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Impact of indoor humidification on hygrothermal performance of building envelope in Northern Finland

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Abstract. Dry indoor air is known to increase the risk for respiratory infections, viability, transport of influenza virus and intensifies sensitivity of nasal systems. The aim of this study was to investigate the effect of humidification on the hygrothermal performance of the common timber wall structure of a day care building located in Northern Finland. Hygrothermal performance of structures under different indoor moisture loads was analysed. Numerical simulation and the Finnish mould growth model were used to evaluate the impact of humidification on moisture safety of the envelope. Largest impact of indoor air humidification is observed in the low humidity ranges on inner side of water vapour barrier. At the outer side of the water vapor barrier the indoor humidification has no effect on the hygrothermal conditions or mould growth risk. The most favourable conditions for mould growth are obtained at the corner of the building envelope, at the interface of load bearing timber and windshield where hygrothermal conditions are almost 60% of the time over 80% of relative humidity. However, the Finnish mould index does not indicate any mould growth risk. The study demonstrates that the indoor air can be humidified to RH of 35% during the cold dry period.

1. Introduction

Dry indoor air increases the risk of respiratory infections, viability and transport of the influenza virus, and intensifies sensitivity of nasal systems [1]. When the relative humidity (RH) is between 10% and 20%, susceptibility to infections increases due to intensified sensitivity of nasal systems and mucous membranes [19]. In cold climates, low indoor air humidity is related to the low moisture content of outdoor air, high indoor temperatures, low moisture production indoors, and efficient mechanical ventilation systems. Buildings in Finland are designed for critical indoor moisture content, which must be considered when planning humidification systems [2]. Standard EN 16798-1 suggests that humidification and drying of indoor air are often unnecessary in the European climate and provides indoor air humidity design values for Class I to 30%, Class II to 25%, and Class III to 20% [20]. Increasing indoor air moisture content may increase the risk of moisture damage and microbial growth inside the building envelope. Therefore, analyzing the hygrothermal performance of structures under increasing moisture loads is essential to improve building sustainability.

One of the challenges impacting indoor air quality is mould growth in buildings [3]. In the European Union, 14.8% of the total population lives in dwellings with damp walls, floors, foundations, or leaking roofs [4]. In Finland, 12-18% of day care and school buildings have moisture and mould damage, and approximately 172,000–259,200 people spend a large proportion of their time in these buildings every day [5].

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This study monitors indoor temperature (T) and RH in a day care located in Northern Ostrobothnia, Finland, since January 2021. The focus is on the coldest periods when indoor RH drops below 25%. The impact of indoor humidification on the hygrothermal conditions inside the building envelope is assessed at 25 points located nearby thermal bridge areas. In total, there are four different indoor hygrothermal scenarios being analyzed. Given that air humidification is an energy-intensive process, the goal of this study is to maintain a minimum level of humidity that benefits a healthy indoor environment while minimizing energy consumption, rather than targeting optimal RH values.

2. Methodology

2.1. Monitoring
In this study, we utilized seven Internet of Things (IoT) sensors to measure indoor temperature (T) and relative humidity (RH), along with two IoT sensors to record pressure differences over the building envelope, with data recorded at 10-minute intervals. As a reference, a separate wing of the same building without a humidifier was also monitored using five RH and T sensors, as well as two pressure sensors. The RH sensor technology used is based on capacitive micro-electro-mechanical systems (MEMS) with an accuracy of ±2% ± 0.2°C. The designed maximum air exchange rate for the rooms is 1.99 air changes per hour (ACH). The day care is equipped with a demand-controlled variable air volume system (VAV) that regulates air volume based on CO_2 concentration, with 100% air volume corresponding to a CO_2 concentration of 900 ppm.

2.2. Climate conditions
In 2021, indoor temperature (T) and relative humidity (RH) were measured at 10-minute intervals in a day care center. Hourly data was obtained by averaging six measurements each hour. Outdoor conditions were sourced from the Finnish Meteorological Institute's measurements in Oulu/Finland in 2021 [6].

