Methodological framework for HAM-simulations: the litigation case of a CLT-balcony subjected to rain loads during construction

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ABSTRACT

Cross Laminated Timber (CLT) is increasingly used as structural component in low and mid-rise buildings. It comes with excellent carbon storage and prefabrication potential, and provides an interesting alternative for traditional construction methods. However, as it consists of wooden components, these panels are prone to degradation and delamination if exposed to long-term moisture sources, typically originating from on-site exposure to rain spells during the construction period. This study investigates different drying strategies by analyzing the wetting and drying processes by means of HAM-simulations for a CLT floor in a case-study with moisture-related degradation problems. Bore samples were taken from the CLT balcony where the most severe deterioration was observed, caused by insufficient rain protection during construction. After a rainy winter period the CLT was prematurely sealed off with an unventilated ETICS system (EPS + silicone plaster). In the analyses, it is seen that an unventilated finishing system results in a critical deterioration of the timber. The simulations show this could have been prevented by either choosing a ventilated finishing system or by sufficient rain protection during construction. In order to compare simulations with measurements, it is important to adopt a clear methodological approach for the hygrothermal simulations. Hence, a framework was developed that elaborates on each step of the development process of HAM-simulations, by means of a strategic three level selection system for model parameters. This approach allows to increase the usability and reliability of HAM-simulation in practice. At the end of the stepwise framework, the hygrothermal response from simulations was compared with the visual and experimental assessment of the wood samples. The study highlights the potential of HAM-simulations in both design as litigation context, and it was concluded that practice would benefit from a stepwise framework to conduct HAM-simulations, that provides guidelines to select climate, materials and performance criteria.

INTRODUCTION

New constructions are expected to be safe, provide thermal comfort, and protection against moisture-related problems seems obvious. Unfortunately, a certain proportion of the building stock suffers from moisture-related problems such as stains, corrosion or mold growth, caused by e.g. rain ingress, interstitial condensation. In order to study, prevent or repair moisture-related problems in a systematic and comprehensible way, Heat-, air and moisture (HAM) simulations can be used. These hygrothermal simulations have proven their added value for research and renovation strategies in the past. They help to understand and predict the various hygrothermal processes and risks on a material, component, and building scale. In recent years, research has been further extended by adopting climate projections which in turn allows to predict the robustness of an assembly subjected to different degrees of climate change over the expected service life. Although the potential of such

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numerical simulations is widely recognized, the results are highly dependent on the assumptions made by the simulation model and the user. Hence, a methodological framework for hygrothermal simulations was developed and proposed in this paper.

In most cases, a building component is subjected to mechanical loads, temperature variations and moisture loads which can cause, in addition to natural aging phenomena, a decrease in performance and durability of certain materials or of the assembly as a whole. When the durability of a structure is compromised, ideally a holistic risk analysis is conducted based on the design details, accurate assessment of the applied materials, high resolution data on boundary conditions and a reliable numerical simulation and performance model. However, in many cases this ideal is challenging, and not feasible, and instead statistical data is used in combination with professional judgement (e.g. assessment of concrete structures). In contrast to strength requirements, durability risks related to moisture only become apparent over a long period of time, and there is a lack of clear guidelines on the application of numerical models in this field.

With this paper, the authors aim to propose a methodological framework to perform HAM simulations that goes well beyond existing guidelines in standards and codes. The framework focuses on the main variables required for hygrothermal modeling: implementation of component configurations, climatic boundary conditions, and material characteristics. Three strategic levels are adopted to guide the selection of the different simulation parameters: Superior, Advanced, and a Minimum requirement. The methodology was demonstrated using a litigation case where a CLT floor construction, more specifically a balcony, showed significant decay and deflection. For this case it is important to simulate the rainfall wetting processes as accurate as possible in the HAM model, which shows to be crucial to understand the degradation phenomena. Subsequently, simulations are used to study the drying behavior and conditions to prevent damage in future projects. The case study highlights that a stepwise framework would increase the potential and use of hygrothermal risk assessments in practice.

