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FEDERATED USE OF HYGROTHERMAL MONITORING DATA IN MASS TIMBER BUILDINGS: OPPORTUNITIES AND CHALLENGES

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ABSTRACT: Several structural health monitoring projects have recently emerged to document the hygrothermal behaviour of mass timber buildings during both construction and service. Understanding moisture conditions on site can significantly impact the construction efficiency of mass timber structures. It is also essential to comprehend the effectiveness of moisture control strategies and construction practices in different climates to streamline project delivery and prevent long-term durability issues. This paper describes the first period of hygrothermal monitoring of three mass timber buildings in three different climate zones, outlining potential approaches for enhancing and integrating data, which can leverage the increasing availability of data from various monitoring projects.

KEYWORDS: moisture monitoring, mass timber, construction phase

1 INTRODUCTION

Faced with timber products and construction systems that are growing in scale and spreading to new climate zones, the mass timber building community increasingly needs information to understand the impacts of environmental exposure during a building's entire life cycle and the efficacy of existing moisture management practices. Several monitoring studies have provided insights on wetting, drying and durability performance of wall and floor assemblies in varying exposure conditions (for instance [1-7]), and have also highlighted the potential benefits of developing more unified monitoring methods and data-driven approaches to moisture management. Oregon State University, InnoRenew CoE, the University of Primorska and the University of Helsinki have established a research alliance to share information on mass timber buildings performance. The alliance will utilize monitoring data from three mass-timber projects, Peavy Forest Science Center (PFSC) in Oregon, USA, InnoRenew CoE in Slovenia, and the Hyytiälä Forestry Field Station in Finland. A federated use of data from the three monitoring projects presents an opportunity to provide valuable insights into the hygrothermal behaviour of mass timber buildings, enabling a comprehensive understanding of moisture levels in CLT panels during construction and in service, while taking into account specific building systems, construction processes, water management strategies and climate zones. However, data integration can be challenging due to differences in data collection methods, equipment, and techniques, as well as variations in the number and types of monitored locations and measurement periods. These differences can result in variations in accuracy, resolution, and quality of the data obtained. In addition, data ingestion and processing techniques can also significantly impact data integration, such as the way data is formatted, organized, and stored, affecting its usability and compatibility with other data sources. Variations in data processing techniques, including algorithms used for data cleaning, filtering, and normalization, can also impact data integration. This paper outlines the methodology used in the development of the three monitoring projects and provides examples of

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the challenges and opportunities that arise when using hygrothermal monitoring data from different mass timber buildings.

2 METHODOLOGY

2.1 SCOPING THE MONITORING PROGRAMS

The first crucial step in planning a monitoring program is to clearly define the project's objectives and the phenomena of interest. Next, the required measurands and data collection and management approach should be defined, taking into consideration factors such as budget and building constraints.

The PFSC is a three-story building completed in Corvallis, Oregon in 2019. The location has a Mediterranean/dry-summer subtropical climate with mean annual precipitation of 1295.4 mm and temperatures ranging from 2°C to 30°C over the course of the year. The building’s gravity load-bearing system comprises glulam beams and columns, cross-laminated timber (CLT)-concrete composite floors, and a mass ply panel (MPP) roof. The lateral force resisting system features self-centering, post-tensioned CLT shear walls. The construction of the timber structure began in winter 2017 and was planned in three sequential spatial zones to minimize exposure to the weather. To protect against moisture during construction, a vapor permeable coating was applied in the shop to exposed end grains, such as panel edges, connections, and cut-outs, as well as to the faces of glulam members and visible CLT panels. Additionally, temporary tarps were placed on the upper edges of the CLT wall panels to prevent water from entering through any discontinuities (Figure 1).

