall panel bottom surfaces, ideally during the manufacturing stage of CLT.

6. Conclusion

This study evaluated the effectiveness of moisture safety measures and strategies in two non-residential CLT buildings, focusing on their design, implementation, and predictive analyses using hygrothermal modelling and a moisture safety prediction framework based on 30-year climate data. The findings highlight the importance of well-designed and clearly specified moisture safety solutions, along with proactive on-site moisture safety measures.

While the predictions generally aligned with actual outcomes, moisture issues arose where protective measures were compromised. These localised failures, not accounted for in the prediction framework, show the need to factor potential vulnerabilities into early-stage risk assessments. A guaranteed moisture-safe outcome was predicted 6 out of 10 times for the building G, 10 out of 10 times for the first-floor wall panels in the building H, and 0 out of 10 times for the second-floor wall panels in the building H. The predicted mean moisture content range in the lower areas near the end-grain surfaces of the CLT wall panels, based on 30 years of calculated data, was 17%–20% for the building G, 13%–17% for the first-floor panels in the building H, and 34%–78% for the second-floor panels in the building H (reaching up to 146% in the 10 mm layer closest to the end-grain surface). Considering only the areas where the protective end-grain coating remained intact in the building G, the measured moisture content ranged from 9% to 18%. In the building H, the measured moisture content ranged from 12% to 18% in the first-floor panels and reached up to 40% in the second-floor panels, as measured with an electrical resistance-based wood moisture meter. Excessive moisture content was addressed in each case, as the construction schedules allowed sufficiently long drying periods (>10 weeks) before covering the CLT. Additionally, mechanical ventilation systems were required for the second floor of the building H to aid the drying process. Simulations using specific climate data from a nearby meteorological station during the construction period indicated dynamics similar to those observed in the measurements. The prediction method was deemed sufficiently accurate. The initial hypothesis—that the moisture safety strategy predicted to result in poorer outcomes by the analysis method would indeed lead to worse conditions in practice—was confirmed. Likewise, the strategy predicted to perform better yielded superior results. However, the findings showed that even with a well-planned moisture safety strategy and an experienced contractor, moisture safety could still be compromised in certain areas. As CLT construction remains relatively new, ensuring moisture safety requires significant ongoing effort. Thus, the second hypothesis was not confirmed.

In conclusion, this research reinforces the important role of integrating predictive analyses, comprehensive risk assessments, and well-documented moisture safety strategies into the early stages of construction planning. These measures, supported by on-site moisture safety practices, can significantly enhance moisture safety in CLT buildings.

Acknowledgements

This work has been supported by the Estonian Centre of Excellence in Energy Efficiency, ENER (grant TK230) funded by the Estonian Ministry of Education and Research, by the Estonian Research Council (grant no. PRG2732 “Climate Resilient Renovation to Achieve Future-proof Buildings”), by the European Commission through LIFE IP BUILDEST (LIFE20 IPC/EE/000010), and by the ERA-NET Cofund Action ‘ForestValue“ project WoodLCC (N° 773324).

Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Authorship contribution statement

Kristo Kalbe: Conceptualization, Methodology, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Targo Kalamees:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

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PUBLICATION V

Kalbe, K., Annuk, A., Ruus, A., & Kalamees, T. (2021). Experimental analysis of moisture uptake and dry-out in CLT end-grain exposed to free water. Journal of Physics: Conference Series, 2069(1), 012050. https://doi.org/10.1088/1742-6596/2069/1/012050

Experimental analysis of moisture uptake and dry-out in CLT end-grain exposed to free water

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Abstract. This paper presents the results of a series of laboratory tests of CLT end-grain moisture uptake and dry-out. We put CLT test details (TDs) in direct water contact from the end-grain edge and then left the TDs to dry for two weeks in the laboratory and in an outside shelter. Half of the TDs had their wet sides attached to another CLT detail. Fibre saturation point was quickly reached in the bottom part of the TDs during the seven-day water contact. A tendency of increasing moisture content (MC) was up to 90 mm from the wet edges, but we did not record MC levels above the critical level at that height. However, MC exceeded critical levels at 60 mm from the water level. The measured water absorption coefficient A_w was 3.51×10^{-3} kg/m^2·s$^{0.5}$. Drying was negligible for the TDs which were in contact with another CLT detail. Thus, moisture dry-out is very complicated in joints where the CLT end-grain is covered, such as the exterior wall to foundation or intermediate ceiling connection. The dry-out of CLT is not expected in a cold and humid outdoor environment once the CLT end-grain has absorbed moisture even with wet edges exposed to air.