METHODOLOGY

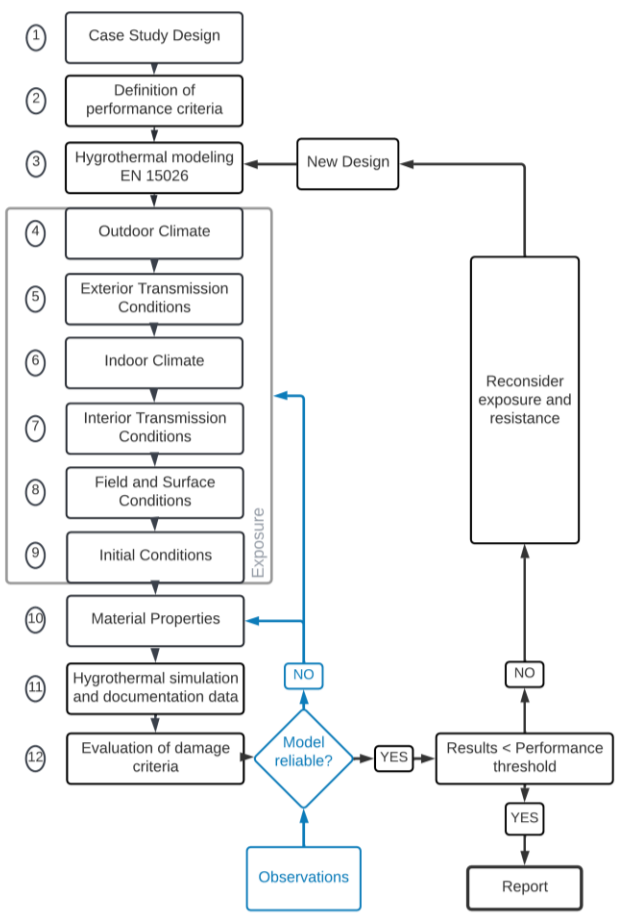


Figure 1 Methodological framework as a guideline to perform performance assessment by means of HAM-simulations

The methodological framework to conduct risk assement by means of HAM-simulations is visualized in Figure 1. It represents a stepwise process from case study design to the simulation and reporting. The steps are numbered from 1 to 12 and relate to the definition, assumptions, simplifications for the configuration, and the input variables for the model.

In the first step, the design and purpose of the risk assessment are defined, and the critical performance risks are identified. One can determine the performance risks for the assembly based on the durability guideline by Lacasse et al. (2018) and ISO 13823. Subsequently, the appropriate HAM simulation software is selected, which will relate to the purpose and configuration of the assembly and its risks. In the next phase, the definition of boundary climates and associated transfer coefficients is discussed based on the three strategic levels: Superior, Advanced, and Minimum requirements. Throughout the framework, these levels are used to describe the reliability and accuracy of the model parameters. In general, a Superior category will base the parameter on on-site measured values, whereas in the Advanced category, the value is based on an equivalent case from literature. The Minimum requirement category allows to adopt tabulated values from literature or standards (e.g. EN 15026) but also requires to assess the impact of each important parameter by means of sensitivity analysis. These categories also apply for the material modeling. With the choice for a Superior category, a large part of the uncertainties typically associated with hygrothermal modelling will be eliminated.

A feedback loop is integrated as a control mechanism, in which the simulation results are compared with reality and, if applicable, a visual inspection. When the simulations do not match the observations, the HAM-model is reconsidered to enhance the accuracy, e.g. by increasing the material category from Minimum requirement towards Superior in the definition of its characteristics. In the following sections each step of the methodology, with its various choices for categories is explained by means of a litigation case study on a CLT balcony that showed severe deterioration five years after completion.

Step 1: Case study design

In this step, all relevant configurations must be thoroughly documented which includes the existing situation, and if applicable new design approaches or retrofit solutions. Such information could be combined with measurements, visual inspections, technical documentation and design drawings of all possible configurations and variations.

Due to the sensitive nature of the case some confidential information cannot be disclosed. The building element in question is a balcony floor, visualized in Figure 2. The adopted geographical location in the HAM-model is assumed at 50.8˚N; 4.3˚E. It is constructed with a multilayer wood element (CLT) and finished with an unventilated ETICS system at the bottom and a cement-based screed on top with roofing and terrace tiles. The ETICS system is considered a classical unventilated system with EPS insulation and a silicone plaster. An overview of the applied materials and its configuration is shown in Figure 2.

