Validation of Hygrothermal Numerical Simulation with Experiment for Future Climate Control

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Abstract

Future climate is expected to be warmer, more humid, and cloudier with more frequent extreme weather conditions. Current building design should consider these changes as they can significantly influence the function of buildings in the future. Here, we study common building envelope assembly subjected to different climatic scenarios. An experiment was set up to validate a numerical model, which is further applied to assess hygrothermal performance (heat and moisture transfer) of the building envelope subjected to different boundary conditions. The assessment is provided via Finnish mould growth model that identifies risk of biological growth through dynamic hygrothermal conditions. Finnish meteorological institute provides data that predicts the climate in 2030, 2050 and 2100. The humidity inside the building envelope is assumed to increase slightly in time, however, increased temperature in the future may cause more favorable conditions for mould growth, especially, if mould sensitive building materials are used. The hygrothermal assessment of building structures with consideration of climate change in structural design is a key factor to provide sustainable building designs. Numerical model was successfully validated with experiments providing data within tolerances of measurement equipment.

Keywords: Numerical simulation, heat and moisture transfer, validation, experiment, climate change

1 Introduction

Building designs are going through a paradigm change in development of new high energy efficient structural systems and materials. High thermal resistance is usually achieved by applying thick layers of insulation, which may cause airtight conditions that slow down moisture diffusion and increase risk for microbial growth (e.g. Fedorik et al., 2015). Hygrothermal performance of building assemblies is currently more important than ever; around 45% of the Finnish national wealth resides in residential or public buildings (ROTI, 2021), which shows the importance of preventing future uncertainties with different methods (Hagentoft et al., 2020) to provide long healthy life cycle and functionality of building elements.

In the future, due to climate change, heating and cooling demand of the buildings will be decreased in Nordic countries by about 20% by 2061 but the moisture problems will be increased by the more humid outdoor climate conditions (Nik, 2012). Humidity has a significant impact on hygrothermal properties of building material, and hence on the hygrothermal performance of entire building envelope. Higher relative humidity increases thermal conductivity, which in turn causes reduction in building energy efficiency. Relative humidity above 80% (≥85% for non-sensitive material) at temperatures between 0 and 50°C may sustain microbial growth (Viitanen & Ojanen, 2007). These hygrothermal conditions may consequentially cause damage and/or deterioration of building material and reduce life span of buildings which in fact increases environmental impact over lifecycle (Marsh, 2017). Therefore, one of the key elements for sustainable building design in long-term is to provide suitable hygrothermal functionality of building assemblies, keeping in mind that today's buildings must also withstand the conditions of tomorrow, and the next 50 to 100 years, thus the ongoing climate change.

The climate is expected to be warmer, wetter, and cloudier with increasing extreme weather conditions (Jylhä *et al.*, 2009). Hence, climate change is transforming the future outdoor circumstances towards more unfavorable for the hygrothermal performance of conventional structures. Prolonged and higher relative humidity and temperature conditions can significantly affect the mould susceptibility of the structures, as these conditions are in a longer period at the favorable range for mould growth (Fedorik *et al.*, 2017; Fedorik *et al.*, 2018). In dry and cold conditions, moulds and other microbes do not usually grow. A previous study has shown that mould growth is mostly affected by the outdoor and

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indoor climate conditions than the position of the insulation layers (Kang *et al.*, 2016). This means that hygrothermal performance of structures is important to take into consideration in design of structures to manage future climate.

2 Aims

The aim of the study is to validate a numerical approach with experimental data in a case study of common structural wall-element assemblies. Experimental data is collected with temperature θ and relative humidity φ sensors at two points across element cross-section (Figure 1). The structural assembly is subjected to constant boundary conditions θ=10°C and φ=90% outdoor and θ=21°C and φ=30% of indoor air, respectively.

Validated numerical model is then subjected to future weather conditions following the work by Jokioinen (2004) to assess suitability of a presented structure to the current design approach. Predicted climate change data for 2030, 2050 and 2100 are applied to monitor and study the development of hygrothermal conditions inside the building envelope assembly at these forecasted future conditions (Vinha *et al.* 2013).

