Moisture safety strategy for construction of CLT structures in a coastal Nordic climate

Berit Time[1],*, Erlend Andenæs[2], Trygve Karlsen[3], Stig Geving[1], and Tore Kvande[2]

[1]SINTEF Community, Trondheim, Norway
[2]Department of civil and environmental engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[3]Veidekke Entreprenør, Trondheim, Norway

Corresponding author: berit.time@sintef.no

Abstract: To reduce the carbon impact of new buildings, wood is seeing increased use as a structural material. Cross-laminated timber (CLT) and glue-laminated wood (glulam) elements allow the construction of multi-storey buildings. However, wood is vulnerable to moisture, especially when naked wood is exposed to weather during the construction process. This paper presents the moisture strategy employed during the construction of a four-storey CLT/glulam building in Trondheim, Norway. The building was constructed without the use of a weather-protective tent, requiring alternative protective measures. The construction of the main structure was scheduled to be as short as possible. Local protective measures were employed to protect the structure from rain and free water was removed after rain events. The project was closely supervised by the client, with particular care for moisture control. Moisture was regularly measured at 50 points throughout the building. No wooden surfaces were encapsulated until a wood moisture content below 15 weight-% was measured. The performance of the moisture strategy was evaluated using measurements of wood moisture, indoor climate, airtightness, and visual inspections. The wood moisture content quickly decreased as the building envelope was assembled, indicating that drying was well facilitated. In the first year after construction, gaps between the flooring and baseboards were observed, suggesting that the wooden elements have experienced some shrinkage. The moisture safety strategy is deemed to have been generally successful. The overall experiences were important in the development of new recommendations in the SINTEF Building Research Design Guides for CLT structures.

1. Introduction

Wood has been used as a building material in the Nordic countries for millennia. It has remained integrated in building traditions and supply chains up to the modern era. The modern inventions of cross-laminated timber (CLT) and glue-laminated wood (glulam) have been readily adopted, to allow for new types of wooden buildings, including large office buildings. Wood is a material with little embodied carbon and manufactured using relatively little energy, which makes it suitable for low-emission buildings [1]. The small CO_2 footprint compared to alternatives like concrete and steel is another reason why CLT has seen a surge in popularity in recent years [2,3].

Structural wood materials are extensively used in the ZEB Laboratory, which is a new office and education building at the Gløshaugen campus of Norwegian University of Science and Technology in Trondheim, Norway. The ZEB Laboratory began construction in the summer of 2019, was handed over in late autumn 2020, and began regular operations in spring 2021. The building, illustrated in Figure 1, is four stories tall with a floor area of approximately 2000 m². It is designed to be carbon neutral with respect to its construction, operations, and materials, following the requirements of a standard known as ZEB-COM [4]. To achieve a carbon footprint as small as possible, the building is chiefly built out of wood, in the form of CLT and glulam elements. The foundation of the building is a concrete slab-on-ground, made of low-carbon concrete and designed to minimize material usage. The roof and exterior façades on the sun-exposed sides are covered in solar panels which generate surplus zero-carbon electricity for export, which will compensate for the carbon cost of the building over a lifetime of 60 years [5,6]. The CLT and glulam elements in the ZEB Laboratory are made from a mix of spruce and pine wood. To reduce material usage, wooden surfaces are not covered and hence constitute parts of the visible interior surfaces throughout the building.

Figure 1: Left: the completed ZEB Laboratory (photo: Nicola Lolli, SINTEF). Right: the building under construction, showing the arrangement of glulam beams and columns and CLT shear wall elements and floor plates (photo: authors).