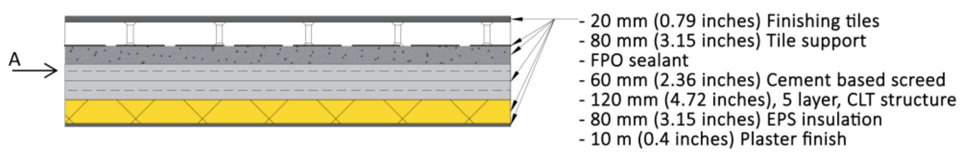


Figure 2 Cross-section of the CLT balcony floor with and overview of applied materials.

For the case-study it was known that the CLT-elements were fully exposed to the outdoor climate for the 2014-2015 winter period during construction. Subsequently, in the spring of the following year an ETICS system was applied, but perhaps the CLT may not have yet dried out sufficiently before the installation of the system. After 5 years, moisture related problems were identified in several areas of the building, which in turn led to biological deterioration of the structure. The most severe problems were observed in the balcony flooring system, at location A, i.e. on the contact surface between the first and second layer of the 5-layer CLT system (please refer to Figure 2). Based on the mycelium fungus present in the bore samples, the moisture content was estimated to be at least between 30 to 50%. These organisms degraded the structural integrity of the wood and caused the floor elements to sag excessively.

Step 2: Definition of performance criteria *(Case = Minimum requirements)*

Undesirable effects due to moisture are a major cause of durability risks in materials, building components and buildings. The structural integrity as well as the occupant's health can be compromised and should hence be avoided at all times. There are very diverse performances and are represented by various criteria. To define the performance risk, the durability guide established by Lacasse et al. (2018) and ISO 13823 are adopted, both entail a portion of professional judgement when used. The performance risk can be quantified in several ways, below a distinction is made in three different categories:

1. Superior: material-specific degradation and performance criteria are used based on an experimental characterization of the material-specific sensitivity or threshold levels.
2. Advanced: the performance is based on a dynamic prediction model, e.g. time of wetness models or dose-response functions. The wetness/dose will be induced by multiple factors such as temperature and humidity.
3. Minimum requirement: the most severe threshold levels are adopted, this entails the verification if a moisture equilibrium is reached, if interstitial condensation is avoided, if runoff is prevented and if energy losses are reduced.

For the case study, damage was already observed. Severe brown wood rot was evident in the top layers of the CLT with spores of insect infestations, this location is referred to as location A for the remainder of this study and is visualized in Figure 2. The softening of the wood rot affected bore samples was tested according to the method described in CEN/TS 12037:2003. In the most critical situation, failure of the wood was observed, which led to the conclusion that the top layer was severely degraded and had been exposed to excessive moisture contents.

The mycelium present in the wood was classified as *Tapinella Panuoids* (Huckfeldt and Schmidt, 2006a). These require very high moisture conditions to develop and degrade wood, with an optimal moisture content between 50-70% (Huckfeldt and Schmidt, 2006b). The criterion for initial moisture content in CLT with an ETICS finish was set to 17% by Kukk et al. (2019), to avoid the risk of mold growth.

Step 3: Hygrothermal modeling software

With the description of the case and the different performance risks, an informed choice for a HAM-simulation software can be made. The standard EN 15026:2007 or ASTM E3054 are to be used for conducting numerical simulations and to determine the balance equations necessary to simulate the hygrothermal response of materials and building assemblies.

EN 15026 by default proposes a simplification to 1-dimensional simulations. The authors are convinced that such simplification should be considered as the exception and only to be used when literature or preliminary studies show the assumption to be at the safe side. It should be noted that if no 2-dimensional transport is present, a 1D configuration is evidently justified. After this, the configuration is subjected to a discretization process of the assembly with a fixed or variable thickness.

For the case study, a 1-dimensional model was created using the Delphin 5.9.6 software according to the configuration in Figure 2. Two models were created to analyze the situation during construction and the situations after completion. In the first model, only the 5-layered CLT-element is modeled, whereas in the second model the top and bottom finishes are applied as well. In the latter, the roof tiles are not modeled as it can be assumed that the climate below the tiles is close to the outdoor climate without direct solar radiation.