3 Methods and Materials

3.1 Structure and Experimental Work

The structure subjected to the study represents a common Finnish timber-frame building envelope consisting of gypsum board, wood fiber insulation board, vapor barrier, wood fiber insulation and windshield board (Figure 1). The experiment was performed for period of 18 days from which the temperature and relative humidity were measured every 10 minutes from within the wall element. Conditions were monitored at 2 points in the direction of heat and mass transfer: at the interface of windshield and thick wool insulation and another at interface of air barrier and inner wool insulation (Figure 1). The experiment setup built inside Memmert climate cabin (CTC256 model) was used to develop the outside conditions that were then used to validate the simulated one-dimensional heat and moisture transfer model.

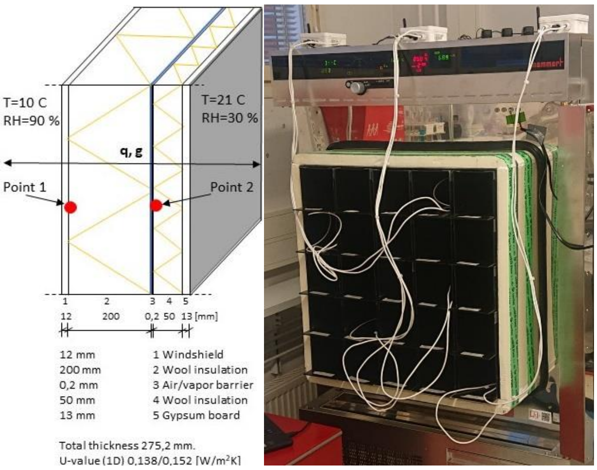

Figure 1. Illustration of building envelope assembly, validation points and laboratory measurement setup.

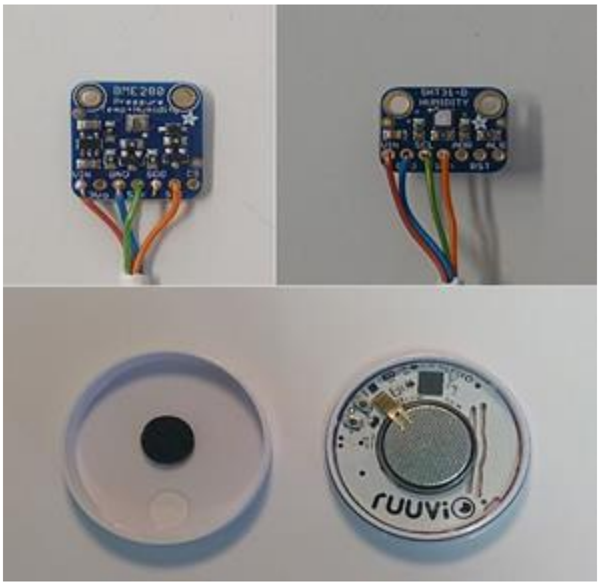

Figure 2. Different types of data collection sensors.

Climate cabin's interior and exterior temperature, relative humidity and barometric pressure were monitored by using Bosch BME280 sensors (top left, Figure 2). This sensor design provides accuracy for temperature ± 1.0°C, relative humidity ± 3% and pressure ± 1hPa. Commercial cased version of the BME280 by Ruuvi Ltd (Figure 2) was used for CTC256 interior measurements because the outside conditions simulated by the cabin were challenging to uncased version. Data collection from the inside of the wall structures was carried out by utilizing the SHT31-D sensors that monitor temperature and relative humidity within tolerances of ± 0.3°C, ± 2%, respectively (top right, Figure 2).

3.2 Future Climate

Finnish Meteorological Institute's building physical test year by Jokioinen (2004) and the future scenarios (for 2030, 2050, 2100) were applied to the structure to investigate its hygrothermal performance and possible mould growth at the cross-sectional validation points (Figure 1). The future test years are based on a rather pessimistic SRES A2 -climate change scenario for southern Finland. In this scenario, the assumption is that greenhouse gas emissions would continue to rise throughout this century.

3.3 Numerical Approach

Numerical simulations were performed using Comsol Multiphysics simulation software. The model represents dynamic one-dimensional simultaneous heat and mass transfer that is suitable for analysis in hygroscopic range (φ<95%) (Dong *et al.*, 2020). The validation of numerical model was performed for a period of 18 two with a 10-minute time-steps between measurements. Surface convective coefficients were considered the same on both sides of the building assembly, as the outdoor and indoor conditions during the experiment correspond to indoor convective conditions. Hence, surface heat transfer coefficient was h=1/0.13 [W/(m^2·K)] and moisture transfer coefficient is $\beta_p = 2.45\cdot10^{-8}$ [s/m]. The initial conditions correspond to the initial conditions of the experiment set up.