Figure 1: *Zone 1 of the PFSC, Corvallis, Oregon, during construction (up), detail of temporary moisture protection during transportation and erection (bottom)*

The objectives of the hygrothermal monitoring plan during construction of the PFSC were manyfold: a) to provide benchmark data on the wetting/drying behaviour of domestically produced Douglas Fir CLT exposed to the rainy Pacific Northwest climate, b) to evaluate the effectiveness of localised moisture exclusion measures in reducing moisture uptake in CLT and glulam members and, consequently, mold risk; c) to provide indications on proper dry-out schedules to avoid build-in moisture that minimize checking and uncontrolled building movement. Additional MC, RH and T sensors were installed to evaluate conditions in service [8] and correlate hygrothermal behaviour and long-term performance of structural systems (such as, for instance, effects of mechano-sorptive creep and moisture induced movement on tension losses in post-tensioned shear walls [9]).

InnoRenew CoE’s building is located in a Mediterranean seaside climate in Izola, Slovenia, with 1313 mm mean annual precipitation and temperatures ranging from 1.7°C to 28.9°C over the course of the year. It is a 4-story 8194m^2 building with a concrete podium and three timber stories featuring CLT panels and glulam. The building was completed in February 2022. No extraordinary measures against rainwater were taken during construction, and the building was exposed to outdoor conditions until the roof was installed. CLT panels were not equipped with protection membranes. However, in-plane panel-to-panel floor connections were sealed using surface-applied tapes to avoid water penetration between the panels (Figure 2).

The main objectives of the hygrothermal monitoring plan of the InnoRenew CoE building mostly target the service life of the building, after commissioning. Specifically, internal MC sensors were installed for early detection of leakages in wet room areas. MC, RH and T sensors in the envelope measure conditions in air-gaps or breathable materials.

Figure 2: *InnoRenew CoE’s building, Izola, Slovenia, during construction (up), detail of the CLT floors (bottom*

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Figure 3: *The main building of Hyytiälä Forestry Field Station after removal of construction shelter. Six groups of MC sensors are indicated with black text.*

The four new mass timber buildings at the Hyytiälä Forestry Field Station, Finland, are located in the boreal climate zone with 711.0 mm and mean monthly temperature extremes ranging from -10.3°C to 21.8°C. Construction started in spring 2021 and completion is scheduled in autumn 2023. The buildings have 1-2 stories with CLT walls and exterior wood cladding. Wooden pedestrian bridges and platforms connect the facilities. One week prior to the transportation of CLT elements to the construction site in early November 2021, a construction shelter was fully installed over the building. The top of the shelter was opened periodically until the roof construction was completed, at which point the tent was fully removed in late January 2022. To cover the window openings temporarily, plastic sheeting was used until the windows were installed in the first week of February (Figure 3). Measurements are taken from the interior CLT wall element located adjacent to the lower floor fenestration on the northwest side of the building.

Overall, the objective of wood moisture content measurements in the new Hyytiälä Forestry Field Station is to ensure the long-term health and safety of the building's structure by providing a reliable system for monitoring and maintaining the moisture levels of the CLT elements. In addition, data collected during the construction period enables monitoring the success of practices for protecting the elements from moisture during transportation, storage, and construction.

2.2 DATA COLLECTION

Sensor installation in the PFSC was conducted in two stages. During the initial construction phase, 19 permanent resistance-based MC sensors (SMT-PMM) were installed in the timber framing. These sensors were placed in the first erected CLT shear wall panels and a floor, which were deemed representative of areas in the building that could be affected by prolonged exposure to precipitation. Subsequently, 111 additional MC sensors were installed in locations where in-service wetting was a concern or where structural behaviour was being monitored. During the first monitoring period, in addition to continuous MC measurements, discontinuous MC readings were made using a resistance handheld meter (Delmhorst 18-ES), both in locations contiguous to those continuously monitored and in comparable locations but with different exposure conditions. Internal temperatures in the CLT wall panels were measured in specific locations to have accurate corrections of MC readings in internal CLT laminations. Air humidity (RH) and temperature (T) sensors were integrated in the local data acquisition systems. Weather data was collected by a nearby weather station [10]. Additional RH and T gauges were installed during the second phase.

One of the sampling criteria in the project was to include redundant sensors to account for potential malfunctions and data losses.

