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Moisture Safety in Prefabricated Roof Renovations: Causes and Strategies

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Abstract

Achieving carbon neutrality by 2050 requires extensive energy renovation of the existing building stock. In this study we focus on deep renovation with prefabricated insulation elements as a potential solution to attain the required renovation speed and volume. The use of such elements without a proper moisture safety strategy can, however, lead to moisture-related problems, including mould growth. Here we examine the causes of moisture and mould damage in a case study of a building that has been renovated to near-zero energy standards using prefabricated insulation elements.

The study elucidates the reasons for the moisture damages detected and proposes two moisture safety strategies to improve the situation. The first strategy emphasizes the importance of ensuring dry construction conditions by either using a full temporary roof or avoiding rainfall during installation. The second strategy addresses localized water damage to the attic floor and involves the use of protective measures, active ventilation and a correct installation sequence. In the case of local moisture damage, the required amount of ventilation air flow during summer is 0.5–0.55 l/(s·m^2). During cooler periods, heating is needed.

The employed methods include modelling the case-study building with the IDA Indoor Climate and Energy software, as well as mould growth risk assessment based on temperature and relative humidity measurements. The results highlight the effectiveness of both strategies in preventing mould growth if applied correctly, and emphasize the need for thorough planning, moisture safety regulations and rapid response to ensure successful renovation with prefabricated insulation units.

The study provides valuable information on moisture safety strategies for serial renovations with prefabricated elements. The existence and proper implementation of a moisture safety strategy is important for achieving the desired energy performance goals while maintaining building durability and occupant health, and it needs to be applied throughout the chain of site management: from the main contractor down to the skilled worker.

Keywords: moisture safety; flat roof; prefabricated renovation; deep renovation; serial renovation.

Introduction

Decarbonisation of buildings is crucial to meet Europe's carbon neutrality goal by 2050. Because the existing EU building stock is energy inefficient, improving energy efficiency in buildings has a key role to play in achieving this ambitious goal. Sandberg et al. (2016) modelled the European building stock and showed that 70–80% of the dwelling stock is in need of energy renovation by 2050. The building envelope must have good qualitative characteristics so that the energy performance of the building can be maintained throughout its life, irrespective of changes in the building's service systems or occupancy (Wahlström & Maripuu, 2021). To fulfil the requirements for nearly zero energy buildings (nZEB), the thermal transmittance of the building envelope must decrease 2–20 times depending on the climate and the existing properties of the envelope (Kalamees et al., 2016). One widely used renovation measure for apartment buildings has been additional thermal insulation of the building envelope (Hirvonen et al., 2019; Kuusk et al., 2016; Thomsen et al., 2016).

Today, the rate of energy renovation is not high enough to fulfil the ambitious goals set. For instance, Göswein et al. (2021) have analysed the Portuguese building stock and concluded that the current annual renovation rate of 0.4% should increase to 3.3% in order to allow for all dwellings to be renovated by 2050. Likewise, McKenna et al. (2013) have evaluated energy efficiency in the German residential sector and have shown that the renovation rate should be increased from 1% to 2% to reduce the heat demand of residential buildings by 80% by 2050. As regards the Dutch housing stock, Filippidou et al. (2017) have shown that the 3.5% deep energy renovation rate observed for the period 2010–2014 is not enough to support fulfilment of the goals set by the government. Analysis of the performance of a renovation grant scheme in Estonia by Kuusk & Kalamees (2016a) reveals that the ensuing increased renovation demand raised the average renovation cost by 20% during a two-year period. Automating the renovation process and using prefabricated additional insulation elements could be one solution to help achieve EU's deep renovation goals.

However, building renovation with prefabricated elements is not only a matter of improving energy performance but also involves a number of hygrothermal challenges. Colinart et al. (2019) analysed renovation of buildings with prefabricated ventilated façade elements and showed that the drying-out period can be as long as two years. Even though no interstitial condensation was observed in the envelope, critical values for mould growth were occasionally exceeded. Pihelo et al. (2016) have also evaluated hygrothermal risks in the building envelope after installation of prefabricated modular elements and demonstrated that the risk of mould growth in this structure can be minimized by controlling the initial moisture content and vapour permeability of the air and vapour barrier. In a similar vein, Goto et al. (2016) concluded in their study on a prefabricated wooden façade module for building renovation in Sweden that it is important to design the module to be vapour permeable so that the entire wall system has a sufficient potential to dry out after refurbishment. In addition, Coupillie et al. (2017) have shown that protection of the façade could be an advantageous measure to reduce the risk of degradation of prefabricated timber-frame façade elements used in building renovation.

Although the influence of roof insulation on a building's primary energy consumption is small (Kuusk & Kalamees, 2016b), flat roofs of older apartment buildings are still in need of renovation because of their poor condition stemming either from the use of old technologies, poor materials and roof insulation that does not meet today's requirements (Miniotaite, 2015), or from degradation due to exposure to ultraviolet radiation and elevated temperatures (Terrenzio et al., 1997). If the roof is opened in order to install insulation, the building will no longer be protected from precipitation. Installation of prefabricated insulation elements would allow renovation without opening the roof structure. Nevertheless, moisture due to precipitation may still accumulate in load-bearing structures or other materials in the attic. Renovation under a temporary roof is possible when using onsite manual construction methods, but installing prefabricated roof elements under a temporary roof is complicated if not impossible. Therefore, roof renovation requires moisture safety solutions different from those applicable to the façade.

This study describes possible moisture-related failures during renovation of a roof with prefabricated insulation elements when proper moisture safety measures are not implemented, and outlines a strategy to ensure moisture safety in similar future renovations.