Step 4: Outdoor climate *(Case = Minimum, Superior, -)*

The outdoor climate refers to the boundary conditions at the exterior surface of the assembly. Several variables are combined to define the outdoor climate, e.g. temperature, wind driven rain, radiation. A complete list of variables needed in the simulations is available in EN 15026. Some climate variables can be derived from other when required, e.g. the downward longwave radiation can be computed from cloud cover, air temperature, relative humidity and air pressure according to ISO 15927. In selecting the outdoor climate, it is important to consider the spatial and temporal resolution. Therefore:

1. Superior: the climate data are representative and validated for the location of the building site. Furthermore, very local features, e.g. urban heat island effect, orography etc. are accounted for. The temporal resolution is 10 min.
2. Advanced: the climate data are representative and validated for the location of the building site with hourly temporal resolution. The validation is performed with an available dataset or climate statistics.
3. Minimum requirement: the closest location to the building site is selected, an hourly temporal resolution is used.

The type of climate data also depends on the nature of the study: is only a static climate considered where no change over a longer period is considered or is the impact of climate change included as well?

1. Superior: the static approach is a long-term climate dataset for at least 10 (measured) years, ideally 30. In case climate change is considered, different climate models and Representative Concentration Pathways (RCP) or Global Warming (GW) levels are included in the ensemble. A historical baseline is compared to 30-year climate projections. The ensemble approach accurately quantifies the uncertainty of the climate model results.
2. Advanced: a Moisture Reference Year (MRY) is used as input. Vandemeulebroucke et al. (2022) developed a comprehensive framework to select MRY's. The climate change is considered by comparing a 30-year historical (baseline) to an ensemble of ca. three 30-year climate projections (all derived from the same model). The ensemble quantifies the uncertainty of the results to a limited extent.
3. Minimum requirement: for a static climate an MRY is used as outdoor climate input, whereas for climate change a 30-year historical period is compared to a single 30-year climate projection from the same climate model. In this case, location specific biases from the climate models are not accounted for. The uncertainty induced by uncertainties in climate change effects is unknown.

In the case study, climate change and local effects were excluded from the analyses. A 10-year static climate dataset was, provided by Royal Meteorological Institute (RMI) with an hourly time resolution. This included the two years evaluation period. The longwave radiation was not available for the location but was calculated based on the cloud cover according to Finkenstein and Häupl (2007).

Step 5: Exterior transmission coefficients *(Case = Superior)*

For hygrothermal modeling, it is necessary to define transfer coefficients for the climate conditions. These comprise the heat, vapor, rain and radiation transfer at the contact surface between the outdoor climate and the finishing material.

1. Superior and Advanced: the surface heat and vapor transfer coefficients are defined based on a variable air velocity according to EN 15026, this method is preferred if the wind speed is available from climate data.
2. Minimum requirement: if wind speed is not available, a constant value from literature can be used.

The catch ratio, , is the ratio of wind driven rain projected onto a vertical surface to the corresponding horizontal rainfall, depending on the wall factor and rain exposure. The value usually ranges between 0 and 1 but will exceed that when run-off on the façade is accounted for.

1. Superior: the exposure coefficient is determined based on rain gauge measurements or CFD simulations.
2. Advanced: the coefficient is determined based on CFD simulation for similar building geometries.
3. Minimum requirement: the sensitivity for a low, average and high rain exposure is determined based on tabulated values from literature or standards (e.g. ISO 15927-3).

In the case study the heat and vapor transfer at the contact surface was modeled with a variable air velocity. The coefficients for exchange were set to the values proposed by Nicolai (2006). The rain exposure was set to 1 by means of a sensitivity analysis in combination with the feedback loop based on the experimentally defined MC.

Step 6: Indoor climate *(Case = -)*

The interior boundary conditions used in the hygrothermal simulations include the following variables according to EN 15026: the temperature, the relative humidity or the pressure differential across the assembly.

1. Superior: the indoor climate is defined by measured values, or by the setpoints of HVAC systems. This does not account for a change in use over time, this could be implemented by means of an increased moisture load.
2. Advanced: the indoor climate is modelled with an appropriate building simulation software.
3. Minimum requirement: the indoor climate is determined based on calculated moisture loads and ventilation rates. If this is not available or applicable, an adaptive internal humidity based on EN 15026 can be calculated.

No indoor climate was considered in the case study as the assembly was completely exposed to outdoor conditions.

Step 7: Interior transmission coefficients *(Case = -)*

The surface transfer coefficients for heat and vapor transfer to be applied on the internal finishing surface are based on EN 15026, assumption that no forced convection on the inside is applied.