In the InnoRenew CoE's building, eleven (11) resistance-based MC sensors (MoistureGuard MHT sensors) were installed during construction, in 2020, but measurements started in April 2022 after the power and Ethernet networks were fully functional and the building was commissioned. One MC sensor was installed on each side of the building, on the external lower part of the exterior CLT walls. Seven additional MC sensors were placed in high-risk interior areas of the CLT structure to monitor water damage during normal building operations (toilets, bathrooms, and kitchens). Fifty-one (51) sensors for relative humidity (RH) and temperature (T) were installed in the building envelope to measure conditions within air gaps or breathable materials. (MoistureGuard HT sensors). During construction, measurements were taken manually on a weekly basis at 289 floor locations. Two types of moisture meters were used: a pin-type resistance meter (Humimeter WLW) to measure moisture content (MC) at a depth of 2.5cm, and a pinless capacitance moisture meter (Humimeter M20). Each location was labelled with a unique ID number, and manual measurements were continued until MC values reached 21% or lower, and there was no risk of additional wetting. Thermal imaging was used as a secondary, screening method [11] to identify possible wet spots in the interiors [12]. Data from two nearby weather stations were also used for data correction and post-processing.

In the Hyytiälä Forestry Field Station, continuous wood MC measurements were initiated already at the CLT plant, where 4 groups of 4 or 3 Wiiste WM1-WAN resistance-based wood moisture meter sensors (Wiiste Oy) with different measurement depths were pre-installed in CLT panels in November 2021. The panels were delivered on site in 5 days and erected in 9 days, hence the measurements also cover the short periods of storage and transportation. Additional 9 groups with 4 sensors were mounted in exterior CLT panels at the construction site in winter 2022 to cover a representative sample of microsites with potentially differing environmental conditions. Each group of four sensors in the 240 mm thick exterior CLT panels covers measurement depths from 13 mm to 218 mm at 5 to 50 mm intervals. The single group of three sensors in the 180 mm thick interior panel covers depths from 8 mm to 148 mm at 10 to 30 mm intervals. Weather data are constantly monitored near the building by both the Finnish Meteorological Institute and the University of Helsinki.

It is important to note that while some data collection occurred during transportation, the majority of the sensor installation was conducted after the wall elements were in place. This is because installing sensors during transportation or early construction phases requires an elevated level of coordination and significantly increases the risk of physical damage to the sensors.

2.3 DATA INGESTION

Table 1 shows measurement range, resolution and listed accuracy of the MC sensors used in the three buildings, as well as sample time intervals used in each monitoring project. Specifications of the hand-held meters used in the PFSC and InnoRenew buildings are also included in the table.

Table 1: *Sensor specifications in the three projects*

Project / sensor	measurement range	resolution	accuracy	sample interval
PFSC / PMM	8–30%	0.1%	+/-1%	1st phase: 1 minute - averaged hourly 2nd phase: 60 minutes
PFSC / Delmhorst 18-ES	5–60%	0.1%	Not available	1st phase: varying
InnoRenew / Humimeter WLW	7-150%	0.1%	+/-1%	1st phase: 1 week
InnoRenew / Humimeter M20	2-30 %	0.1%	Not available	1st phase: 1 week
InnoRenew / MHT	7–28%	0.1%	+/-1%	2nd phase: 15 minutes
Hyytiälä / WM1WAN	6–30%	0.1%	+/−1%	60 minutes

The data from the permanently installed MC sensors in PFSC is periodically transmitted to a local data acquisition unit, where it is stored and wirelessly transmitted to a dedicated computer equipped with a receiver. Finally, the data is synchronised with a cloud database for further analysis and storage.

In addition to the commercially available solution, the collected data is transmitted to a local, custom server, where data from other sensors/suppliers is also collected [13].

The MC sensors permanently installed in the InnoRenew CoE building are equipped with a digital RS485 wire interface and are powered by the same cable. The cable connects the sensors to EDGAR ethernet gateways, which are powered over ethernet and connected to the building's LAN. As a result, each sensor is accessible from any computer or system on the building's network. A dedicated PC runs a LabVIEW code developed by the research team which stores the data a local database for further analysis. To supplement the data collected from the sensors, precipitation data (daily sum in mm/day) is collected from the nearby official Slovenian Environmental Agency weather station in Strunjan (located 3km away). Additionally, temperature and relative humidity data are retrieved from the weather station in Portorož, which is situated 9 km away.