A challenge faced by the ZEB Laboratory and other wood structures is that wood is susceptible to biological deterioration if exposed to moisture. Thus, a comprehensive moisture control strategy is required to ensure the long-term integrity of wood structures. A recommended strategy for Norway consists of the following five points: 1) Limit the supply of exterior moisture, 2) Limit the supply of interior moisture, 3) Limit built-in moisture, 4) Provide drying capacity, 5) If moisture cannot be kept out, use moisture-resilient materials [7]. This strategy must be anchored in the organization of the building project, with clear lines of responsibility drawn to ensure that it is carried out in practice. An example of such an organizational strategy is found in the Swedish moisture safety method ByggaF [8]. This industry standard establishes a method that "guarantees, documents and communicates moisture safety throughout the construction process, from planning to management". It suggests an organizational structure and lines of responsibility that meet legal requirements and ensure that sound practices are followed. A similar methodology is described in the new Norwegian standard NS 3514 [9]. Note that these methodologies do not specify the specific measures for moisture safety in a construction project, but rather the way they are organized and followed up. Specific measures to ensure the integrity of CLT elements are presented in a Danish industry standard design guide [10]. Its main recommendation for ensuring moisture safety during the construction process is to keep CLT elements covered by weather protection. Rapid drying of the elements using building dryers is not recommended.

To protect buildings during the construction phase in the rainy Nordic climate, weather protection systems (WPS) are often used. These are big "tent" structures that encapsulate the building, creating a drier and warmer environment for the building's construction. However, WPS are not always feasible to use for several reasons. Perhaps foremost is the monetary cost, but in some projects (like the one presented in this paper) the "carbon footprint" is also a consideration. The WPS also complicates deliveries to the construction site, including the hoisting of structural elements. The WPS must be opened to enable structural assembly. Inside the WPS, the climate is sheltered and mild, but may become very hot on sunny days. Wind may also make the WPS flap loudly and make the work environment very noisy.

For a combination of these reasons, and others like the unwieldy shape of the building (non-rectangular, with the roof rising to a very tall point), it was chosen not to use WPS in the construction of the ZEB Laboratory. Building without WPS was found to be more cost efficient for the project and offered an opportunity to research and evaluate common Norwegian practices of moisture control in the construction phase. The ZEB Laboratory was and remains thoroughly monitored during its construction and operation, as a subject of research by students and academics at SINTEF and NTNU – hence its designation as a laboratory.

To compensate for the lack of WPS in the construction of the ZEB Laboratory, an alternative moisture control strategy became necessary. To present the concept and evaluate its performance, the following research objectives are formulated for this paper:

- To present the moisture safety strategy of the construction of the ZEB Laboratory as an alternative to weather-protective systems (WPS).
- To evaluate the moisture safety strategy after two years of operation.

The following limitations apply to the research: information on the moisture control strategy of the ZEB Laboratory was retrieved by contacting key personnel and reviewing project documentation. Moisture performance is evaluated using measurement data from specific locations in the building. No measurements were conducted specifically for the purpose of this paper, but for other research purposes.

2. Moisture safety strategy in the ZEB Laboratory

2.1. Physical measures

The moisture safety strategy was chosen based on reducing the moisture load on the materials during construction. The assembly phase of the process was scheduled for July and August, typically a dry part of the year in Trondheim. The assembly kept a rapid pace to be finished before the rainy autumn season began. Nevertheless, substantial rain events occurred in the weeks before the roof was completed, which caused wetting of the entire structure.

The building envelope contains only a minimum amount of CLT wall elements, which are known to dry slowly. CLT wall elements were used for shear walls including the elevator shaft and the secondary stairwell, both of which have one side facing the building's exterior. The outer walls are otherwise built as a wood-frame curtain wall, with load-bearing glulam frames located on the inside of the building envelope to reduce thermal bridges. Hence, the vapour barrier runs on the exterior side of the load-bearing structure. However, no vapour barrier is mounted exterior to CLT wall elements in the exterior walls (the elevator shaft and secondary stairwell). Here, wind barrier tape is used to ensure an airtight connection between the edge of CLT floor elements and the CLT wall elements. No tape was used in the connections between wall elements.