Methods

Case-study building

The case-study building is a typical five-storey large concrete panel apartment building (series 111–121, total area 4318 m^2), constructed in 1986 (**Fig. 1**) and renovated as a nearly zero energy building (nZEB) by using prefabricated façade and roof elements (Pihelo et al., 2017). The thermal transmittances of the building envelope before renovation were as follows: U_{wall} = 1.1 W/(m^2·K); U_{roof} = 1.0 W/(m^2·K) (Kuusk & Kalamees, 2015).

Fig. 1

Overview of the case-study building before (left) and during nZEB renovation with prefabricated timber-frame insulation elements (right)

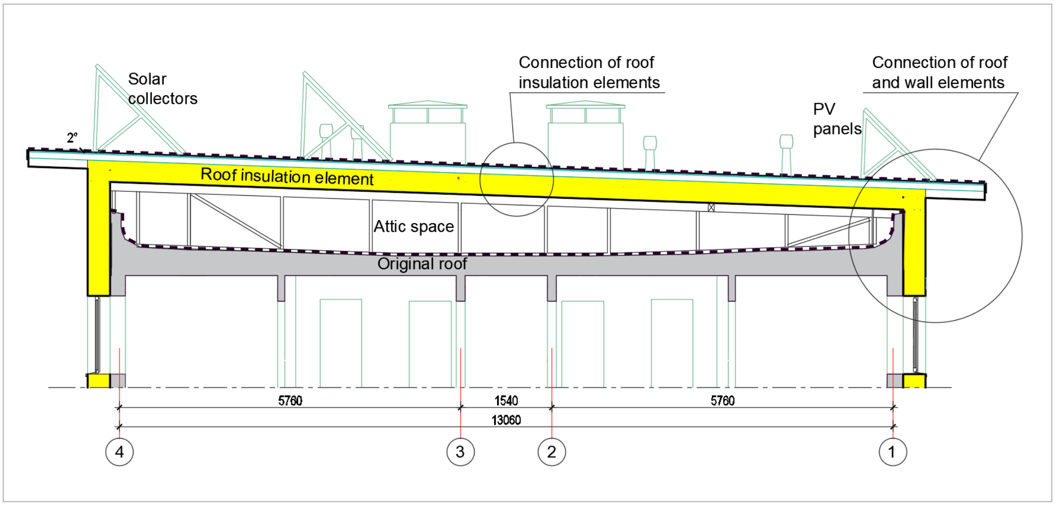
Fig. 2

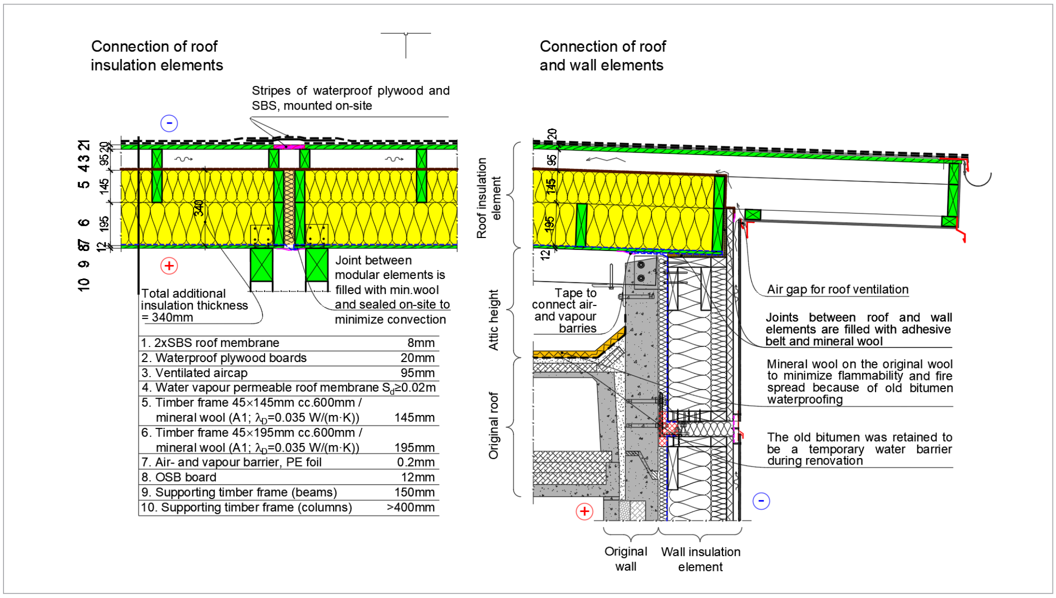
Installation or roof insulation elements

Installation or roof insulation elements (**Fig. 2**) was done on a sloping timber frame because the original roof had an inward slope and a parapet. Therefore, a 0.6–1.2 m high attic space was formed between the old and the new roof (**Fig. 3**), providing a space for technical appliances (e.g. heat exchangers, ventilation ducts, automatics equipment, etc.). The roof elements (**Fig. 4**) consist of a timber frame and a 340 mm mineral wool insulation between the beams. The frame is covered with an air and vapour barrier on the internal side and a roof underlay membrane on the external side. The roof is ventilated by outdoor air through a 95 mm high channel between the roof underlay membrane and the roof covering (SBS (Styrene Butadiene Styrene) elastomeric waterproofing membrane).

Fig. 3

Section of the roof





1. 2xSBS roof membrane	8mm
2. Waterproof plywood boards	20mm
3. Ventilated aircap	95mm
4. Water vapour permeable roof membrane $S_d \geq 0.02$m	
5. Timber frame 45×145mm cc.600mm / mineral wool (A1; λ_D=0.035 W/(m·K))	145mm
6. Timber frame 45×195mm cc.600mm / mineral wool (A1; λ_D=0.035 W/(m·K))	195mm
7. Air- and vapour barrier, PE foil	0.2mm
8. OSB board	12mm
9. Supporting timber frame (beams)	150mm
10. Supporting timber frame (columns)	>400mm

Fig. 4

Roof insulation elements

The bitumen waterproofing on the external side of the old roof was retained to provide a temporary water barrier during renovation. The original roof was covered with mineral wool to minimize flammability and fire spread due to the old bitumen waterproofing.