At Hyytiälä, the MC sensors are also equipped with sensors that measure ambient humidity and air temperature at the sensor positions on the faces of the CLT elements. The MC data collected from the construction site are transmitted periodically to a cloud database via a commercial LoRaWAN network, which is supported by a local repeater to improve the signal quality. To monitor the weather conditions at the site, open data collected by the Finnish Meteorological Institute is used, which is obtained from a weather station located 200 meters away from the building site.

2.4 DATA CONVERSION AND TEMPERATURE CORRECTION

Raw resistance ohmic values from MC sensors is converted to moisture content using equations designed for specific wooden species; published correction factors for Douglas Fir were used for the PFSC data, and for spruce and pine in the other two projects [14].

Temperature compensation is also applied to the data collected [14-16], using either temperature data from the closest thermistor depths (in some locations in PFSC [10]), air temperature measured in correspondence of each MC sensor (Hyytiälä), or air temperature values from nearby sensors (in some monitored locations in PFSC and in the InnoRenew's building).

The conversion of data and temperature correction are typically offered as post-processing features in dedicated hygrothermal monitoring platforms (e.g., SMT-Analytics). Alternatively, these functionalities can be implemented directly in sensors or developed through custom code.

2.5 DATA ENHANCEMENT

To facilitate automated data processing, unifying the data formats from various sources is the initial step. Moreover, it is essential to ensure the quality of the data is assessed and validated before integrating it into a larger dataset.

Hygrothermal data enhancement can be performed with several objectives in mind. These include: a) data cleaning by removing outliers, applying a moving average, performing wavelet packet analysis, and correcting for environmental effects; b) data enriching and correlation by calculating the equilibrium moisture content (EMC) from temperature and RH data using the Hailwood and Horrobin equation [14].

This section provides examples of data enhancement for the studied projects.

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2.5.1 Reconstruction of missing data

Data monitoring infrastructures are not always fully dependable and data loss during communication is common. Wireless data transmission, such as the LoRaWAN network used in the Hyytiälä forest station monitoring project, is susceptible to various effects that can cause data loss, including signal attenuation in building structures, adaptive spreading factor and transmitting power, interference from other devices, changing transmission conditions, infrastructure outages, and cable interruptions.

To date, wired communication technologies are more reliable than wireless communication technologies. However, during construction works, cable connections and the entire power infrastructure may become less reliable, which can result in outages, and consequently data loss. Table 2 shows percentage of monitoring data loss for the three projects.

To obtain a complete time-series dataset that can be processed by advanced algorithms, such as mold growth models, missing data must be reconstructed using one of the standard methods, such as using the last previous valid data or using linear, cubic, or other interpolation techniques (see, for instance, [17]). Other methods for reconstructing structural health monitoring data, include machine learning and model-based estimation techniques [18-21].

Table 2: *Data loss observed in the three projects.*

Sensor ID & Type / Project	Communication type	Transmission period	Observed data loss
WM1 WAN 33874 / Hyytiälä	wireless LoRa	1 hour	11,2%
WM1 WAN 33875 / Hyytiälä	wireless LoRa	1 hour	8.9%
WM1 WAN 33876 / Hyytiälä	wireless LoRa	1 hour	16,4%
MHT03 + EDGAR converter / InnoRenew	wired RS485+Ethernet	15 min	17.7%
PMM562 / PFSC	Analogue (sensor->DAQ)+ wireless (DAQ -> cloud)	1hour	7.9%

Figure 4 shows an example of MC data reconstruction performed for the data in the Innorenew building using the last valid data in the set.