1. Introduction

Wetting of timber structures can have a harmful effect on their durability [1–3] and could lead to adverse health effects due to microbial growth [4–7]. Pasanen et al. [8] brought out that capillary absorption of water in wood-based materials results in rapid fungal contamination and that mould growth is abundant when the moisture content (MC) is above 20%. Olsson [9] reported that the probability of mould growth is very high when timber is exposed to free water. In a more recent study, Olsson indicated that it is very probable that cross-laminated timber (CLT) will get wet and develop mould growth if constructed without weather protection [10]. Olsson observed that "water does not easily absorb into the perpendicular fibres or through glued layers" thus indicating that the wetting of end-grain is more critical. Kalbe, Kukk and Kalamees observed the construction of a CLT building in Estonia and identified that the most critical areas of CLT regarding wetting are the joints where the end-grain portion is exposed [11]. Niklewski et al. [12] studied the moisture conditions of rain-exposed glue-laminated timber members and measured the highest MC in exposed end-grain details. It is thus evident that the end-grain parts of timber details are the most vulnerable due to moisture. However, CLT panel cut edges differ from the end-grain sides of typical glue-laminated timber members due to there being both end-grain and tangential wood faces which could have cracks and gaps between them. This could affect the moisture uptake and dry-out characteristics of wetted CLT panels. Previous studies have described the hygrothermal characteristics of CLT, but have concentrated on moisture transport perpendicular to grain [13–15]. Öberg and Wiege discuss that end-grain water uptake is crucial for wood and CLT panels, but state that end-grain water intrusion was not part of their calculations [16].

This paper presents the laboratory measurements of water uptake in the end-grain of CLT panels and subsequent drying under laboratory and outdoor conditions considering dry-out limiting factors which may occur in intermediate ceiling or foundation joints. Knowledge about these characteristics help to design better solutions for moisture-safe CLT construction.

2. Methods

2.1. Test details

Twelve test details (TDs) were prepared from a five-layer CLT panel obtained from a local producer in Estonia. The panel was produced in a controlled environment and had an initial MC of ≈ 12% upon delivery. The TDs had a width and height of 400 mm and a thickness of 100 mm. Three edges of the TDs were covered with a liquid-applied membrane coating to prevent moisture transfer through these edges. The side surfaces were left untreated. Thereby, one TD corresponds to one 400 mm by 400 mm portion of a larger uninsulated CLT wall panel where the three end grain edges would be in contact with timber (i.e., with surrounding parts of the larger panel, rather than air) and the side surfaces would not yet be covered. The bottom end grain edge was left untreated (Figure 1). This mimics a scenario where the CLT panel is installed on site and is open to water contact from the bottom connection (e.g., exterior wall to foundation connection) and insulation or any other layers are not yet installed providing a possibility of moisture dry-out through the sides. The TDs were left to stabilise for two weeks in a controlled environment before the wetting started.

2.2. Test setup for moisture uptake and subsequent drying

A moisture uptake test was prepared where the untreated bottom end-grain edges of the TDs were held in constant water contact throughout seven days (Figure 2). A similar situation could occur on the construction site if the CLT panels had been installed without weather protection and rainwater had accumulated under the CLT edge. Such occurrences have been documented by Kalbe, Kukk, and Kalamees [11].