During the construction of the roof, rainwater accumulated in the mineral wool on the attic floor. After the completion of the roof, the water started to evaporate into the attic, causing high relative humidity and mould growth on wood, especially on the interior surface of the roof elements. For the location of roof insulation elements and the corresponding precipitation intensities, see Fig. 5.

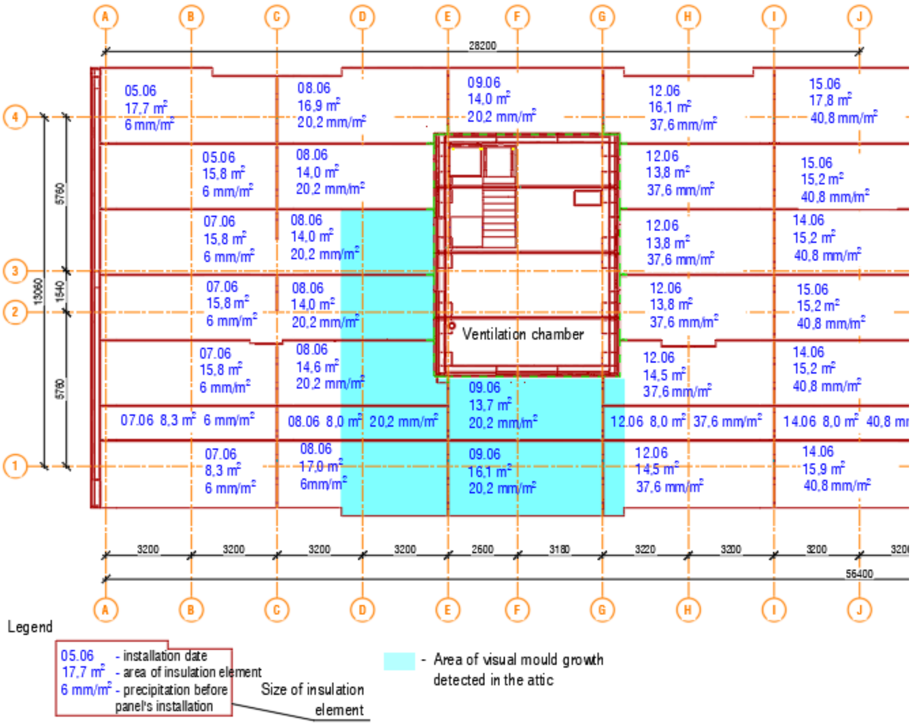


Fig. 5

Location of roof insulation elements and precipitation intensity during installation (only one half of the building's roof is shown)

Measurements

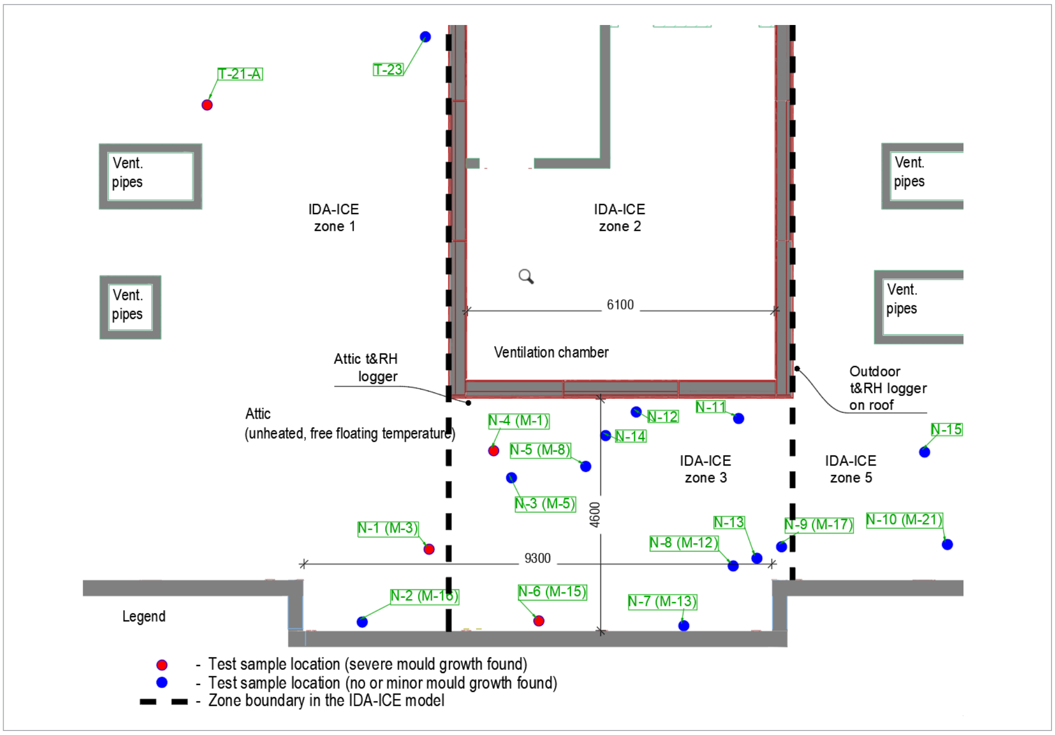
Air temperature and relative humidity in the attic and outdoors was measured with HOBO temperature (t) / relative humidity (RH) data loggers (U12-013, measurement range from -20° to 70 °C, RH 5% to 95%, accuracy ± 0.35 °C, ± 2.5% for RH from 10% to 90%, to a maximum of ± 3.5%). The loggers were installed after mould growth was detected (for sensor locations, see **Fig. 6**). Solar radiation, rain and wind data were retrieved form the nearest meteorological station (3.7 km away).