As a key part of the moisture safety strategy, wooden elements were allowed sufficient time to dry to an acceptable level before being covered up by other materials like thermal insulation. The CLT elements in the elevator shaft and the secondary stairwell were not covered up until the building envelope was finished. For the CLT floor plates, bidirectional drying was allowed for as long as necessary before the acoustic floor and linoleum flooring was mounted. No screed or other concrete materials were used in the floors, which greatly limited the moisture load during construction. After the load-bearing structure was completed, heaters were used on the fourth floor to dry the roof underlay. Once the building envelope was completed, heaters on the first floor ensured drying of built-in moisture and comfortable working conditions during winter.

To avoid wetting of materials in storage on the construction site, the first (ground) floor of the building was used for storage of materials. The upper floors were not used for storage, as stored materials could interfere with the drying of CLT floor plates. Exceptions were made for materials that could be elevated from the floor during storage, for instance using pallets. Non-structural materials were not delivered to the construction site until the building envelope was established, to ensure they could be stored dry.

As a WPS was not used, some precipitation water could enter the building before the building envelope was completed. The morning routine on the construction site hence involved mopping the water off the edge of the floor plates. Nevertheless, some discolouration of the structure occurred due to the flow of precipitation water and solar radiation. Stains were expected in advance and measures were planned. Before handover, all wooden surfaces were sanded and coated with a transparent coating.

2.2. Measurements and evaluation

Wood moisture measurements were regularly conducted during the construction process to determine the moisture level in the CLT and glulam elements of the building structure. No structural element was covered up until it was determined to have dried to an acceptable level of moisture, < 15 weight-%, measured as described in Section 3. The fourth floor, which bore the worst brunt of the precipitation load, had to be dried using heaters for a short period before the completion of the building envelope.

After the completion of the ZEB Laboratory, the indoor climate has been continuously monitored as part of a PhD. project [11]. The following parameters are logged: Temperature, relative humidity, CO_2 concentration, volatile organic compounds (TVOC), and particulate matter concentration ($PM_{2.5}$).

Blower-door measurements were conducted to evaluate the airtightness of the building envelope, at the point of handover and after one year [12]. The measurements after one year were conducted to determine whether repairs had become necessary due to cracks and shrinkage in wood materials.

It was predicted that cracks would appear due to drying, which would affect the acoustic insulation between rooms on the same floor. Repairs were hence scheduled in advance. Acoustic measurements were conducted at handover and after one year, to locate and document where measures were necessary.

3. Methodology

Two different methods of moisture measurements were employed: with manual sensors and fixed sensors permanently attached to one CLT element. Manual wood moisture measurements were conducted using a FME moisture meter, which features an electrode spike hammered into the wood to conduct measurements at different depths. For walls and columns, moisture was measured at the surface and at a depth of 20 mm. For floor plates, measurements were conducted at the surface and at 30 mm depth. Measurements at 40 mm were also attempted, but the effort was abandoned since the electrode spike tended to break upon removal from the wood at these depths. These measurements were conducted until the wind barrier was mounted. Hence, the structure was exposed to the exterior climate (but shielded from precipitation) during the measurement period.

Table 1 shows the number of measurement points per structural element and floor. Measurements in floor plates were made from above. The corners of the building were assumed to receive the highest moisture load; hence the floor plate measurements were conducted close to the corner of each floor. Three of the column measurement points were in the same column, but on different floors. The column is located near the middle of the north façade, which receives little sunlight for drying and was the last façade to be clad. Measurements were conducted on shear walls on each floor, close to the floor plates to catch eventual absorbed moisture from puddles. Moisture measurements were conducted on six different days, after the completion of the roof, but before the completion of the building envelope. The measurement times are indicated in Figure 2. The results of these measurements are shown in Figure 3.

Table 1: Locations of the manual wood moisture measurement points.