Simulations applying the current and three future test years were performed for 2-years with 1 hour time step. The initial temperature and relative humidity were considered 21℃ and 30%, respectively. The outdoor and indoor surface heat resistances correspond to standard recommendation, where exterior thermal resistance is R_{se}=0.04 [(m^2·K)/W] and indoor R_{si}=0.13 [(m^2·K)/W]. The moisture surface coefficients were set to $\beta_i=2.45\cdot10^{-8}$ [s/m] and $\beta_e=1.3\cdot10^{-7}$ [s/m].

Indoor boundary conditions were derived according to Finnish national guideline (RIL 107-2012, 2012) that determines indoor moisture excess more suitable for Finnish weather conditions than ISO 13788:2012 (Vinha *et al.*, 2018). The first-year calculation was performed to eliminate the effect of initial conditions on results. Therefore, the hygrothermal conditions were assessed for the second year of the numerical simulation only.

3.4 Materials Tested

Each layer of a building envelope assembly plays a significant role in the overall hygrothermal performance of a building. The material properties needed for hygrothermal simulation are thermal conductivity λ [W/(m·K)], heat capacity C_p [J/(kg·K)], density ρ [kg/m^3], moisture isotherm w [kg/m^3], liquid transport coefficient D_w [m^2/s] and water vapor resistance factor μ [-]. The individual material properties were obtained from manufacturers, some measured and remaining were taken from literature (Table 1). Density ρ, heat capacity C_p and water vapor resistance factor μ are considered constant for each material. Thermal conductivity, moisture isotherm and liquid transport coefficient vary depending on conditions; where thermal conductivity λ and liquid transport coefficient D_w depend on water content w and moisture isotherm is described by water content w in relation to relative humidity φ.

Table 1. Material properties applied in numerical hygrothermal simulation.

Material	***λ (w)***	***ρ***	***C_p***	***w (φ)***	***D_w (w)***	***μ***
Gypsum board	0.19-0.6	820	1100	0-23.8	0-4.85·10^{-7}	10
Wood fiber insulation board	0.0485-0.6	37	2100	0-15.2	0- 4.85·10^{-9}	1.6
Vapor barrier	0.33	980	1500	0	0	3500
Wood fiber insulation	0.04	60	2100	0-15.2	0-1.07·10^{-7}	1.5
Wind-shield	0.049	235	1500	0-71.3	0-4.85·10^{-9}	13

3.5 Finnish Mould Growth Model

Finnish Mould Growth Model was applied to assess the suitability of building design against biological growth (Viitanen & Ojanen, 2007). It represents a suitable tool for the assessment of different design strategies whether mould growth appears on or inside building components based on dynamic hygrothermal conditions (Lie *et al.*, 2019; Fedorik *et al.*, 2015). The Finnish mould growth model achieves good agreement between the predicted and observed mould growth (Jensen, 2019) and represents the basis for international building standard ASHRAE 160 p (ASHRAE, 2016).

With the Finnish mould growth model, mould growth can be predicted on different building materials in changing hygrothermal conditions. The mould growth risk in the model is presented with a mould index M, which varies between 0-6 and describes amount of the mould appearance on a material surface. Temperature and relative humidity both affect the mould growth rate, and value of mould index M. The model also considers mould decline when hygrothermal conditions are not in favorable area for mould growth. Favorable area for mould growth is defined at a temperature range between 0-50 °C and relative humidity over 80% for sensitive and very sensitive materials and 85% for medium resistant and resistant materials (Ojanen *et al.*, 2010). Hence, the Finnish mould growth model classifies materials for four sensitivity and four decline groups according to their associated factors (surface type, coating and contact with other materials) (Viitanen & Ojanen, 2007; Vinha *et al.*, 2013).

4 Results

4.1 Validation of Numerical Simulation

The experiment provides hygrothermal data to validate the numerical model (Figures 3 and 4), which can be further applied for future prediction and risk management tools. The numerical results agreed well with the measurement and the calculated hygrothermal conditions are within accuracy (±0.3°C for temperature and ±2.0% for relative humidity) of the measurement system (Figure 3 and 4). The small-scale variation occurring in the experimental setup is not present in the calculated moisture content or temperature.