Mould growth on surfaces was initially detected visually and later confirmed in selected locations using a NIKON SMZ800 stereomicroscope. The mould species were identified with a NIKON Microphot FX universal microscope at 400x magnification. The test chamber was disinfected with laboratory grade ethanol (96.6°), used without further purification. Distilled water was readily available from the laboratory's own distilled water system.

The locations of samples taken to determine surface contamination as well as climate measurement points are shown on **Fig. 6**.

Fig. 6

Plan of the attic and zones of the IDA ICE model, focused on a problematic area near the ventilation chamber, with test locations for mould growth labelled as N-1, N-2, etc



Modelling

Whole-building heat air and moisture modelling

A whole-building dynamic indoor climate and energy simulation with the IDA Indoor Climate and Energy software (Björsell et al., 1999; Shalin, 1996) was performed to examine and compare different moisture safety strategies. The IDA ICE software has been meticulously validated (Achermann & Zweifel, 2003; Kropf & Zweifel, 2001; Mateo & Aranaz, 2011; Moinard & Guyon, 2000; Travesi et al., 2001; Woloszyn et al., 2009) and allows modelling of a multi-zone building, internal and solar loads, outdoor climate and HVAC systems, as well as dynamic simulation of heat transfer and air flows. The program has been used in many indoor climate and envelope moisture interaction applications (Frasca, 2015; Kalamees et al., 2015; Napp et al., 2016; Rode & Woloszyn, 2007). To calculate moisture transfer in IDA ICE, the common wall model RCWall should be replaced with the HAMWall model (Kurnitski & Vuolle, 2000).

In the program, a mathematical model was created of the building in which the movement of air, heat and moisture through the structures (**Table 1**) and the energy required for heating, ventilation, and humidification-dehumidification were considered. The simulation model consisted of two storeys (5th floor and the attic) and the attic itself was divided into six zones (allowing air change between the zones; see **Fig. 6**): west side of the attic (1), ventilation chamber (2), areas south (3) and north (4) of the ventilation chamber, middle of the attic (5) and east side of the attic (6). The thermal and hygric properties of the materials for the heat, air and moisture (HAM) simulation are shown in **Table 1** and **Table 2**. The roof and the exterior walls of the attic were divided into 13 layers (**Table 3** and **Table 4**) in order to calculate the movement of heat and moisture through the structures.

The IDA ICE pool model was used to calculate water evaporation:

$$\dot{m}_{evap} = 4 \cdot 10^{-5} \cdot A(p_{ps} - p_a)F_a \tag{1}$$

where: $\dot{m}_{evap}$ – mass flow rate [kg/s]; A – area of zone 3 [m^2] (see **Fig. 6**); p_{ps} – water vapour pressure on the pool surface [Pa]; p_a – water vapour pressure in the attic air [Pa]; F_a – activity factor [-].

The maximum amount of water that could evaporate into the attic was 30 kg/m^2, corresponding to the maximum thickness of the water layer on the attic floor, which equals the thickness of the mineral wool cover, i.e. 3 cm.

The modelling results are presented for zone 3 as this area was the most critical for mould growth.

Table 1

Structures and materials and their thermal properties

Structure	Materials (from indoor to outdoor)	Thickness d, m	Thermal conductivity λ, W / (m·K)	Specific heat c J / (kg·K)	Density ρ, kg / m^3
Exterior wall	Oriented strand board (OSB)	0.012	0.13	2700	532
	Air and vapour barrier	0.0002	0.5	1670	1000
	Mineral wool/timber frame	0.27	0.036	750	20
	Wind barrier board	0.03	0.031	750	50
Roof	OSB	0.012	0.13	2700	532
	Air and vapour barrier	0.0002	0.5	1670	1000
	Mineral wool/timber frame	0.35	0.036	750	20
	Underlay membrane	0.0002	0.5	1670	1000

Table 2

Hygric properties of the materials

Material	Water vapour transmission[1]			Sorption isotherm[2]			
	δ_0,m^2/s	B	C	RH$_1$,%	w$_1$, kg/m^3	RH$_2$,%	w$_2$,kg/m^3
OSB	1.35×10^{-7}	3.5×10^{-7}	9.0	75	50	100	75
Air and vapour barrier	1.00×10^{-9}	1.0×10^{-8}	5.0	30	0.01	100	0.02
Mineral wool/timber frame	2.00×10^{-6}	1.0×10^{-7}	5.0	30	0.1	100	0.3
Wind barrier board	2.00×10^{-6}	1.0×10^{-7}	5.0	30	0.1	100	0.3
Underlay membrane	5.00×10^{-8}	1.0×10^{-7}	5.0	30	0.01	100	0.02

[1] Water vapour permeability $\delta_v = \delta_0 + B(RH/100)$ [m^2/s], where δ_0 [m^2/s] is at RH = 0%; B and C are constants.

[2] Sorption isotherm is given by three lines: start: w = 0 kg/m^3, RH = 0%; first breakpoint: w$_1$, RH$_1$; second breakpoint: w$_2$, RH$_2$ = 100%.

Table 3

Discretization of the roof structure

Roof																
		OSB				Air and vapour barrier	Mineral wool							Underlay membrane		
Layer no	+	1	2	3	4	5	6	7	8	9	10	11	12	13	-	∑ 13
Thickness, mm		1	2	4	5	0.2	10	40	100	100	50	40	10	0.2		∑ 362

Table 4

Discretization of the exterior wall structure

Exterior wall																
		OSB				Air and vapour barrier	Mineral wool						Wind barrier board			
Layer no	+	1	2	3	4	5	6	7	8	9	10	11	12	13	-	∑ 13
Thickness, mm		1	2	4	5	0.2	10	20	100	100	30	10	15	15		∑ 312.2