2.5.2 Data validity check

Temperature and RH measurements are typically assumed to be accurate within the specifications of the sensors used. As a standard practice, the average values of temperature and RH data from multiple sensors are compared to ensure the reliability of the measurements. However, obtaining accurate wood moisture measurements can be challenging due to numerous factors that can affect electric resistance measurements. These factors include the loss of contact between the electrode and the wood, which can lead to erroneous readings of very low moisture levels. Resistance-type meters are also commonly known to become less accurate beyond the fibre saturation point (FSP), as the presence of free water in the wood cell can affect resistance readings. Therefore, all out-of-range data should be filtered from the dataset. Loss of battery capacity can also be a phase during which the data can become corrupted. A simple moving average is often applied for cleaning MC data [6, 8]. When using moving averages in different projects, consistency in the used period is important. In some cases, statistical processing has been implemented to remove unreliable data. In [9-13], wavelet packet analysis was utilized to apply a standardized statistical filtering approach to data collected from various types of sensors. Figure 5 shows trimming of erroneous MC data measured by one of the WM1 WAN sensors in the Hyytiälä's building. Note that it was found that approximately 7% of the data were invalid because they fell outside of the sensor's measuring range. Removal of out-of-range data allowed to observe wood MC changes more accurately within the hygroscopic range.

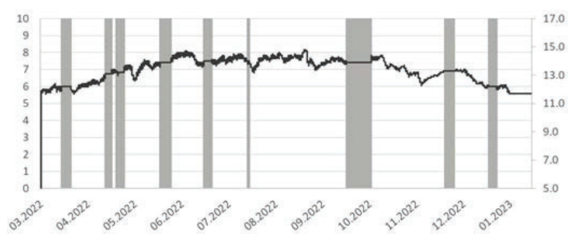

Figure 4. *MC data loss (grey bars) & reconstruction (MC measurement, InnoRenew).*

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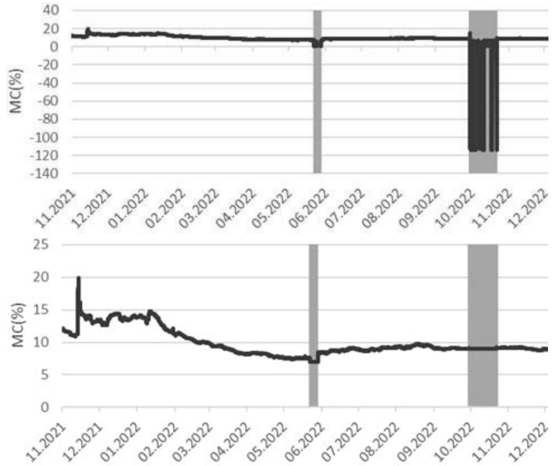

Figure 5. *Data validity check and trim (MC measurement, Hyytiälä) before correction (top), after correction (bottom).*

2.6 DATA ANALYSIS AND VISUALIZATION

This section presents examples of hygrothermal and climate data plotted against construction events, and predicted mold growth curves. The objective is to utilize visualization to facilitate a comprehensive understanding of the data and enable better-informed decision-making. The graphs in Figures 6 and 7 display moisture content (MC) data in CLT walls of the buildings in Corvallis and Hyytiälä, respectively, along with meso-climate data such as air relative humidity and temperature at the wall location, and macro-climate data (i.e., precipitation) recorded at the weather station locations. The unprocessed MC data can aid in identifying patterns in the behaviour of the material during construction, although it may exhibit unrealistic spikes during rainy periods and abrupt drops during lower humidity periods due to direct sensor exposure to precipitation. In addition to the measurements, the graphs in Figures 6 and 7 show the mold growth index calculated using meso-climate data. The Mould index (M-index) is computed utilizing the VTT model [22]. The model considers periods of mold decline, which are influenced by the duration of unfavourable environmental conditions, specifically when the RH falls below a certain threshold.

Vertical lines on the graphs depict certain construction key dates. Figure 6 refers to the first six months of construction of the PFSC in Corvallis. Throughout this period, the monitored location was continuously exposed to outdoor conditions. The plotted MC data correspond to measurements taken in the fourth ply of the CLT panel, from south to north, at the upper part of the tendon shaft of the shear wall. During the monitoring period, the location was subject to wetting, resulting in moisture content (MC) increases exceeding 24%. Subsequently, a slow drying process occurred, bringing the MC to around 18% after 5 months. The M-index, which was calculated using the air temperature and relative humidity (RH) data collected near the installed sensor, indicates a slight risk of mold growth.