Building element	**Ground (first) floor**	**Second floor**	**Third floor**	**Fourth floor**
CLT wall	5	2	2	1
Glulam column	1	0	1	2
CLT floor plate	0	4	4	4

Fixed wood moisture sensors were also mounted in a CLT wall element in the exterior wall of the second floor, to measure wood moisture at different depths and different locations across the element. The placement of the sensors is illustrated in Figure 4.

The blower-door measurements were conducted according to the standard ISO 9975:2015, Method 3 [13]. A pressure difference of ±50 Pa relative to the ambient pressure was applied. A measurement was conducted at the point of handover, on 2020-10-23, and another after one year, on 2021-10-29. The weather was dry with slight wind (~2 m/s) and an indoor temperature of 21°C during both tests. The exterior temperature was 3 °C during Test 1 and 8 °C during Test 2 [12]. The volume of the building was determined by the architect to be 7691 m^3.

Visual inspections have also happened regularly during the building’s operation. Although no formal measurement schedule is followed, this paper still includes some results obtained from these observations and user feedback. More thorough inspections were conducted after one and two years of operation.

4. Results

4.1. Wood moisture measurements

Figure 2 shows the dates and results of the manual wood moisture measurements, as well as the temperature and precipitation in the final weeks of building envelope assembly. Figure 3 shows the results of the manual wood moisture measurements. The outlying data point in the final set of measurements (October 31) was caused by a puddle that had formed on the floor plate, as the door to the exterior scaffolding elevator had not been closed properly overnight.

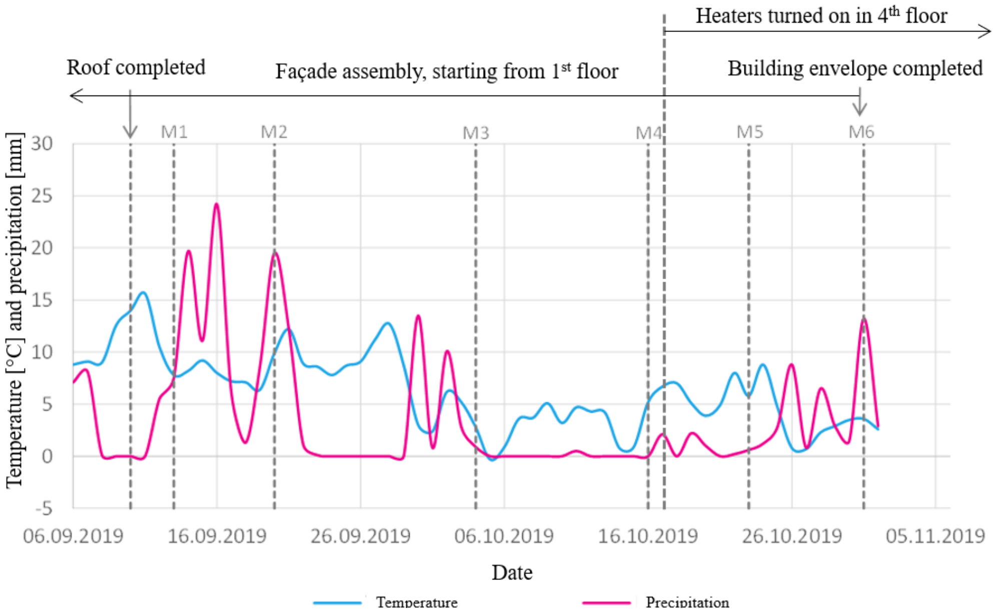

Figure 2: Outdoor temperature and precipitation at the time of manual measurements. Relevant events in the construction timeline are also marked.

Figure 4 shows the moisture measurements from the fixed moisture sensors in the CLT wall element, and their placement. The measurements indicate that the structure dried quite quickly after assembly and remained at acceptable levels of moisture in the long term. The exterior side and edge exhibited higher moisture levels initially. Moisture levels across the whole element converged relatively quickly after the building envelope was completed in November 2019.