Four cases were simulated, with indoor RH levels of 28%, 37%, and 47% spending different percentages of the year below 25%, 30%, and 35%. We analyzed the effect of increasing the indoor humidity to a minimum level of 25%, 30%, and 35% over a one-year period starting from 1st of January (Figure 1). Measured indoor conditions were used as a reference for the analyzed indoor scenarios.

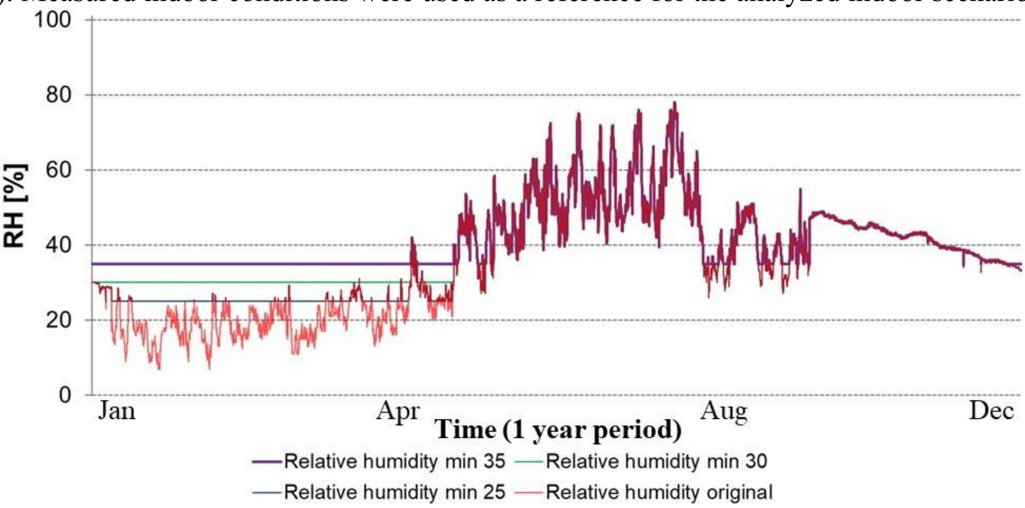

Figure 1. Measured and humidified indoor relative humidity considered in study.

2.3. Structural assembly
The building envelope studied in this research is a common timber-framed structure with mineral wool serving as the main thermal insulation material (see Figure 2). From the inside out, the structure consists of gypsum board, mineral wool, a water vapour barrier, pine wood as a load-bearing material, another layer of mineral wool, and windproof gypsum board. We selected two locations for observation, denoted as "a" and "b". Location "a" includes points (3a, 4a, 8a, 10a, and 12a) where heat and moisture transfer

are mostly one-dimensional, as well as points (1a, 2a, 5a, 6a, 7a, 9a, and 11a) in the ambient of the timber studs where transfer is two-dimensional. The second location, denoted as "b", is a corner of the building envelope where the focus is on points located on the inner surface of the water vapour barrier and in the ambient of the timber studs (see Figure 2). This area poses a high risk for the development of favourable conditions for mould growth [7].

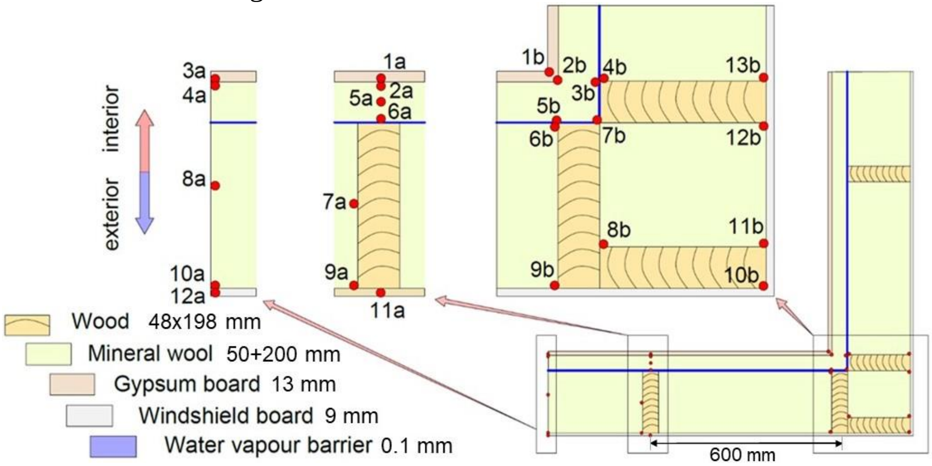

Figure 2. Horizontal cut of the studied structure and location of analysed points.