Modelling of mould growth

Assessment of the risk of mould growth is based on the frequency of exceeding mould growth limit values and on the mould growth itself; this risk is expressed as the mould index (Hukka & Viitanen, 1999). The risk of mould growth was calculated from modelled values of relative humidity and temperature that exceeded the mould growth limit curve values for wooden materials in the temperature range of 0–50 °C (Equation 1). The model consists of differential equations describing the mould growth rate in different climatic conditions, taking into account the exposure time, temperature, relative humidity and dry periods. The extent of mould growth is expressed as the mould index on a seven-grade scale: 0 – no growth, spores not activated; 1 – some growth detected only by microscopy, initial stages of hypha growth; 3 – some growth detected visually (10–30% mould coverage on surfaces), new spores produced; 6 – very heavy and dense growth (coverage around 100%).

$$\mathrm{RH_{crit}} = \begin{cases} -0.00267 \cdot t^3 + 0.160 \cdot t^2 - 3.13 \cdot t + 100\text{, when} & 0 < t \le 20\,°C \\ 80\% \text{, when} & t > 20\,°C \end{cases} \qquad (2)$$

In the year 2017 when the roof was constructed, the situation regarding the mould growth risk was worse than usual, since the mould index calculated directly from the outdoor climate was higher for that year (M_{max} = 2.8) as compared to the moisture reference year 1989 (MRY = load at the 90% criticality level) (M_{max} = 2.3 (Kalamees & Vinha, 2004)).

Results and Discussion

Mould and moisture damages

Visual signs of high water level on the attic floor during construction as well as mould growth were detected during the first month after the end of construction (**Fig. 7**). The highest mould growth was observed in the area where rainfall intensity on the day of installation was ~2 cm/day (see **Fig. 5**). In locations where no visual mould growth was evident, microscopic analysis still showed mould growth (see **Table 5**). Mould started to grow mostly on oriented strand boards (OSB). The main mould genera detected were *Aspergillus, Penicillium, Cladosporium, Aureobasidium, Phoma and Chaetomium*, most of which are fungi indicating a moisture problem (Mahooti-Brooks et al., 2010). OSB has been shown by laboratory measurements to be a very favourable surface for mould growth (Kallavus et al., 2017) and therefore requires especially careful handling during construction to prevent its wetting.

To eliminate the risk of creating health issues to the residents as a result of spreading of mould spores from the attic to the living rooms, all materials affected by mould were replaced and repeat measurements of surface contamination were performed in 2021. Four years later the attic ceiling surfaces were mainly free from mould growth. Although no samples showed any mould 4 years after the construction, a few old, degraded hyphae were still detected. This indicates how sensitive mould sampling can be. It is not always possible to make sure that a surface is clean from contamination. Therefore, it is preferable to prevent the occurrence of critical hygrothermal conditions.

Fig. 7

Moisture damage signs on the roof's timber frame (left) and on the inner surface of the roof (OSB) (right)

Table 5

Microscopic analysis of the inner surface of the roof (OSB)

Sample code	Result in 2017	Result in 2021
N-1 (M-3)	Mould growth	No mould
N-2 (M-10)	No mould	No mould
N-3 (M-5)	No mould, a lot of glass fibres	Wood dust, partly covered with mould hyphae
N-4 (M-1)	Mould growth	No mould
N-5 (M-8)	No mould	Few old, degraded hyphae
N-6 (M-15)	Mould growth	No mould
N-7 (M-13)	No mould	No mould
N-8 (M-12)	No mould, a lot of glass fibres	No mould
N-9 (M-17)	No mould, a lot of glass fibres	No mould
N-10 (M-21)	No mould, a lot of glass fibres	No mould, wood dust
N-11, 12, 13, 14, 15	No mould	No mould
T-21-A	Mould growth	No mould
T-23	Blue stain fungi	No mould

Temperature and humidity conditions in the attic: measurements and modelling to calibrate the whole-building HAM model

The measured and modelled temperature and humidity conditions show good agreement (**Fig. 8**, **Fig. 9**, **Fig. 10**) throughout the whole 1.5 year observation period. This allowed to estimate the hygrothermal conditions for the period between the end of construction and the start of measurements (temperature and humidity measurements in the attic started after visual mould growth was detected).

After the installation of roof insulation elements there were favourable conditions for mould growth: t ≥ 20–30 °C and RH ≥ 80 %, because the moisture trapped in the mineral wool on the attic floor and in timber-frame structures that became wet due to rain (see precipitation intensity during installation in **Fig. 5**) started to evaporate and the sun heated the dark outer surface of the roof.

The increased RH in the attic could also have been caused by night time clear sky radiation, which has been shown by several studies to be a contributing factor in other cold climate regions (Hagentoft & Kalagasidis, 2014; Harderup & Arfvidsson, 2013; Jensen et al., 2020). However, the thermal transmittance of the newly installed roof is quite low (U_{roof} = 0.10 W/(m^{2}·K)), which should minimise the temperature drop on the inner surface of the roof.