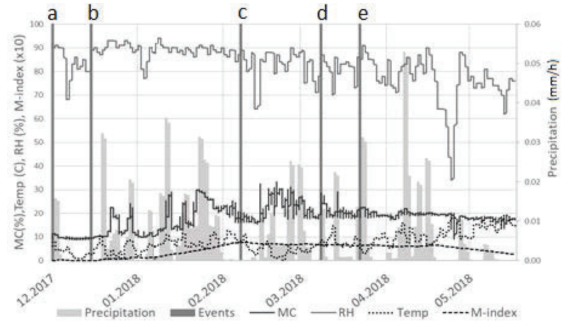

Figure 6. *Corvallis. MC, RH, Temperature, precipitation data, M-index. Vertical lines: (a) installation of sensors in the shear wall; (b) installation of the 1st floor, which partially sheltered the north side of the wall; (c) completion of the roof framing and (d) weather protection, with the exclusion of the stairwell where the monitored shear wall was located; and (e) temporary construction suspension.*

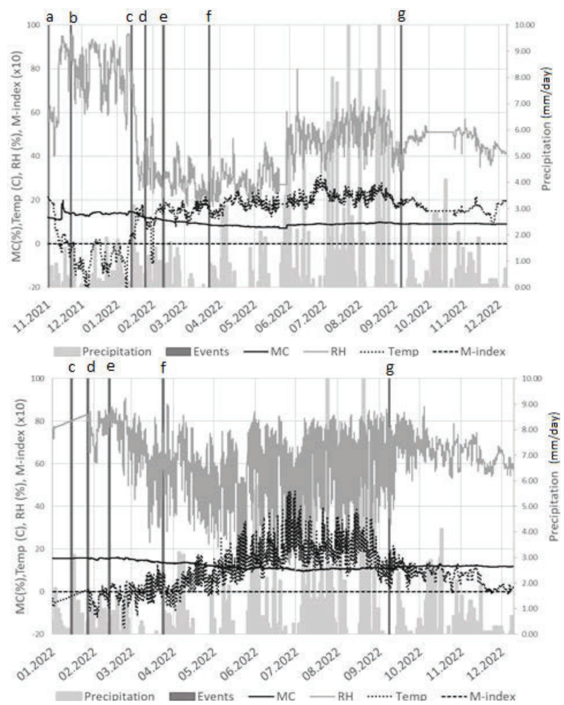

Figure 7. *Hyytiälä. MC, RH, Temperature, Precipitation data, M-index. Vertical lines: (a) installation of the sensors at the CLT facility, (b) wall erection complete, (c) removal of the temporary canopy, (d) installation of windows, (e) indoor heating started, (f) enclosure complete, (g) floor heating turned on.*

Figure 7 depicts the MC readings in two CLT wall locations in Hyytiälä covering a period from transportation to building decommissioning. In all the time the panels were protected from direct exposure to water. The data in Hyytiälä show that, despite some periods of heavier rain in summer, MC values in the panels remained stable and RH did not reach levels of concerns for the development of mold. This is supported

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by the calculated M-index. The data also indicates that turning on the heating caused a rapid increase in temperature and a decrease in humidity, which led to a reduction in the wood MC and stabilization at 10%.

A third example, in Figure 8, shows discontinuous MC hand-held readings taken on a CLT floor panel in the building in Izola. The measurements were taken at different depths and positions close to an in-plane floor connection and the average of these readings is presented in the plot. The figure also includes climate data, key construction dates, and the calculated M-index.

As it can be observed, a spike in the MC corresponding to a period of heavy rainfall, which began in December 2020. During this time, the building's structure was complete, but the roofing assembly had not yet been finished, resulting in leaks and wetting of the floor connection details.

The plot also illustrates the increase in the M-index curve calculated from the RH values estimated using the inverse sorption equation based on the MC values [23], as no RH sensors were installed in that location at the time.