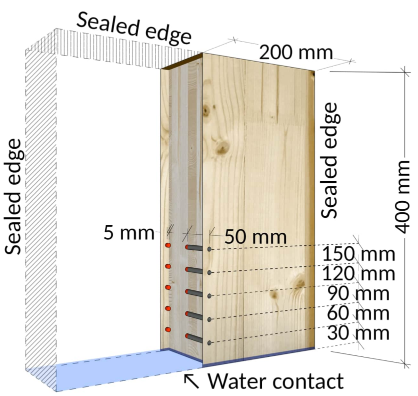

Figure 1. Dimensions of a test detail (TD). Location of the moisture measurement points (red dots) shown on a diagram of the TD.

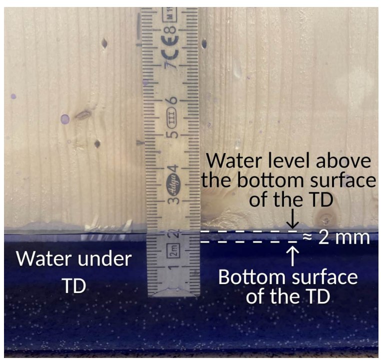

Figure 2. Test detail suspended above water with ≈ 2 mm in water contact.

Water level was kept constant at about 1 mm to 2 mm above the bottom level of the TDs (Figure 2) by regularly adding small amounts of water to the container. Special care was taken to ensure that the water contact remained constant and that the TDs would be level regarding the water surface. Blunt pins were used under the TDs to maximise the water contact and eliminate possible surface effects. Blue dye was added to the water to better illustrate the moisture transport in the CLT structure. The TDs were cut in half after the drying sequence and the moisture ingress was further inspected visually.

The TDs were held in water contact for 168 h at indoor conditions and thereafter numbered (TD13–TD24) and divided into four groups for the drying sequence: 1) TDs in indoor air with the wet surface exposed, 2) TDs in outdoor air with the wet surface exposed, 3) TDs in indoor air with wet surface against another CLT detail that inhibits moisture dry-out and 4) TDs in outdoor air with the wet surface against another CLT detail.

The TDs, which were connected to other CLT details, describe a situation where the wetted area exhibits moisture trapping conditions. This is similar to exterior wall to foundation or exterior wall to intermediate ceiling connection where the end grain edge is on the foundation construction or intermediate ceiling slab [11]. If there is a hydro-insulation layer on top of the foundation structure or a moisture barrier on top of the intermediate ceiling slab and water had gotten between this layer and the CLT panel on top, the moisture dry-out would be rather limited. In this sense, the CLT detail that was connected to the TDs in this study is a rather modest moisture barrier, because timber absorbs some water and thus pulls away moisture from the TD. However, the timber still exhibits vapour retarding properties (compared to freely drying surfaces that are open to ambient air). This approach was chosen because it will establish a base value and if more vapour retarding materials are used on the connection, the moisture dry-out would be even slower than described in this study.

The air temperature and relative humidity (RH) in the laboratory and in the outdoor shelter were measured with a Hobo UX100-023 data logger with its external sensor about .5 m from the TDs. The average ambient air temperature in the laboratory during the drying sequence was +21.6 °C (standard deviation, s = 0.8 °C) and the average RH was 28.6% (s = 5%). The water vapour pressure in the room was thus between 580 Pa and 910 Pa. Assuming an RH of $\approx$ 100 % at the wet TD edge, the corresponding water vapour pressure at the wet CLT surface was $\approx$ 2600 Pa. The difference in the water vapour pressure between the surrounding indoor air and the wet surface describes a situation with good ambient drying potential. The average air temperature in the sheltered but ventilated outdoor environment was +2.1 °C (s = 2.7 °C) and the average RH was 92% (s = 5%). The corresponding water vapour pressure was between 500 Pa and 830 Pa. The water vapour pressure at the wet CLT surface in the outdoor conditions was between 580 and 860 Pa, being often times equal to the ambient air water vapour pressure. The drying potential was thereby marginal.

2.3. Measurements
Moisture content measurements were made according to the EN 13183-2:2002 standard [17]. A calibrated Logica Holzmeister LG9 NG electrical resistance-based wood moisture meter was used. The expanded uncertainty was 0.8 % upon calibration for MC values between 12% and 22%. This increases notably when timber cell walls are completely saturated with water (fibre-saturation point $\approx$ 30% MC), however, in this paper we have opted to report the measurements as is. The high values that indicate a MC over the fibre-saturation point help to describe the extent of wetting (e.g., just about at fibre-saturation point or certainly exceeding it). Nevertheless, if the structure has wetted to fibre-saturation point, there is a large risk of damage due to microbial growth or swelling and shrinkage.