Fig. 8

Measured and modelled attic and outdoor air temperature

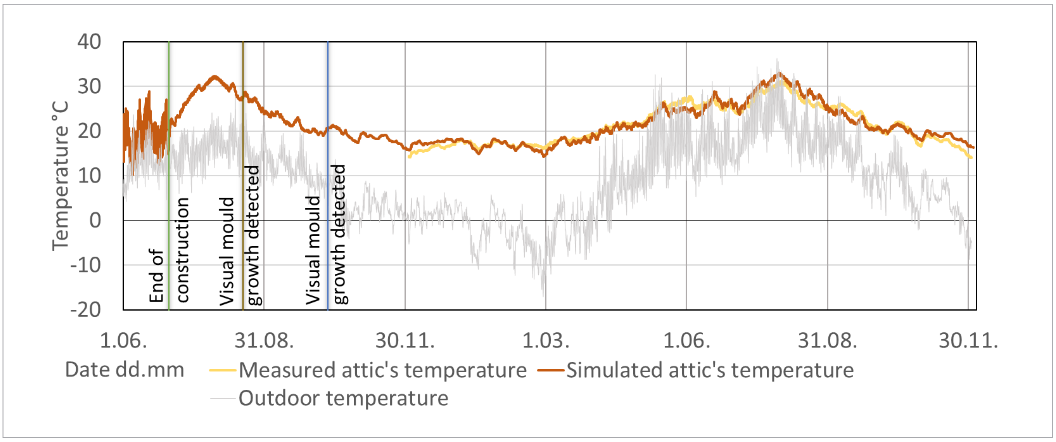


Fig. 9

Measured and modelled attic and outdoor air relative humidity

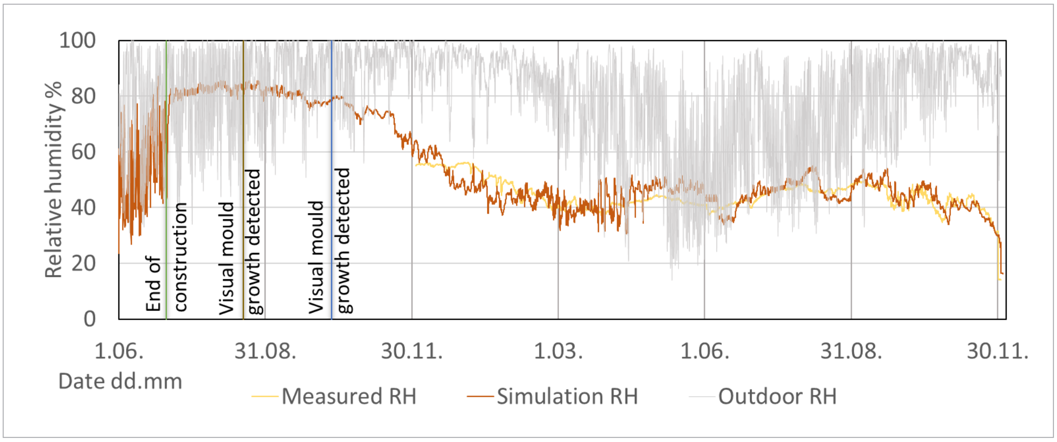
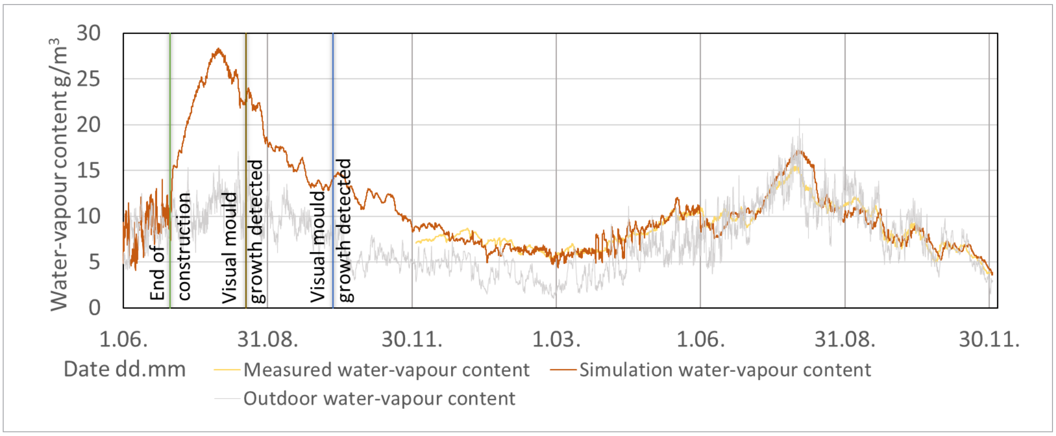


Fig. 10

Measured and modelled attic and outdoor air water vapour content



After the end of installation of roof insulation elements and closure of the attic, the moisture that dried out from the mineral wool on the attic floor and from timber-frame structures caused high moisture excess in the attic: $\Delta v \geq 15$ g/m^3 (see **Fig. 11**). This moisture excess represents moisture loads that are higher than even in swimming pools and other rooms with very high water use and evaporation rate (Dietsch et al., 2015; Janssens & Hens, 2003; Shah, 2014). After mould growth was detected and the attic air had dried, the moisture excess dropped to a level similar to that in common living rooms with low occupancy: $\Delta v \geq 3$–4 g/m^3 (Ilomets et al., 2017; Vinha et al., 2018). The importance of controlling moisture excess in rooms with wooden surfaces has been pointed out by Arumägi et al. (2015), who have shown that if the moisture excess $\Delta v \geq 6$ g/m^3, the number of mould spores in the indoor air is expected to exceed the acceptable level of 500 cfu/m^3. Although the attic was not ventilated with outdoor air during the use of the building, the moisture excess remained close to zero after the construction-related moisture had dried out, because there was no moisture production in the attic. As air leakages from living rooms can also result in increased moisture in the attic, it is essential to ensure that the design and construction of the interface between the uppermost storey ceiling and the attic floor is such that good airtightness is achieved (Kalamees & Kurnitski, 2010). Airtightness of the structures of the uppermost storey of multi-storey buildings is extremely important because these structures work under positive indoor air pressure (Kalamees et al., 2010).