2.4. Material properties

Each layer of a building envelope assembly plays a significant role in the overall hygrothermal performance of a building. To simulate hygrothermal behaviour, material properties such as thermal conductivity (λ) in units of W/(m·K), heat capacity (C_p) in units of J/(kg·K), density (ρ) in units of kg/m^3, moisture isotherm (w) in units of kg/m^3, liquid transport coefficient (D_w) in units of m^2/s, and water vapour resistance factor (μ) are required. These material properties were obtained from the WUFI material database, mainly from Fraunhofer-IRB properties (Table 1). For each material, the density (ρ), heat capacity (C_p), and water vapour resistance factor (μ) are considered constant. Thermal conductivity (λ) and liquid transport coefficient (D_w) vary depending on the water content (w) in units of kg/m^3, while the moisture isotherm is described by the relationship between water content (w) and relative humidity (φ) which varies from 0 to 1.

Table 1. Material properties applied in numerical hygrothermal simulations.

Materials properties	λ (w) [W/(m·K)]	ρ [kg/m^3]	C_p [J/(kg·K)]	w (φ) [kg/m^3]	D_w (w) [m^2/s]	μ [-]
Wood	0.13-0.25 (0-470)	650	1500	0-370 (0-1)	0	200
Mineral wool	0.04-0.6 (0-950)	60	850	0-44.8 (0-1)	0	1.3
Gypsum board	0.2-1.42 (0-650)	850	850	0-400 (0-1)	0-1.0·10^{-6} (0-400)	8.3
Vapour barrier	2.3	130	2300	0-0.04 (0-1)	0	1500000
Windshield board	0.04	159	1700	0-830 (0-1)	0-3.0·10^{-12} (0-830)	2.6

2.5. Numerical approach

Numerical simulations were conducted using the WUFI 2D simulation software, which has been validated in numerous similar applications [8], [9], [10], and [11]. The models employed dynamic two-dimensional simultaneous coupled heat and mass transfer, making them suitable for analyzing the hygroscopic range (φ<95%) [12]. The simulation covered a period of two years with 1-hour time-steps between measurements. The convective heat transfer coefficient for both the indoor and outdoor surfaces was set to α_c=8 W/m^{2}K to correspond to the prevailing conditions. The water vapour transfer coefficients for the outdoor and indoor surfaces were considered β_{out}=1.3·10^{-7} and β_{int}=2.45·10^{-8} kg/m^{2}sPa, respectively, derived from the convective heat transfer coefficient [13].

2.6. Evaluation methodology – The Finnish mould growth model
Hygrothermal numerical simulations and the Finnish Mould Growth Model were employed to evaluate the impact of humidified indoor air on hygrothermal conditions and mould growth inside the building envelope. The Finnish Mould Growth Model was applied to assess the suitability of building design against biological growth [7]. This model is a useful tool for evaluating different design strategies regarding the appearance of mould on or inside building components based on dynamic hygrothermal conditions [14, 15]. In a previous study, the model achieved good agreement between predicted and observed mould growth [16]. The model calculates a mould index M, which ranges from 0 to 6 and describes the amount of mould present on a material surface. An M value below 1 indicates no mould growth. The mould growth rate and M value are affected by temperature, relative humidity, and time. The model also considers mould decline when hygrothermal conditions are not favourable for mould growth. The favourable area for mould growth is defined as a temperature range between 0-50°C and RH>80% for sensitive and very sensitive materials and >85% for medium-resistant and resistant materials [17]. Therefore, the Finnish Mould Growth Model classifies materials into four sensitivity and four decline groups based on associated factors such as surface type, coating, and contact with other materials.