All MC measurements were done with 60 mm long Teflon insulated pins that were attached to a ram-in electrode. The pins had 10 mm long uninsulated peaks that made it possible to measure the MC at different depths, depending on how far the electrodes were rammed in. MC was measured on every TD at two depths: 5 mm and 50 mm from the surface at five height levels from the bottom of the TD (at 30 mm, 60 mm, 90 mm, 120 mm and 150 mm from the water level (Figure 1). Thus, a total of ten MC measurements were made per one TD. The 5 mm deep measurement points describe MC in the outer ply of the CLT and the 50 mm deep measurement points describe the conditions in the inner (3rd) ply of the CLT (5 layers in total). Both timber board layers were in the same direction and had the end-grain part exposed to free water. The measurements were done daily throughout the test period from wetting to drying.

The TDs were also weighed regularly (every 2h for the first 6h and every 24h afterwards) with a Kern DS 30K0.1L platform scale with an expanded uncertainty of 0.8 g for loads up to 10,000 g. Every TD was also photographed from one side before it was put back into water contact. Water uptake rate and water absorption coefficient were calculated on the basis of these measurements. The test was performed largely according to the European standard EN ISO 15148 [18], which provides the procedure to determine the water absorption coefficient of a building material by partial immersion. The difference with our test and the standard procedure was that the standard requires coating of all sides, but we coated only the end-grain sides and top surface. This was necessary for the additional dry-out sequence of the test.

2.4. Critical moisture content

For the estimation of the criticality of MC, we used the limit value of 16% (mould growth initiation). Gradeci et al. made a systematic literature review about mould growth criteria and reported that the minimum RH requirements for mould growth initiation varied from 70% to 85%, while most reviewed studies indicated mould growth when RH was at least 80% [19]. The latter corresponds to a timber MC of ≈ 16% [20] at temperatures ≈ 0–20 °C. Mould growth is also affected by exposure time and temperature [21], but in this study we focused on the MC distribution and thus established only a critical MC level for the evaluation of results.

3. Results

During three weeks, a total of about 2800 MC measurements were done. Figure 3 summarises the results and several effects become evident. The upper five plots describe the MC conditions in the outer 5 mm surface layer of the TDs and the bottom plots describe the MC in the 50 mm deep middle layer of the TDs. Moisture content measurements taken from various heights from the water level are presented on separate plots (from 30 mm up to 150 mm, see Figure 1 for a graphical representation of the measurement points).

At 90 mm and above (from the water level), the MC decreased in the 5 mm deep (surface) measurement points during the wetting period due to the dry ambient air. This indicates that the moisture absorbed from below did not reach the measurement points at that level. Though, we observed some cases where moisture stains reached up to 130 mm adjacent to the measurement points. The trend of decreasing MC in the surface level continued for the TDs which were left to dry in the indoor environment. However, the TDs which were put to the outside environment started to absorb moisture from the ambient air and the MC increased above the critical level. The equilibrium MC was > 22% in the outside environment (calculated with the equation 4-5 given in [20] with the average outside temperature of ≈ 2 °C and RH 92 %). Thus, the increase in the surface MC was to be expected. This effect was not evident for the middle layer measurements taken 50 mm deep. However, the measurements indicated moisture redistribution in the middle layer up to 90 mm high, where a slight upwards trend of the MC levels was visible. The redistribution of moisture in the middle of the TDs was very clear for measurements up to 60 mm above the water level, where the MC had an increasing trend for all TDs regardless of conditions throughout the entire test period.