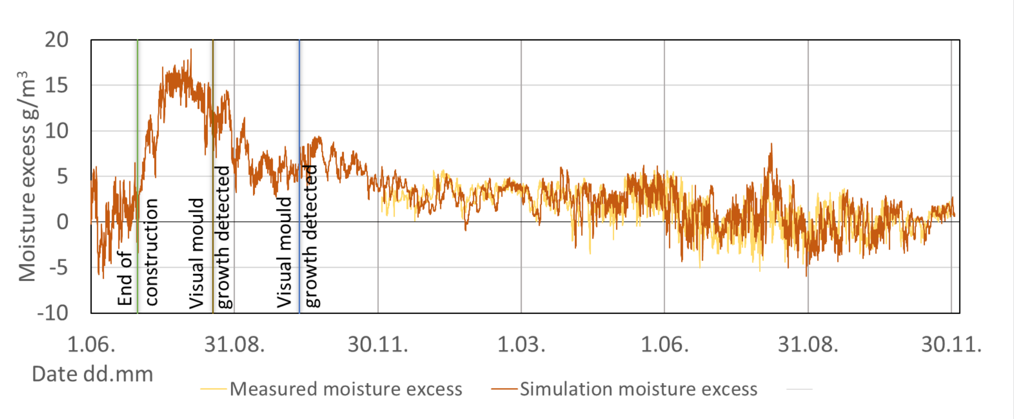


Fig. 11

Measured and modelled attic moisture excess (the difference between attic and outdoor air water vapour content)

The calculated mould index based on temperature and relative humidity measurements in the attic was M = 5 (visually detected mould growth) for very sensitive surfaces , and between M ≥ 2 (moderate growth detected by microscopy, coverage more than 10%) and M ≤ 3 (some growth detected visually) for OSB(Hukka & Viitanen, 1999). Since the actual mould situation as detected in the attic corresponded well to those index values, it can be concluded that the used Finnish mould growth model is suitable for assessing the risk of mould growth and developing appropriate moisture safety strategies.

Strategies to prevent moisture damage

Construction in dry conditions

One common measure to guarantee moisture safety on a construction site is to erect a temporary roof. Several types of moisture damages have been observed in wooden buildings constructed without a temporary roof (Kalbe et al., 2020, 2022; Liisma et al., 2019; Olsson, 2021). In ideal conditions the temporary roof can prevent accumulation of excess moisture of any kind because the building is protected from precipitation. In this case the attic is basically dry during the whole construction. Another option to ensure dry conditions is to do the installation work on precipitation-free days and/or immediately remove any excess water from the attic.

Calculations for the case of constructing in dry conditions were done without a precipitation load, i.e. assuming that installation is done during periods without rain and the old bitumen roof is covered with mineral wool only after the roof is in place. In this scenario, the temperature (**Fig. 12**) and relative humidity (**Fig. 13**) in the attic do not exceed critical levels and no mould growth is observed (mould index M ≤ 1). Fluctuation of the value of moisture excess (Δv in the range of ± 5 g/m^3) is caused mainly by a time lag in the equilibration of the indoor air water vapour content with that of the outdoor air because there is no active mechanical ventilation in the attic.

Fig. 12

Modelled attic and outdoor air temperature in the case of using a total temporary roof during construction

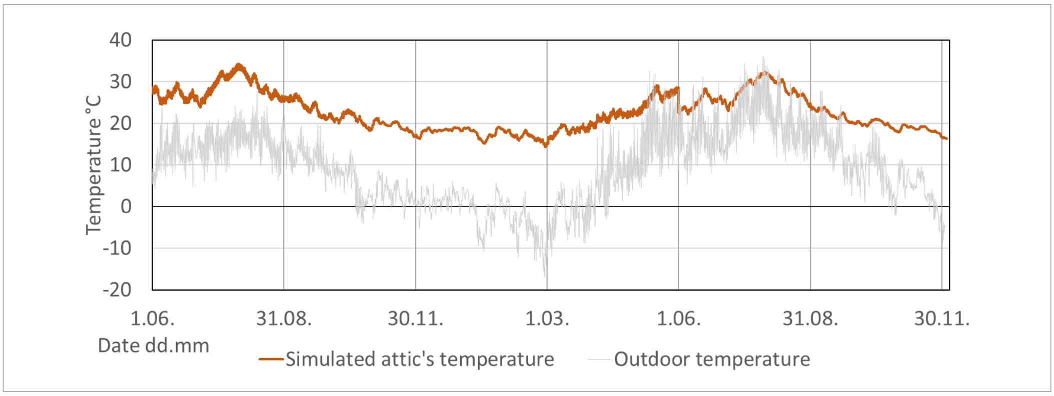
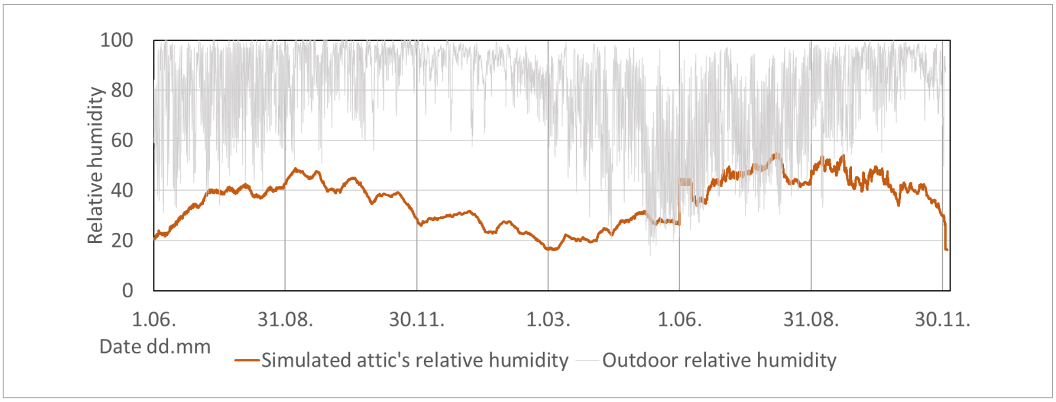


Fig. 13

Modelled attic and outdoor air relative humidity in the case of using a total temporary roof during construction



There have been examples of using a fully covering temporary roof or other weather protection for onsite renovation or construction of new wooden buildings from elements prefabricated offsite (Svensson Tengberg & Bolmsvik, 2021). However, a fully covering temporary roof with a crane to install roof insulation elements might make renovation with offsite-produced prefabricated elements expensive and unfeasible for the owners of a typical residential building. To make renovation with offsite-produced elements suitable for mass-use, its cost should be lower and other solutions for moisture safety should be found.