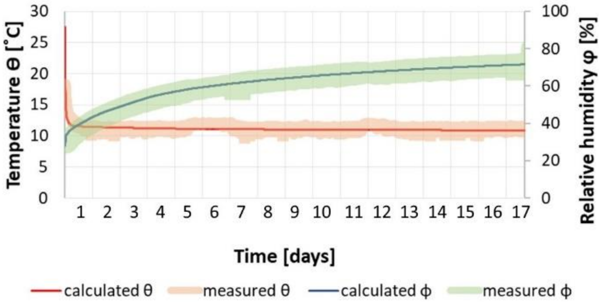

Figure 3. Experimental (expressed with accuracy limits) and simulated temperature and relative humidity at structural analysis point 1.

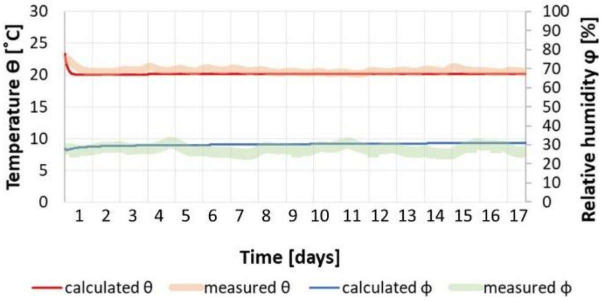

Figure 4. Experimental (expressed with accuracy limits) and simulated temperature and relative humidity at structural analysis point 2.

4.2 Hygrothermal Performance Under Current Building Design Approach

In the simulated climate the temperature is the highest and relative humidity is the lowest in summer. Vice versa in the wintertime temperature has the lowest values and relative humidity has the highest values. However, despite high relative humidity values in wintertime, there was no risk for mould growth because temperature was not continuously in favorable area (0-50°C) for mould growth (Viitanen & Ojanen, 2007). The fluctuation of the temperature and relative humidity at point 1 is greater than at point 2 due to its location closer to the outdoor conditions that change in time. The relative humidity in the wintertime varies from 80% to 90% (Figure 5) at point 1, and is fairly constant at around 40% at the point 2 (Figure 6). The temperature and relative humidity at the point 2 in summertime vary between 15°C and 22°C and 30% and 45%, respectively, and these hygrothermal conditions can be considered unsuitable for biological growth (Figure 6).

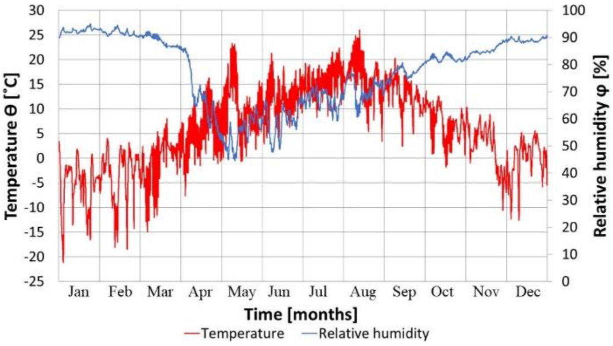

Figure 5. Temperature θ and relative humidity φ at point 1 applying test year data Jokioinen 2004.

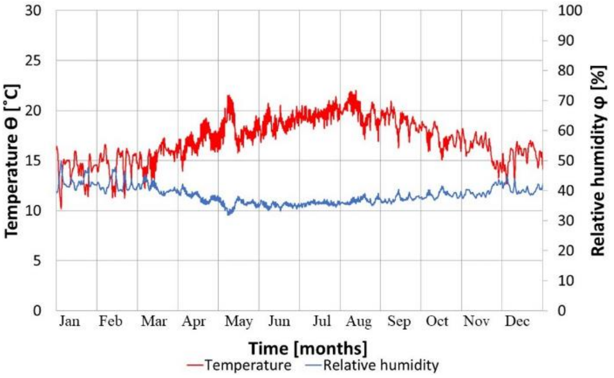

Figure 6. Temperature θ and relative humidity φ at point 2 applying test year data Jokioinen 2004.

Only 2004 results are shown because graphs of temperature and relative humidity were similar in all climate scenarios without any significant differences.