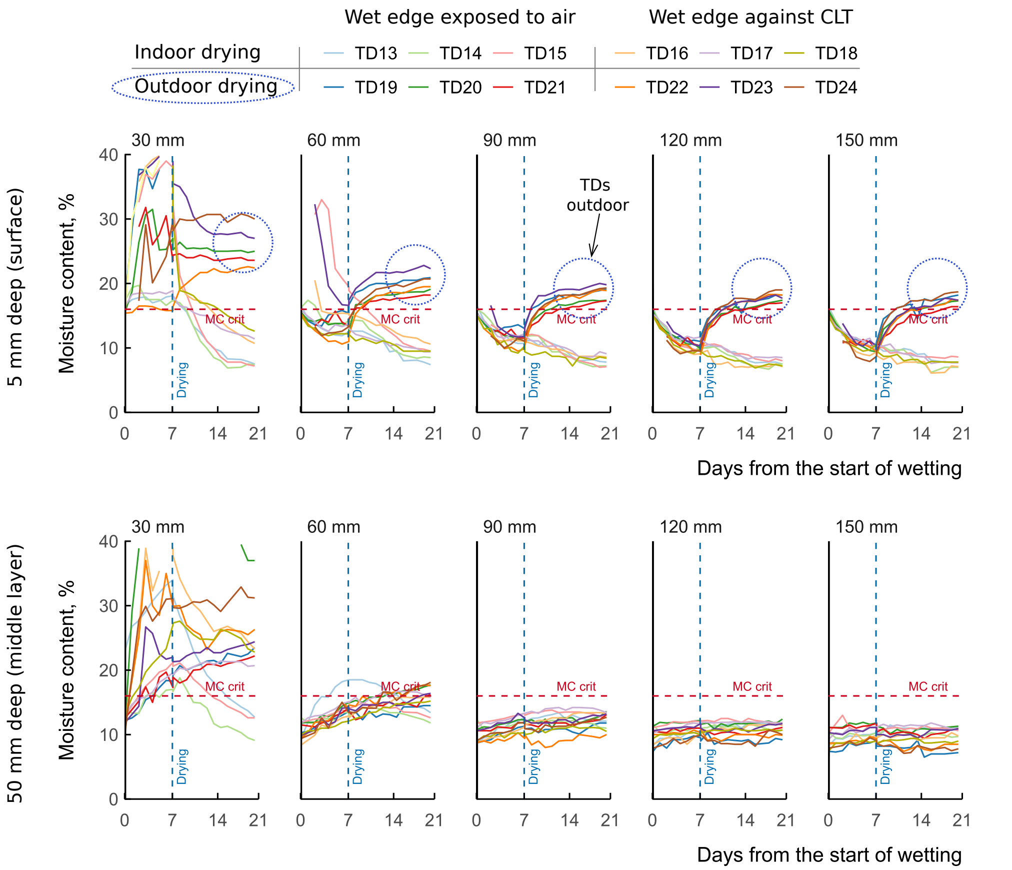

Figure 3. Measured MC in the TDs over wetting and drying. The upper five plots describe the MC in the surface layer (5 mm deep) of the TDs in different heights (Figure 1) from the water level and the bottom five charts describe MC in the middle layer of the TDs (50 mm deep). Each colour represents a different TD.

Further analysis of the results showed that MC in the middle layer of the TDs, which had another CLT detail attached to the wet base, did not go below 20% even in the TDs that were left drying in the inside air conditions (Figure 4, left). MC did decrease in the surface layer (Figure 4, right), but only for the TDs that dried indoors.

The water uptake rate (average of every TD) was 200 g/(m^2·h) for the first two hours, then decreased quickly to about 85 g/(m^2·h) during the next four hours and then decreased gradually during the next 70 hours to about 20 g/(m^2·h) where it stabilised (Figure 5). The water absorption coefficient A_w was 3.51×10^{-3} kg/m^2·s$^{0.5}$ (calculated as per EN ISO 15148 [18]).

The added blue dye illustrated moisture transport on the CLT surface. The results reflected the electrical resistance-based MC measurement adequately from the surface layer. Heterogenic properties of wood were also visible. Figure 6 shows photos of TD20 where the water level at MC measurement points was lower than just next to the measurement points. The main water level stain marks did not rise above 130 mm in any test detail during the seven-day wetting period, but there were few instances where small stain marks were visible higher up in cracks and ply joints. However, the stain line inside the TDs did not correlate with the measured MC in the middle layer. This was probably because the dye trapped in the lowest few millimetres of the TD and did not reach further. Thus, the visual inspection was impractical inside the TD.