Elimination of local excessive water damage on the attic floor by ventilation

The second strategy analysed pertains to the situation where the roof is constructed in almost perfectly dry conditions but accidentally one zone happens to be unprotected from precipitation and water is introduced locally on the attic floor. This moisture safety strategy includes the following steps:

- protecting the roof's timber frame structure locally against precipitation,
- avoiding installation of roof insulation elements during heavy rain,
- ensuring fast drying by active ventilation in situations where the attic floor has become wet,
- installing a thin mineral wool layer on the attic floor (fire protection of old bitumen waterproofing) only after the roof insulation elements have been installed, to ensure that the mineral wool will not get wet;

implementing a qualified construction management method to guarantee moisture safety (Pihelo & Kalamees, 2019).

In the modelled situation, water was on the floor of only one zone of the attic (IDA ICE zone 3, see Fig. 6). Walls between zones were modelled to allow moisture distribution between zones. Drying was intensified by attic ventilation (at different air flow rates).

The results show that there is a small difference in room temperature between IDA ICE zone 3 (with water on the floor) and IDA ICE zone 5 (reference, without water on the floor) because evaporation of water from the floor lowers the temperature in zone 3.

The modelled RH is higher than in the case of dry construction (moisture safety strategy described in section 3.2.1) in all zones, but the problem is especially evident in the zone above the water damage (Fig. 14).

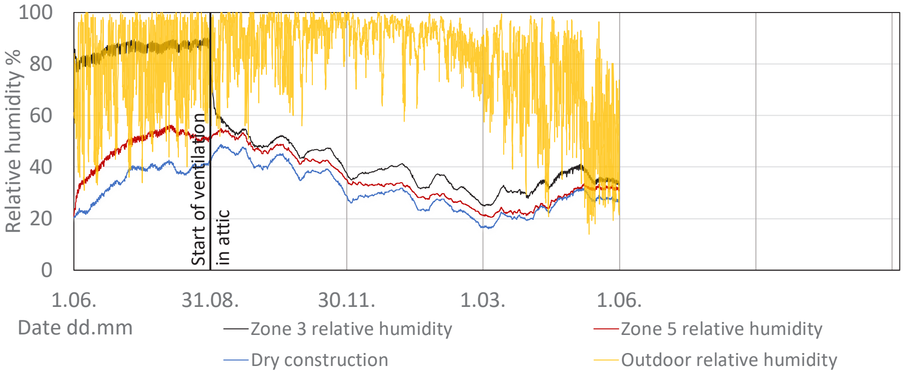


Fig. 14

Modelled attic and outdoor air relative humidity in the case of local water damage in the attic

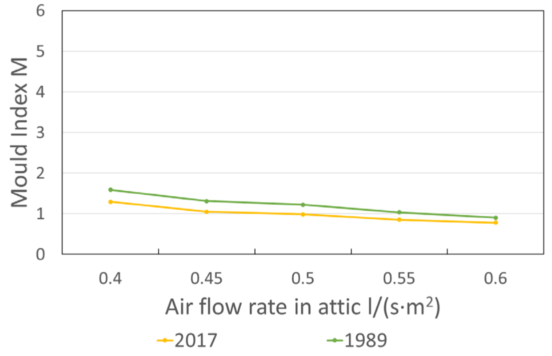


Fig. 15

Calculated maximum mould index at different outdoor ventilation air flow rates in the attic

Based on the modelled temperature and RH values, mould index was calculated for the inner surface of the attic roof at different air flow rates (Fig. 15). According to the calculations, there would be no mould growth in the case of constructing in dry conditions and the same holds true for zone 5 in the water damage scenario, while in zone 3 the maximum mould index in the water damage scenario would stay below 1 (no mould growth) at a ventilation airflow of 0.5–0.55 l/(s·m^2), depending on the outdoor climate. During winter, heating in the attic is needed to drive out the excess moisture.

Limitations of the study

In this study, two moisture safety strategies were analysed that are the easiest to use in practice. There may be other viable options worth considering.

Kurnitski (2000) has studied humidity control in outdoor-air-ventilated crawl spaces in a cold climate, exploring the use of dehumidification in addition to ventilation. Dehumidification could also be employed as a possible moisture control strategy for drying out attic structures. Since cold air has low moisture-binding capacity, it may be necessary to preheat the air in winter. These moisture control strategies should be analysed in future studies.

Conclusion

In this study, we have analysed the causes of moisture and mould damage in the attic of an apartment building renovated with prefabricated insulation elements, and have developed two moisture protection strategies.

The expected temperature and humidity conditions in the attic, calculated with the help of a calibrated whole-building heat, air and moisture model, indicate that the cause of the mould damage was moisture originating from wetted mineral wool, causing a very high moisture load. Mould damage would not have occurred if dry conditions were maintained during construction with no local accumulation of water (the mineral wool would not have been allowed to get wet or would have been installed after the roof elements were in place). We have establihed that in the case of local moisture damage in the studied attic, the required amount of air flow for ventilation without heating is 0.5–0.55 l/(s·m^2).

Renovation to nZEB standards using prefabricated timber-frame insulation elements requires introduction of a moisture safety strategy, thorough inspection, strict moisture safety regulations and analysis of the designed solutions. One also needs a knowledgeable team and a well-analysed action plan to carefully follow proper construction techniques and ensure quick response. The existence of a moisture safety strategy and its implementation are necessary throughout the chain of site management: from the main contractor down to the skilled worker.

IDA ICE allows to perform whole-building heat, air and moisture simulations and predict the drying out of building moisture with sufficient accuracy to develop suitable moisture safety strategies. Likewise, the Finnish mould index used in the study is a good indicator for moisture safety evaluation in buildings, as the calculated mould index showed good correlation with the actual situation encountered in the attic.

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