4.3 Hygrothermal Performance Under Different Future Climatic Scenarios

The progress of temperature and relative humidity during one year inside the building envelope (points 1 and 2) subjected to the future scenarios (Jokioinen 2030, 2050 and 2100) are very similar to Jokioinen 2004 test year. The mean annual temperature increases by 1.14°C in 2030, 2.02°C in 2050 and 4.85°C in 2100 in comparison to test year Jokioinen 2004. The relative humidity assumes slight decrease in 2030 by 0.04% but increase in 2050 and in 2100 by 0.25% and 1.12% respectively (Figure 7). Consequently, the annual temperature increases between windshield and wool insulation (point 1) by 1.05°C in 2030, 1.88°C in 2050 and 4.54°C in 2100 scenarios. However, the impact of increasing temperature outdoors in the future is smaller on the interior surface of the water vapour barrier (point 2) where the thermal conditions are estimated to be increased by 0.27°C in 2030, 0.49°C in 2050 and 1.19°C in 2100 (Figure 7).

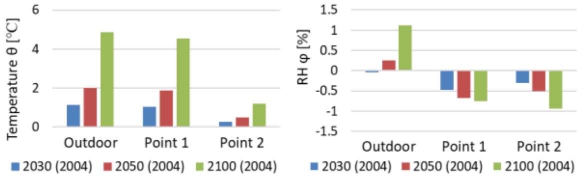

Figure 7. Annual temperature and relative humidity increment for future climate in relation to test year Jokioinen 2004.

The temperature at point 1 with Jokioinen 2100 test year is slightly higher than 2004 test year in the simulated year. The temperature difference between 2004 and 2100 year is almost 3.4°C in mid-April and 4.5°C in mid-October (Figure 8). Between the years in mid-April the temperature increases from 21.9°C to 25.2°C and relative humidity decreases from 46.4% to 46.3% (Figure 8) which means that absolute humidity increases by 1.86 [g/m^3]. Then, dew point increases from 9.7°C to 12.8°C. This reflects the assumption that the outdoor climate will be warmer and more humid in the future.

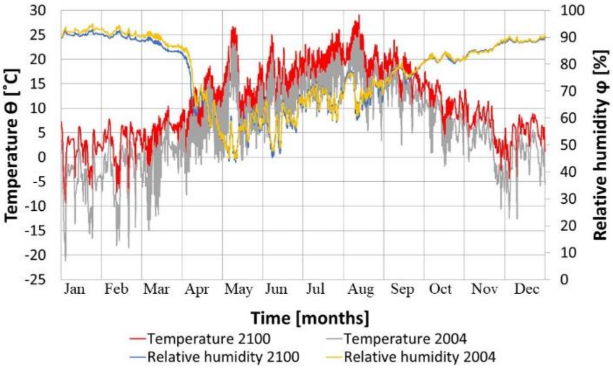

Figure 8. Temperature and relative humidity at structural analysis point 1 for test year Jokioinen 2004 and Jokioinen 2100.

To visually compare all studied (Jokioinen 2004, 2030, 2050 and 2100) scenarios, moving averages of two hundred hours were applied (Figures 9 and 10). Progressive increment in temperature is apparent, especially at structural analysis point 1 (Figure 9), from which the effect of climate change decreases in the wall element from outer wall towards indoors (Figure 10). Therefore, the impact of different climatic scenarios on hygrothermal conditions inside building envelope decreases with the depth of the structure.

The differences in humidity at structural analysis point 1 and 2 referenced to Jokioinen 2004 test year vary between -11% and 2%, with average -0.8% at point 1 and -5% and 1% with average -0.9% at point 2 in 2100, -7% and 1% with average -0.7% at point 1 and -3% and 1% with average -0.5% at point 2 in 2050 and -4% and 1% with average -0.5% at point 1 and -2% and 1% with average -0.3% at point 2 in 2030 (Figure 9 and 10). However, there were no significant differences between relative humidity in longer term cycles.

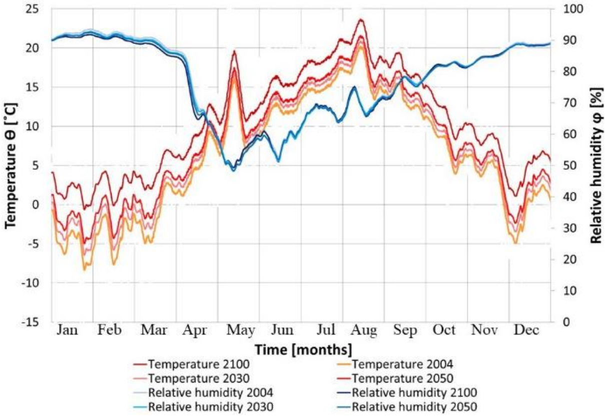

Figure 9. Temperature and relative humidity presented as moving average of two hundred hours at the structural analysis point 1.