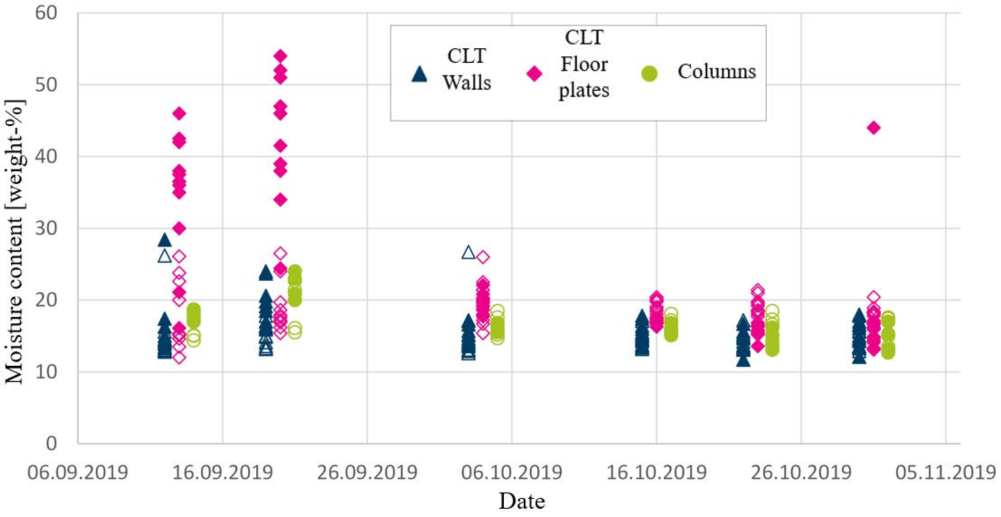

Figure 3: Measured wood moisture content, in weight-%, at the six times of manual measurement (M1-M6).

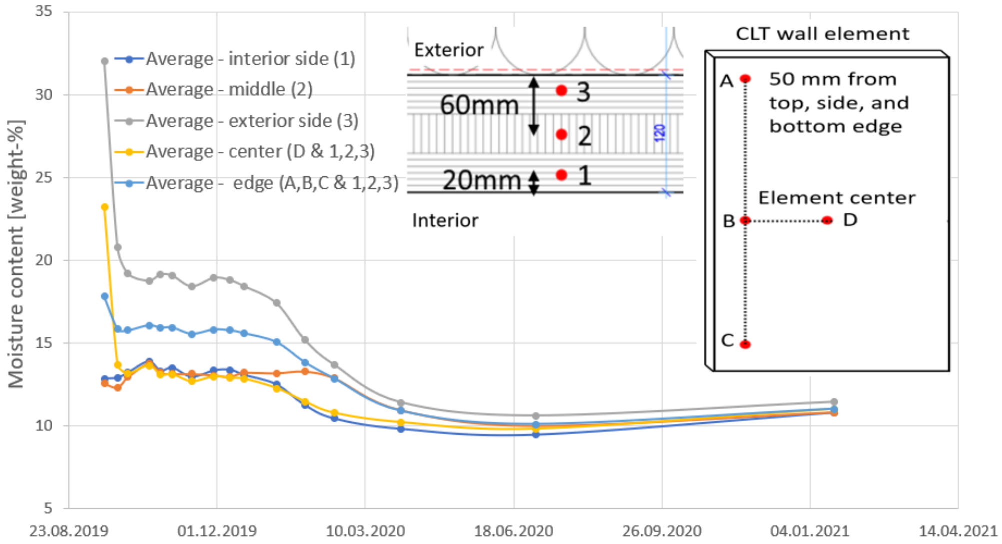

Figure 4: Moisture development in a CLT wall element, measured by fixed sensors.

4.2. Air leakage measurements

The results of the air leakage measurements, as recounted by Svenning et al. [12], are shown in Table 2. The table displays the air flow/air change rate required to maintain a pressure of 50 Pa relative to the ambient pressure. Note that the difference between the two test results is very small: approximately 2 %, which is within the margin of error of the measurements.