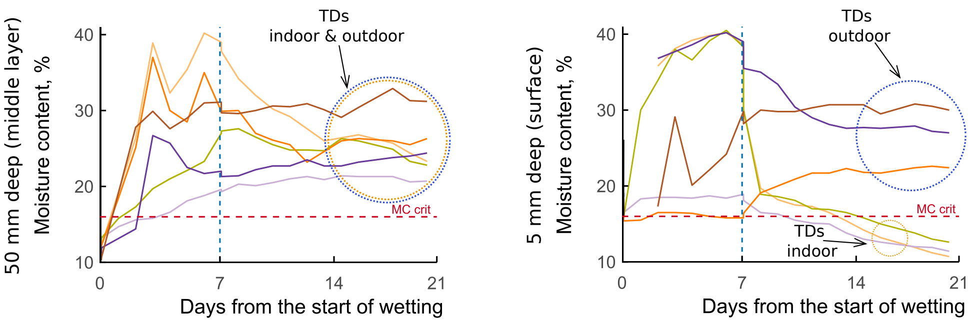

Figure 4. MC at 30 mm from the bottom of the TDs that had wet edges against CLT. Measurements from the middle (50 mm deep, left) and surface (5 mm deep, right) layer.

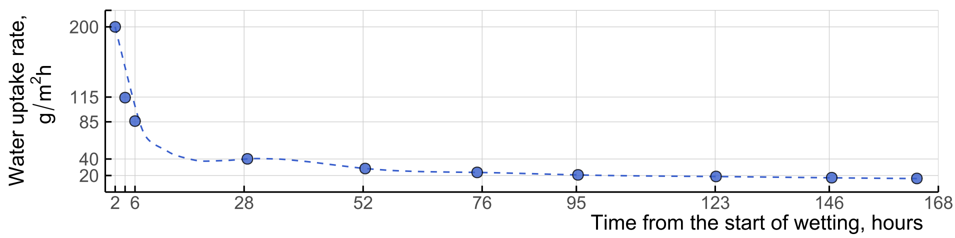

Figure 5. Water uptake rate during the test as an average of every TD.

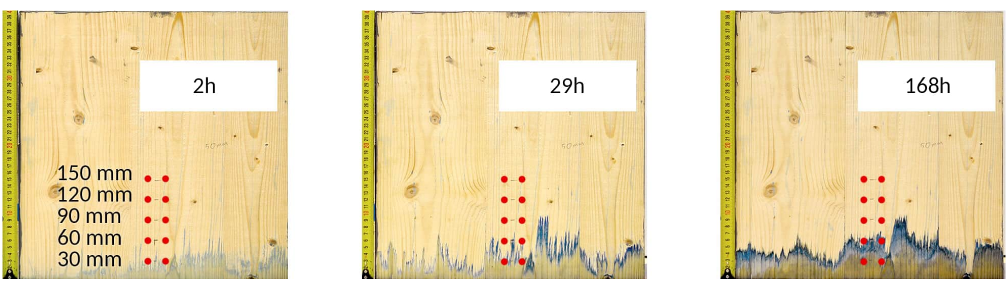

Figure 6. Photos of TD20 at 2, 29 and 168 hours after the start of water contact. Water was dyed blue and left stains on the timber surface. Red dots mark the MC measurement points.

4. Discussion

Our findings show that the most vulnerable area to moisture damage leading from water ingress from under a CLT panel through the end-grain side is up to a height of 60 mm from the bottom of the panel. There is a tendency of rising MC in the middle layer of the TDs up to 90 mm high, but we did not record MC levels above the critical level at that height during the seven-day continuous wetting period and 14-day drying period afterwards. A greater risk to dampness related problems in the higher areas are on the surface and more due to outside environment conditions. However, in low temperature conditions, the probability of mould growth is low [19].