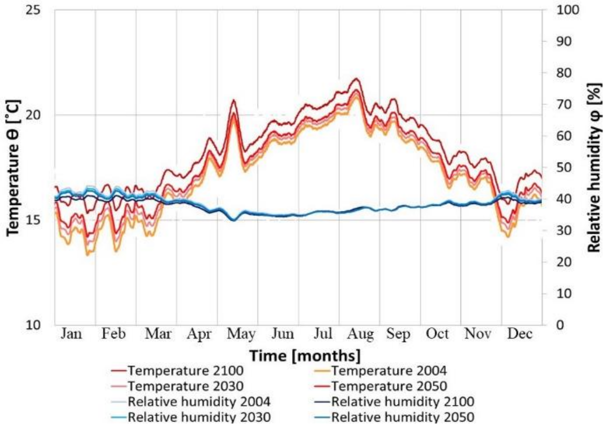

Figure 10. Temperature and relative humidity presented as moving average of two hundred hours at the structural analysis point 2.

4.4 Mould Growth Risk

The temperature and relative humidity data obtained on indoor surfaces of windshield (point 1) and water vapour barrier (point 2) do not show risk for mould growth. At structural analysis point 2, the hygrothermal conditions were unfavorable for mould growth during the entire analyzed period in all climatic scenarios. The reason is relative humidity that varies between 30% and 45%, hence does not exceed critical value of 80%. Hence, the mold index for this area would be 0.

Favorable hygrothermal conditions were obtained only at structural analysis point 1 located between windshield and wood fiber insulation. The wood fiber is mould sensitive material classified in the Finnish mould growth model by class 2. The mould index illustrates the highest risk of mould growth initiation in the case of Jokioinen 2100 test year where the relative humidity was over 80% for 26.5 weeks during a year. The relative humidity exceeding 80% was achieved especially in wintertime, in which the temperature drops under 0°C, representing unfavorable conditions for biological growth.

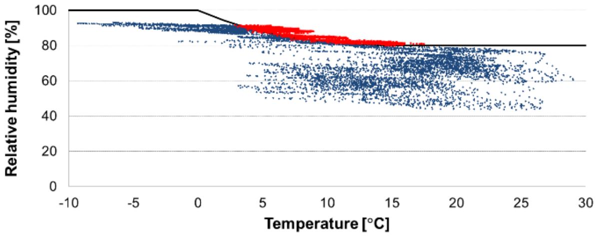

Figure 11. Temperature and relative humidity calculated at each time-step during year using Jokioinen 2100 outdoor conditions (red dots indicate favorable and blue dots unfavorable conditions for mould growth).

However, in all analyzed cases the maximum mould index achieved is below 1 (Table 2) leading to an assumption that the studied assembly following current manufacturer specified wall structure could be considered suitable also for future climate.

Table 2. Maximum mould index achieved at point 1 in different climatic scenarios: Jokioinen 2004, 2030, 2050 and 2100.

Simulated year	*Point 1*
Jokioinen 2004	0.002
Jokioinen 2030	0.009
Jokioinen 2050	0.022
Jokioinen 2100	0.117

5 Conclusions and Future Development

Numerical hygrothermal simulation agrees with measured data in the case of wood fibred insulated wall assembly. Calculated temperature and relative humidity data at analyzed points were within tolerances of measurement equipment.

There is a significant difference between temperatures in 2004 and 2100. Relative humidity is at similar level, which means that the absolute humidity levels and dew points inside the wall structures increase significantly. However, according to the Finnish mould growth model, risk for mould growth remains very low at analyzed points. Validation and future test years models converged with good accuracy and without numerical errors which supports the accuracy of the results.

Study shows that the impact of different climatic scenarios on hygrothermal conditions inside building envelope decrease with depth of the insulated structure. Validated numerical model can be applied for future performance assessment and risk management for healthy long life cycle buildings.

The future work consists of improving dynamic experimental validation and building elements exposed to real conditions.

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