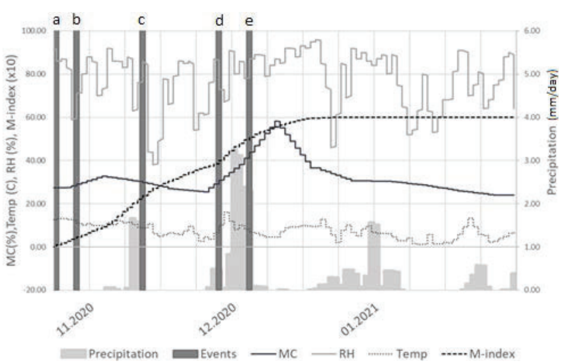

Figure 8. *Izola. MC, RH (estimated), Temperature, precipitation data, M-index. Vertical lines: (a) erection of the CLT floors (b) timber structure complete, (c) window installation complete, (d-e) period of heavy rainfalls and reported leaks.*

2.7 CONTINUING RESEARCH ON A UNIFIED FRAMEWORK FOR DATA EXCHANGE, INTEGRATION AND ANALYSIS

The examples presented in this paper underscore the significance of implementing a data integration framework that can effectively oversee the complexities of merging data from various monitoring projects, while also guaranteeing a smooth and precise integration process.

Such a framework can also provide tools for data analysis, knowledge extraction, and recommendation generation.

Our previous work [24] described a unified framework based on the concept of avatars [25], which are decentralized computing agents that use Web languages and protocols to create a virtual representation of entities such as buildings, building elements, and sensors. This avatar-based framework has been compared to state-of-the-art Structural Health Monitoring (SHM) solutions and offers a promising approach to data exchange, integration, and analysis.

In this approach, each entity in the framework is represented as an avatar, which is a software that operates on a device connected to a physical object. Avatars compute essential information about their corresponding physical objects locally and can share, integrate, and analyse data with nearby avatars. For example, an avatar installed on a building can combine its data with that from an avatar on a meteorological station for moisture monitoring. By elevating the avatar concept to represent individual buildings, the framework overcomes interoperability issues, enables the sharing of information and knowledge among buildings, and promotes the widespread adoption of SHM systems and data exchange.

3 DATA-CORROBORATED ON-SITE OBSERVATIONS

The areas of concern for moisture ingress were primarily observed at edges, gaps, and connection points. Despite the presence of local measures to protect against moisture, such as taping at the floor joints and using end grain sealant at panel cuts, extended exposure to precipitation and limited ventilation in these areas can result in water retention and create conditions that can lead to mold growth. Although using a temporary canopy was successful in preventing the structure Hyytiälä from becoming wet, this practice is not widely accepted in many countries. Therefore, it is important to consider alternative measures to prevent moisture accumulation in vulnerable areas. This can be achieved by locally deflecting water, implementing effective drainage systems, and promoting drying prior to enclosing the mass timber elements in less breathable assemblies.

The detection of checking in the CLT panels in Hyytiälä, developed during a period of significant temperature increase, indicates the need for not only monitoring excessive wetting during construction but also controlling the drying process once the building is enclosed and during its initial period of use. Hygrothermal monitoring data can aid in the creation of effective drying protocols on site to address these concerns.

4 CONCLUSIONS

This paper showcases three hygrothermal monitoring projects in mass timber buildings and emphasizes some factors in a project implementation that impact the quality of data and subsequent opportunities for data integration within a single project and among multiple projects. This paper also explores various methods for improving data quality and introduces a new integrated framework for data management and integration to facilitate the collective use of hygrothermal monitoring data across multiple mass timber projects. Certain data enhancement techniques were particularly applicable to utilizing data in predictive models, particularly for assessing the risk of mold growth.

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The hygrothermal data was presented in a format that promotes more comprehensive comprehension of relevant phenomena and facilitates informed decision-making. Hygrothermal data was utilized in conjunction with visual inspection to identify areas of concern, highlighting the potential to improve wetting and drying control in mass timber panel construction through more effective use of data. Effective use of data across multiple projects requires intention and planning during the initial stages of a hygrothermal project. Nonetheless, it offers significant potential to advance our understanding of the behaviour of mass timber buildings over their lifespan, thereby supporting this growing industry.

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