Table 2: Results from air leakage measurements at handover (Test 1) and after one year (Test 2).

Test no.	Underpressure [m³/h]	Underpressure [h^{-1}]	Overpressure [m³/h]	Overpressure [h^{-1}]	Average [m³/h]	Average [h^{-1}]
1	3282 (± 4.5 %)	0.43	3959 (± 5.8 %)	0.51	3620	0.47
2	3390 (± 0.5 %)	0.44	3731 (± 4.7 %)	0.49	3560	0.46

4.3. Observations

Minor moisture damage was observed during the construction phase. The vapour barrier was mounted along the edge of the CLT floor plates early during construction as seen in Figure 5. Moisture was trapped beneath it, and some visible mould growth occurred. The entrapped moisture originated from flowing water on the surface of the floor plates and would not reappear after the building envelope had been completed. Ventilating the space allowed the surface to dry. Additionally, despite the efforts, moisture and solar radiation caused some stains on wooden surfaces. Most of these were sanded off and coated, but some surfaces were inaccessible – for instance, above the drop ceiling or inside technical shafts. The back side of diagonal elements placed in front of windows were also inaccessible, causing stains to be visible from the outside.

During the first winter of operation, as the structure continued to dry, some wood shrinkage was expected and observed. Throughout the building, creaking and sounds of splitting wood could occasionally be heard. Cracks were observed in some CLT wall elements, and in the joints between glulam columns and wood-frame walls. Cracks had been anticipated, and repairs of the surface layer had been scheduled in advance.

Deflection was also observed along the floor throughout the building, requiring some readjustments of baseboards as shown in Figure 5. It could not be determined whether this was caused by contraction of the CLT floor plates, or creep of the acoustic floor. The acoustic floor plate could not be fitted properly along certain portions of the interior walls, due to the insertion of doors or glazing. The floor was expected, and later observed, to creak slightly when stepped on in these locations.

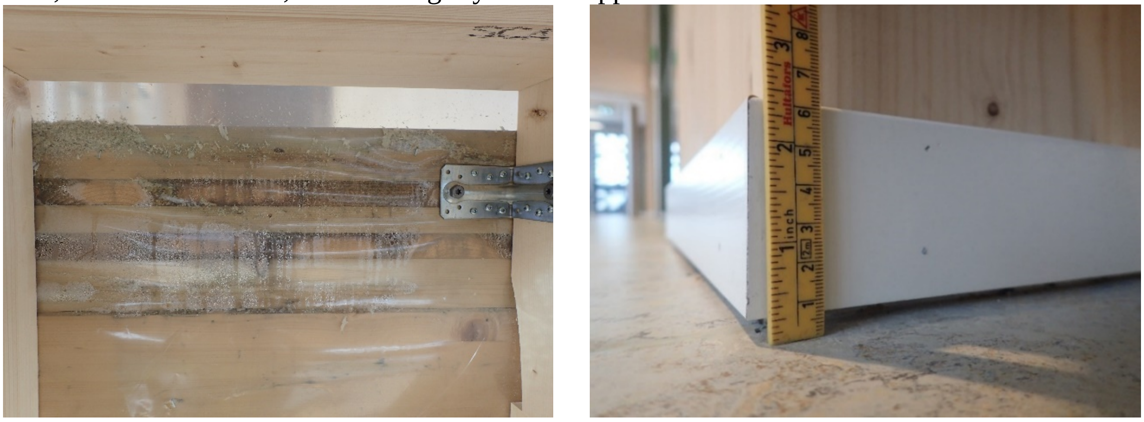

Figure 5: Left: Entrapped moisture behind vapour barrier during construction.
Right: Deflection of floor due to creep and shrinkage, necessitating repositioning of the baseboard.