3. Results and discussion
The results are presented with 1-hour time intervals for a period of 2 years, including initial conditions, which have a negligible impact on the obtained results. The thermal conditions were kept the same for all studied scenarios; therefore, temperature has no significant impact on the hygrothermal conditions inside the building envelope. In the case of the wall section (location a in Figure 2), an increased indoor relative humidity (RH) increases humidity in the low humidity range, but it does not affect humidity near the range for mould growth risk at any of the observed points. For instance, on the inner surface of the water vapour barrier at point 6a (Figure 2), increasing the minimum indoor RH results in a higher number of conditions in the humidity range between 15% and 60% (between the red lines) (Figure 3). The average density of conditions is 47%, 50%, 53%, and 56% for the original indoor relative humidity (RH) level, and for minimum indoor RH set to 25%, 30%, and 35%, respectively. As a result, the minimum RH values increase by over 20% from the measured RH, while the maximum values remain the same. Indoor RH has an impact on the humidity conditions on the warmer side of the water vapour barrier.

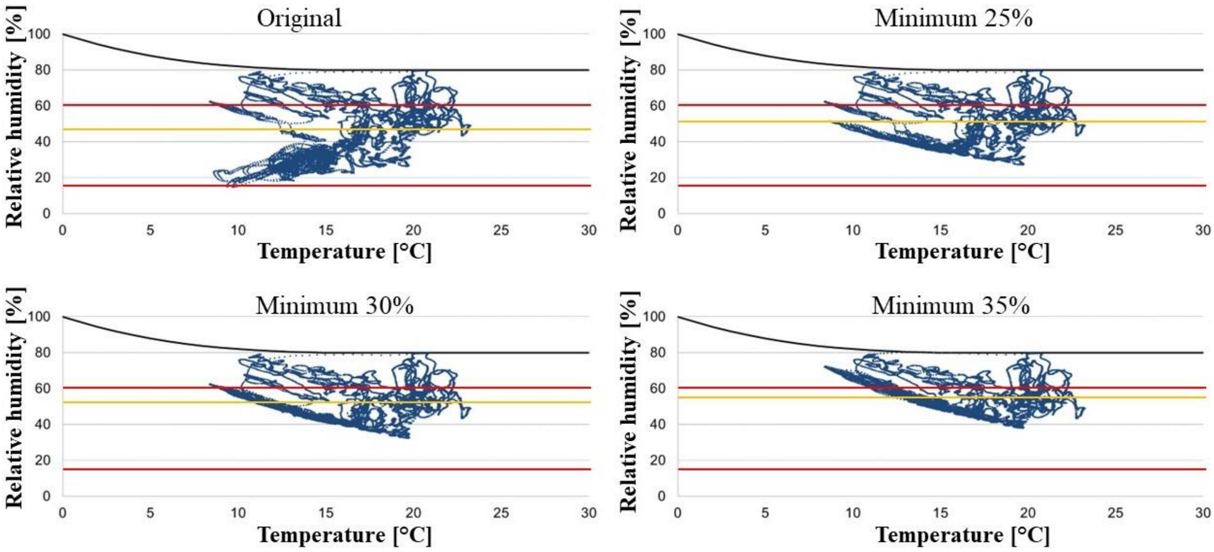

Figure 3. Hygrothermal conditions on inner surface of water vapour barrier (point 6a) with 1 hour time-step during 2 years period, where each dot expresses conditions at one time-step. Average density of conditions are indicated by yellow line.

Favourable conditions for mould growth were observed on the inner surface of the wind shield board at points 9 and 10 (Figure 4). However, none of the analyzed scenarios showed a mould index M value that indicated a risk for mould growth.