Measurements from the bottom area of the TDs (30 mm from the water level) indicate that fibre saturation point was quickly reached in the bottom part of the TDs in both surface and middle layers. During the two-week drying period, it became evident that there is no drying potential even with wet edges exposed to air in the cold and humid outside environment (t ≈ 2 °C and RH 92 %, which approximate to the February averages in the Estonian moisture reference year for mould growth criticality [22]). Drying was also negligible in the indoor environment for the TDs which were in contact with another CLT detail. This suggests that moisture dry-out is very complicated for construction joints where the CLT end-grain is covered, such as the exterior wall to foundation or intermediate ceiling connection. It is possible that moisture stays in the CLT panel bottom part until the construction process reaches stages where temperature around the panel is suitable for mould growth. These findings show that moisture redistribution is probable for up to 90 mm from the water contact surface. This implies that MC in the area could exceed the critical level well after the initial wetting incident and thus would be susceptible to mould growth. Moreover, Li and Wadsö reported that fungal activity is greater during moisture desorption process than absorption at the same RH levels [23]. Researchers have suggested to use whole site weather protection for timber buildings [24] and although this would help to minimise the risk of wetting, incidents might still occur. We propose to use end-grain protection on CLT panels regardless of site weather protection, because the poor dry-out characteristics and possible moisture trapping conditions in several end-grain joints.

Previous studies have measured the water absorption coefficient (A_w) of CLT, but have determined it with the CLT panel face in water contact and not for the end-grain cut edge in water contact. AlSayegh has reported that the A_w for the side surfaces of CLT is $1.6–1.7\times10^{-3}$ $kg/m^2{\cdot}s^{0.5}$ [14, 15]. The European CLT samples from a study by Lepage had an $A_w \approx 1.1\times10^{-2}$ $kg/m^2{\cdot}s^{0.5}$ [25]. In a recent study by Kordziel et al. A_w was also calculated for the side surfaces of CLT and was $\approx 2.5–2.8\times10^{-3}$ $kg/m^2{\cdot}s^{0.5}$ [13]. Longitudinal moisture transport in wood is greater than moisture transport perpendicular to grain [20]. This is evident when comparing our results with the ones of Kordziel et al. and AlSayegh, where the A_w value we calculated was greater. However, Lepage reported higher values of A_w for moisture transport perpendicular to grain. This could be influenced by different wood species and glue formulas. Measured values of A_w for softwoods are in the range $\approx 1–1.6\times10^{-2}$ $kg/m^2{\cdot}s^{0.5}$ in the longitudinal direction and $\approx 1–7\times10^{-3}$ $kg/m^2{\cdot}s^{0.5}$ in the transverse directions [20]. It seems that regarding the moisture absorption coefficient, CLT end-grain acts more like the transverse direction in regular timber.

5. Conclusion

In this paper we characterised the water uptake and subsequent moisture dry-out of CLT panels from the end-grain edge. The measured water absorption coefficient A_w was 3.51×10^{-3} $kg/m^2{\cdot}s^{0.5}$.

Taken together, our results from the drying sequence suggest that if gotten wet, the CLT end-grain edges will not dry out in a timely manner, especially the parts of panels where moisture trapping conditions occur.

We suggest to protect the end-grain edges of CLT panels with a moisture barrier that also prevents water from getting between the CLT and the barrier itself. We reccomend to apply the barrier before the delivery of CLT panels on site and use the barrier regardless of other weather protection practices to minimise the risk of wetting in joints where moisture trapping conditions could occur.

Acknowledgments

This research was supported by the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE (grant No. 2014-2020.4.01.15-0016) funded by the European Regional Development Fund and by the Estonian Research Council (grant No. PRG483), and by the European Commission through the H2020 projects Finest Twins (grant No. 856602) and NERO (grant No. 754177). The work also received valuable support from the Tartu College of Tallinn University of Technology.

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Scientific publications and conference papers

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Teaduspublikatsioonid

Nimekiri teaduspublikatsioonidest on esitatud inglisekeelse elulookirjelduse all.

ISSN 2585-6901 (PDF)
ISBN 978-9916-80-316-5 (PDF)