5. Discussion

Overall, the moisture safety strategy of the ZEB Laboratory is determined to be successful by all investigated indicators. The measured wood moisture is within tolerable levels, airtightness has remained approximately constant from the point of handover, and no signs of mould growth, excessive deformation, or other signs of moisture damage have been observed through inspections. During construction, minor moisture defects were discovered, but quickly addressed and repaired. In two years of operation, the indoor climate monitoring has not indicated any elevated levels of volatile organic compounds [11], which could be a sign of mould growth. Elevated levels of moisture have been measured in the air cavities of the building’s façades and roof [14], but these measurements concern precipitation loads on the exterior parts of the building envelope and not built-in moisture.

The process of managing moisture in the construction phase was found to be largely in accordance with the recommendations of ByggaF [8] and NS 3514 [9], although these documents were not consulted during the process. The moisture safety strategy contradicts Danish CLT guidelines [10], which specifically recommend using WPS during CLT construction.

Kalbe et al. describe an examples of CLT construction projects with and without the use of WPS [15,16]. The recommendations by Kalbe et al. include a fast installation process and drying of moisture before wooden elements are covered. It is deemed practically impossible to avoid wetting of CLT elements during construction without WPS, so measures should be undertaken to manage precipitation moisture. The moisture safety strategy of the ZEB Laboratory is found to align with these recommendations. Kalbe et al. also measured wood moisture developments with similar findings to the present paper, with wood moisture levels quickly dropping once the building envelope was assembled [15]. In their two papers, Kalbe et al. stress the importance of protecting end-grain edges of CLT panels during construction. In the ZEB Laboratory, all interfaces between wood and concrete are protected.

Olsson [17] followed the construction of four seven-floor CLT buildings in Sweden without the use of WPS. According to his findings, it was concluded “difficult or impossible to avoid the emergence of microbial growth during construction”. However, the load-bearing structure of all the buildings was erected during winter and spring (December-May) and only limited alternative moisture protection strategies appear to have been followed. For the ZEB Laboratory, construction during summer was a crucial component of the moisture safety strategy. Compared to the present study, the Swedish study demonstrates the vulnerability of an unprotected CLT structure to wetting and microbial growth. On the other hand, drying is given limited attention and it is not known whether microbial growth continued to an unacceptable extent after the building was completed.

In the ZEB Laboratory, some cracks and deformations were observed after the first year of operation. However, the airtightness measurements indicate that these are mainly cosmetic, as the airtightness of the building is found not to be compromised. Cracks between the building structure and interior wood-frame walls were found to cause some flank transmission of sound. Surface details were repaired and repainted after a year of operation, when the moisture level of the wood had reached equilibrium with its surroundings. It is also recommended by Danish guidelines not to make repairs too early [10].

Practical comparisons to the use of WPS will have to remain entirely theoretical. It is probable that the CLT and glulam elements would have been less exposed to moisture in that scenario, but WPS would have been more expensive and slowed construction. The moisture condition of the ZEB Laboratory as built can be deemed satisfactory; it is unknown whether the use of WPS would have yielded any better results, but from our point of view the opportunity for better results is also quite limited.

6. Conclusions

The moisture safety strategy of the ZEB Laboratory appears to have yielded acceptable results by every investigated indicator. Through wood moisture measurements, air quality measurements, airtightness measurements, and visual inspection, it is determined that no substantial moisture damage occurred despite the lack of weather protection in the construction phase. The moisture safety strategy appears to be a good alternative to WPS, but it has also been quite labour-intensive in terms of monitoring, assessment, and validation. While these activities also greatly overlap research activities in the building, it is not known whether they would be feasible to conduct in other projects. More research is required to determine the necessary level of moisture monitoring to ensure adequate moisture safety.

Future research at the ZEB Laboratory will continue to monitor the building’s performance from a multitude of perspectives, including moisture performance. As the building is heavily monitored by sensors and largely inhabited by building scientists, it is expected that any eventual moisture problems will be quickly discovered and thoroughly studied. It should thus be feasible to conduct follow-up studies of the building’s moisture performance in the long term.

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