Step 8: Field and Surface conditions *(Case = -)*

In a next step, the assumptions for field and resistance conditions are determined. A resistance condition applies to the contact surface between materials whereas a field condition is applied partly or over a complete configuration element. The modeling of surface resistance allows the implementation of vapor barriers while the field conditions can be used to introduce the movement or leakage for air through the assembly. For the case study, no field or surface conditions were necessary.

1. Superior: the field conditions are determined based on in-situ measurements, e.g. the ventilation rate in voids. The specific surface conditions are characterized in accordance with the appropriate standards.
2. Advanced / Minimum requirement: a sensitivity analysis is performed to evaluate the effect and worst-case situation. For example, an increased ventilation rate can both increase or decrease frost risk, depending on the case.

Step 9: Initial conditions *(Case = Superior)*

Initial conditions are applied to specific parts or elements in the cross-section of the configuration at the beginning of the simulation period and refer to the temperature, relative humidity or moisture content. The definition of the initial conditions relates to the current state of the building. If an equilibrium is reached in the assembly, the model will be simulated with the initial conditions defined by ASHRAE 160 and an equilibrium is obtained by means of a conditioning period. The number of years is determined in a preliminary study. When an equilibrium is not yet established in reality, the initial conditions are determined as described below. In the case study the initial conditions were set to 50% MC based on the on-site measurements.

1. Superior: the initial values are derived from on-site measurements
2. Advanced: the initial conditions are calculated by the free water necessary for construction, and if applicable the rain ingress is calculated based on the wind driven rain loads during exposure.
3. Minimum requirement: ASHRAE 160 indicates two times 90% MC should be used for concrete and two times 80% MC for all other materials. Exceptions are possible when drying or protection measures are considered.

Step 10: Material properties *(Case = Minimum requirements)*

To calculate the different equilibrium equations in a HAM-simulation, it is necessary to define the hygrothermal material properties. A list of the different properties required for simulation is provided in EN 15026, accompanied with the source for a tabulated value or characterization procedure. In practice, the choice of material for the HAM-model is based on the available information: it may be a partial or complete characterization, or in the worst case only the material type is known (e.g. brick). For more recent and new materials, a technical sheet is typically available, entailing following approach:

1. Superior: a fully characterized material is entered in the software.
2. Advanced: based on the available material properties, a similar material from hygrothermal databases is chosen. Subsequently, material functions are adjusted and scaled using the available information.
3. Minimum requirement: a representative or generic material is chosen from the existing hygrothermal material database after a thorough consideration of the technical datasheet.

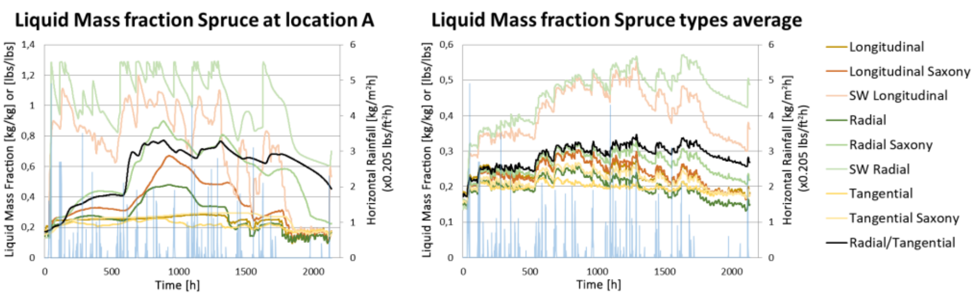
In many cases no technical data sheet is available and properties are unknown (e.g. heritage renovation). Hence, it is crucial to determine the sensitivity of the material to the hygrothermal response, for which following scheme is proposed:

1. Superior: a fully characterized material is modeled in the software and the impact of inherent material variability on the response behavior is evaluated.
2. Advanced: a partial characterization is performed on the most significant material property. The significance of a property can be determined by means of a sensitivity analysis or by similar cases published in literature.

3. Minimum requirement: a one at a time sensitivity analysis for the properties is performed with a low, average and high value. Another approach was proposed by Zhao (2008) and Vanderschelden et al (2022), with the clustering of materials a generic material can be determined to represent a cluster of materials with similar properties and response.

Different materials were applied in the case study, see Figure 2. From bottom to top: the silicone plaster was modeled with a scaled material from the Delphin database (ID242), which is considered safe as a sensitivity analysis rendered the impact of the plaster negligible. The accompanied EPS insulation board is modeled as material with ID 198. At the top, a cement-based screed layer was applied directly on the CLT with an FPO sealant on top. The impact of different types of screeds was analyzed and found negligible, due to the vapor-tight finish on top. For the screed ID 68 was adopted, whereas the sealant material was derived by scaling the vapor diffusion resistance of the bitumen material from the database (ID 28).