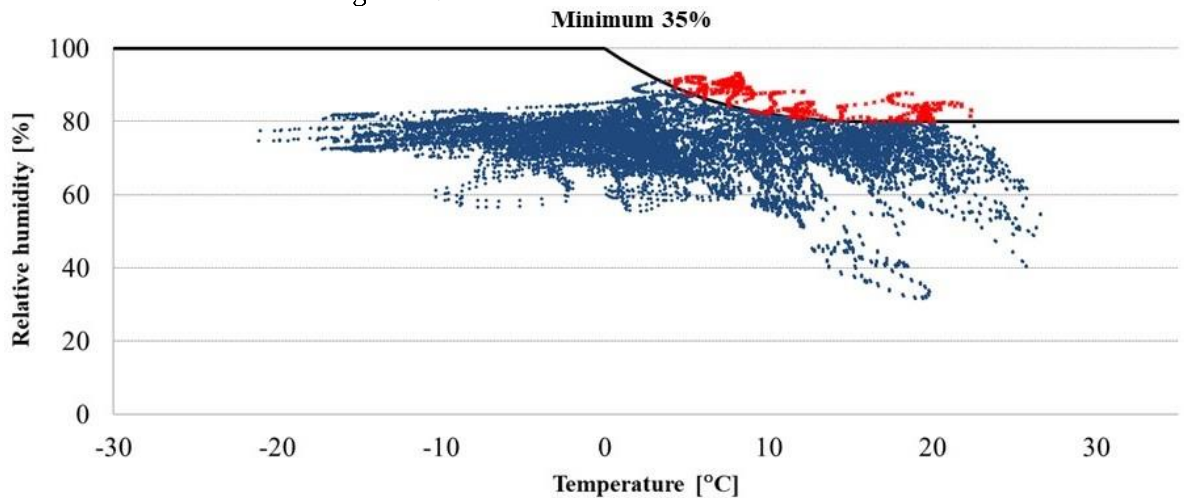

Figure 4. Hygrothermal conditions at point 9, where red dots indicate favourable conditions for mould growth.

In the range of 60-70% and 70-80%, the relative humidity (RH) on the inner surface of the water vapour barrier at point 6 increases by 25% and 6%, respectively, when the minimum indoor RH is set to 35% (Figure 5).

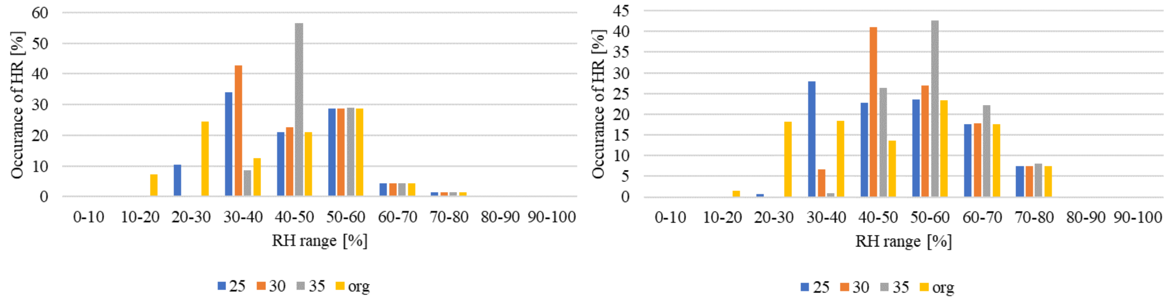

Figure 5. Distribution and change of relative humidity at point 5 (left) & 6 (right) over different indoor boundary conditions.

The impact of indoor air humidification is more significant in the low RH ranges, but it has a minor effect on the high (critical) RH ranges (80-100%) (Figure 6, x-axis represents the percentage of time). The highest risk for mould growth is found at point 9a, located at the outer corner of the wooden stud, windshield, and mineral wool. The conditions at this point exceed 80% RH 21% of the time. The mould index M on the outer surface of the wooden stud is 0.16 and 0.13 at points 9a and 11a, respectively (Figure 7). The maximum mould index value (0.01) is lower on the inner surface and inside the windshield board at points 10a and 12a, even though the hygrothermal conditions remain in the favourable area for mould growth longer than at points 9a and 11a. The reason for this is the material sensitivity, with wood being considered very sensitive (MSC1), whereas the windshield is medium resistant (MSC3). Therefore, increasing the minimum indoor relative humidity to 35% has no significant impact on mould growth risk inside the wall section (location a) (Figure 2). In the case where the minimum indoor RH was set to 35%, the RH increases by 25% and 6%, respectively, in the range of 60-70% and 70-80% on the inner surface of the water vapour barrier at point 6 (Figure 5).