The structure of the balcony consists of a CLT element, comprising 5 Spruce layers (20, 30, 20, 30, 20 mm or 0.79, 1.18, 0.79, 0.18, 0.79 inches) with a total thickness of 120 mm (4.72 inches). The CLT glue is modeled with the same properties as the spruce, only the vapor diffusivity and liquid diffusivity was halved, based on research by Al Sayegh (2012) and Defo (2021). It should be noted that the hygrothermal behavior of the wood is determined primarily by its moisture buffering, vapor diffusion resistance, and its liquid moisture transport. However, little information regarding these properties is available in the documentation. Therefore, a preliminary study for the CLT element was conducted by simulating the winter of 2014 with the different wood species available in Delphin. The results for the MC at location A as well as the average MC are shown in Figure 3. With the combination of the technical data sheet and the study below, the radial/tangential wood was selected. The data sheets contained information regarding the type of wood and some basic properties such as density while the simulation results below, in Figure 3, were compared with the bore sample analyses. A CLT panel consists mainly of radial and tangential wood, only at the edges the end grain is dominant. Figure 3 shows that this simulation approach indeed induces a moisture content of 50% in the top layer at the end of the winter in 2014, in line with the conclusions of the analysis of the degradation of the bore samples.



Properties Radial/Tangential CLT		
Density	425,0	[kg/m³] or x0,0624 [lbs/ft³]
Thermal conductivity	0,079	[W/mK] or x1/3,24 [W/ftK]
Saturation water content	0,596	[m³/m³] of [ft³/ft³]
Water absorption coeff.	0,0024	[kg/m²s^0,5] or x0,205 [lb/ft²s^0,5]
Vapor diff. resistance fac.	73,00	[-]
Liquid cond. at saturation	9,50E-10	[s]

Figure 3 The absolute Liquid mass fraction [kg/kg] or [lbs/lbs] in location A (left) and the average fraction over the whole CLT-element (right).

Step 11-12: Reliability of the model

Using the adopted model parameters, the hygrothermal simulations are performed and post processing is applied. The hygrothermal response according to the model is then compared with reality. The latter may consist of various elements, visual observation of damage, experimentally determined moisture content, etc. When a significant discrepancy between the model and reality is evident, the exposure loads and/or material properties can be reviewed. In that case it is recommended to reconsider the dominant parameters that emerged from the sensitivity analyses. Upscaling from Minimum requirement to Advanced or even Superior should reduce the discrepancies and increase the reliability. For example: when frost damage was observed at a chimney of a house, first the chimney can be modeled and adjusted until the simulation is compliant with the actual observations to calibrate the hygrothermal model and/or degradation model for the remainder of the investigation.

For the case study concerning the wetting process of CLT, it is important to correctly model the initial conditions. The minimum initial moisture content at completion was set to 50% due to the presence of the *Tapinella Panuoids*. Figure 3 shows that the exposure of the top spruce layer (radial/tangential) to the on-site rain loads can induce a 50% MC. The fungal index of Viitanen (2007) was used to examine the critical deterioration on each contact surface of the CLT for compliance with the observation of the bore samples. A critical index was observed for the upper layer and a small growth in the bottom layer according to the model, which corresponds well with the observations.

Step 13: Results

The results for the case study are summarized in Figure 4. The hygrothermal behavior in location A is shown, during construction and after completion. In the construction phase, the exposed CLT is compared to an application where the CLT is shielded from rain impingement. In the latter, no significance increase for MC was observed, unlike for the exposed CLT for which an increase up to 70% MC is seen after a long period of rain. After completion different drying strategies are compared.