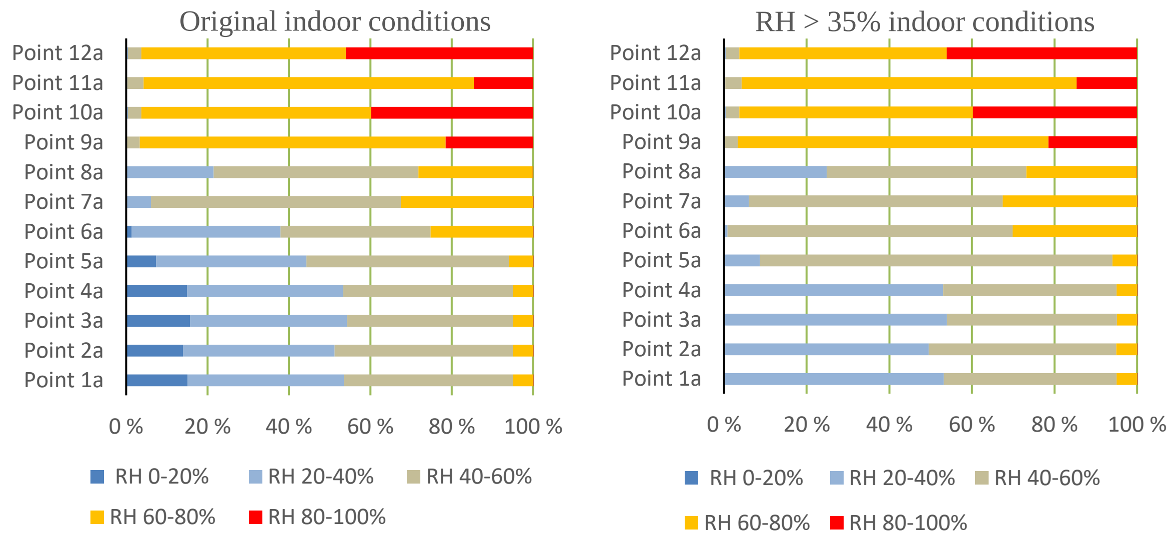

Figure 6. Relative humidity variation at each analysed point for original indoor conditions and conditions with a minimum of 35% RH.

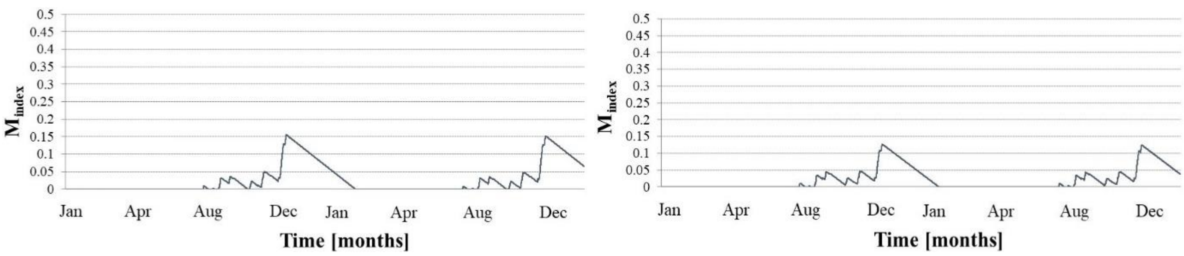

Figure 7. Point 9a and 11a mould index development during a 2-year simulation period.

The most favourable hygrothermal conditions for mould growth were found at the outer surface of the corner wooden stud, specifically at points 10b and 11b located in the corner of the building envelope. The conditions at these points were critical, with almost 60% of the time over 80% RH, which is above the threshold for mould growth (Figure 8). The maximum mould index values were obtained at these points, with M=0.32 and M=0.19 for points 10b and 11b, respectively. On the inner surface of the water vapour barrier in the same corner (point 7b), the mould index was M=0.30, which was caused by 32% of favourable conditions for mould growth during the analyzed period. However, increasing the indoor RH from 20% to 35% had no significant effect on the favourable conditions for mould growth in the range of humidity above 80%. Therefore, increasing indoor RH to a minimum of 35% by humidification appears to have no significant effect on the moisture safety and mould growth of the analyzed building envelope. Another option to increase indoor relative humidity without using humidification would be to decrease indoor temperature, which offers a feasible solution in terms of the hygrothermal functionality of the building envelope and energy savings. It must be noted that material properties play a key role in the hygrothermal performance of building elements. The presented study uses windshield gypsum board with cardboard surfaces. To improve the moisture safety of the building envelope, windshield gypsum board with fiberglass surfaces could be used, as it is more moisture resistant than gypsum board with cardboard surfaces [18].

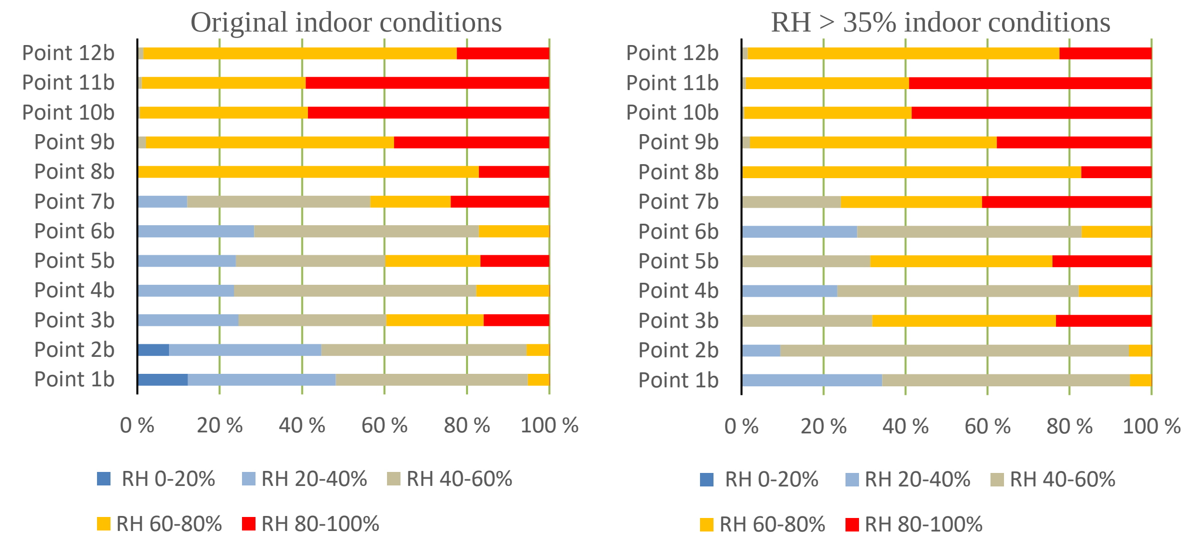

Figure 8. Relative humidity variation at each point for original indoor conditions and conditions with a minimum of RH 35 % in the corner of the envelope.

4. Conclusion

The day care facility located in Northern Ostrobothnia was monitored and found to have a significant period of time with relative humidity below 25%, negatively impacting indoor air quality and occupant comfort. This study examines the effect of increasing indoor relative humidity during the cold period to a minimum of 25%, 30%, and 35% on the hygrothermal conditions inside a timber-framed building envelope. Results indicate that increasing indoor relative humidity above 25% leads to an increase in humidity inside the envelope in the range below 70%. However, increasing the indoor relative humidity to a minimum of 35% does not appear to have a significant impact on moisture safety or microbial growth inside the building envelope.

Favourable hygrothermal conditions for mould growth were observed on the inner surface of the windshield board, but the conditions near the outdoor surface remained the same for all analyzed cases with varying indoor RH. The study suggests that it is safe to increase the relative humidity to 35% during the cold season, with an indoor temperature of 21°C, without increasing the risk of mould growth.

It should be noted that the presented study simulates an idealized construction without considering air leakage via any construction damages or deficiencies. Future research should examine the fault tolerance and resilience of different building design strategies considering future climate.

Acknowledgments

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