First, the current situation was modeled. It is clear that due to the installation of the finishing layers the structure had not dried out sufficiently, and the finishing system hampered adequate drying afterwards. As indicated in Figure 2, the screed was applied directly onto the CLT. Therefore, in the simulation model the free mixing water in the screed can also be modeled (referred to as ‘free water’ in figure 4). A significant difference is found when the effect of both sources is simulated separately or together (FW + 50%). The free mixing water from the screed alone cannot induce a MC up to 50%, however levels above 20% were obtained which may lead to mold growth. When only the rainfall was introduced, a fast drop in MC and drying of the CLT towards the screed was observed, due to the suction of the dry screed (with small pores). However, over time an equilibrium is obtained due to the redistribution of moisture. In Figure 4, the effect of a vapor open system at the bottom side is evaluated. It highlights that single-sided drying was not sufficient to dry out the top layers of the CLT sufficiently. Subsequently, natural drying of the CLT to outdoor conditions before installation of the finishing layers was evaluated. If after rain exposure the CLT is first dried naturally, it would have taken 27 days to reach an acceptable MC for this case-study.

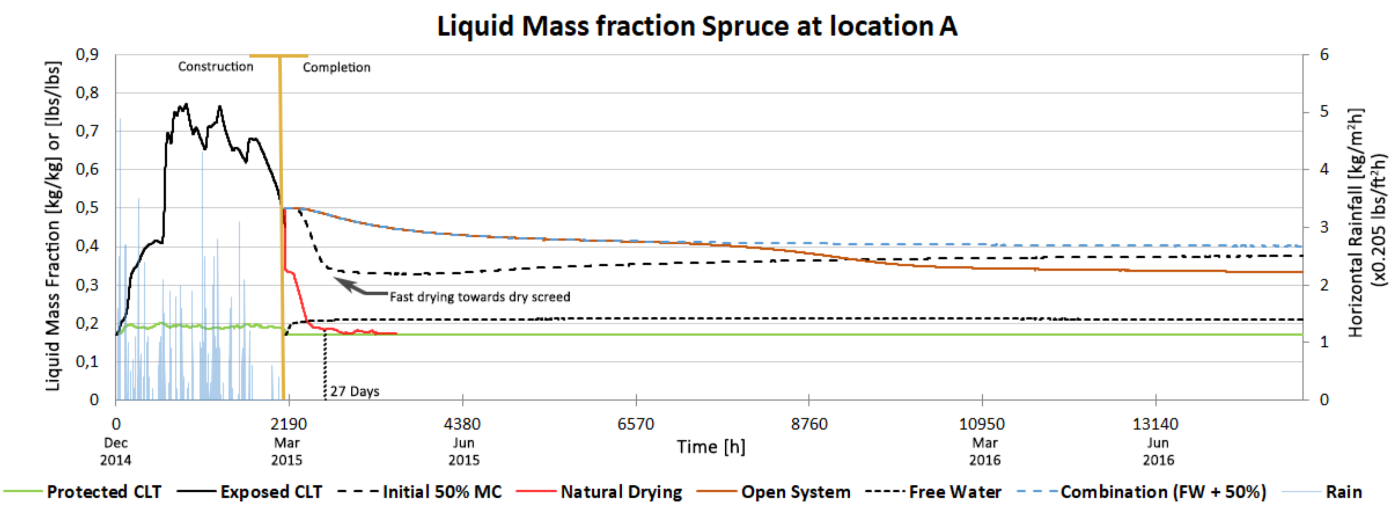


Figure 4 Summary of the absolute Liquid mass fraction [kg/kg] or [lbs/lbs] in the location A (left) for different solutions and approaches compared with the current degraded state.

CONCLUSION

In this paper a methodological framework for HAM-simulations was proposed that focusses on the informed selection of the different model parameters. Three strategic levels for parameters were considered: Superior, Advanced and Minimum requirement, which relates to the level of available information and accuracy of simulation approach. In general, the Superior approach will adopt measured parameters, whereas the Advanced approach will consider a calculation or reference case with close resemblance. As Minimum requirement, parameters are assumed based on tabulated values from standards or literature, complemented with a one-at-a-time sensitivity analysis to determine the impact of each parameter on the hygrothermal behavior. This approach has been applied to a litigation case on a CLT balcony with significant moisture-related degradation.

Rain exposure in the construction phase is difficult to avoid in practice. Nevertheless, it is obvious that all measures should be considered to minimize exposure for wood-based products which are prone to moisture-related degradation. Next, all finishes must be conceived in such a way that drying is facilitated to the maximum extent (vapor permeable or ventilated). If there is excessive exposure, it seems appropriate to do additional on-site measurements to monitor the drying until a safe moisture content is obtained. The potential of HAM-simulations in general and the methodological framework in particular has been demonstrated for this case study by assessing the impact of different moisture loads and construction solutions.

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