Numerical models for long-term performance assessment of lightweight insulating assemblies

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Abstract. This paper presents the results of numerical modelling of hygrothermal processes in test buildings situated in the Botanical garden of the University of Latvia. Long-term performance of wall, floor and ceiling insulating assemblies for five different buildings was simulated using WUFI Pro 6.3. On the experimental side, measurements of temperature and relative humidity at key points of assemblies have been accumulated over a period of roughly six years and material samples were taken from building envelope materials for biological analysis. We found that our models rather successfully reproduce the experientially observed temperature and relative humidity dynamics. In the process, we established material models for building envelope components, as well as different parameters that we previously unknown. We also compared mould growth risk predictions via the Sedlbauer critical curve model derived from both simulations and experiment against the results of lab tests conducted on materials samples - all three were found to be in good agreement, indicating that the Sedlbauer model is applicable to local climate conditions, as well as further validating numerical models.

1. Introduction

In light of increasingly stricter standards imposed on architects in terms of building performance such as indoor comfort and energy efficiency for new buildings, with energy reduction deadlines for existing ones due year 2020 [1, 2], as well as the ever present risks of mould growth [3, 4], condensation within wall, ceiling or floor insulation envelopes [3, 4] and degradation of materials [3, 5, 6], it is important to take care when designing with long-term exploitation and sustainability in mind. Water damage of building materials typically results in swelling, increased mould growth risk, altered material properties, such as thermal conductivity [3, 7]. Mould growth is detrimental in that it degrades building materials, altering their properties, inducing rot and decay in wood (but not exclusively), and rendering them non-functional and/or unreliable [3, 5, 6, 8, 9]. In addition, by-products of micro-organism population growth within building insulating and structural elements, as well as the micro-organisms themselves, are transported to building interior spaces (via liquid and vapour fluxes within materials, and air flow within ventilation systems and rooms) [3, 10], wherein they can exhibit harmful effects on inhabitants, such as allergic reaction, pronounced respiratory symptoms, intensified asthma, weakened immune system, etc. [11–13].

This and the great cost of potential mistakes [3] motivates numerical modelling, which allows one to assess the performance of designed solutions in silico, a risk-free environment. However, given that all of the above is dependent on generally complex temperature and relative humidity...
(RH) dynamics within a building and that numerical models require many input parameters and dependencies, not all of which are known a priori or with sufficient precision, one cannot rely exclusively on simulations. Sometimes using even seemingly slightly different parameters for simulations can lead to poor design choices which can have many serious consequences, should erroneous designs be implemented [14]. This is why long-term building monitoring projects and test sites have been commissioned, for instance, in Finland [15], Spain [16] and Estonia [17].

In Latvia, roughly six years ago five experimental buildings with different insulating envelopes were constructed at a test site located in Riga, in the Botanical garden of the University of Latvia. Each building was equipped with an array of temperature, RH, heat flux and air velocity sensors connected to a data logging system [18, 19]. One of the objectives was to establish which of the different assemblies present on site are better suited for Latvian climate, with its characteristic high RH levels, especially during winter with routinely occurring RH extrema of up to 0.9. While it is now clear which solutions are more optimal for local conditions, the large amount of data on temperature and RH dynamics within buildings and data from the meteorological station (located on site) regarding exterior climate conditions, all accumulated over a period of > 5 years, enables one to go further and use the experiment to verify numerical models. Moreover, samples of materials from different places within building envelopes were taken and analysed to study the degree of biological contamination by micro-organisms. Given that sensors are prone to occasional errors, the data from sensors, biological lab tests and simulations would complement one another to provide a clearer physical picture of how different materials and combinations thereof function under real operational conditions. This is important since, despite much effort from the local project team over the years, [20–24] and others, many aspects concerning actual initial conditions within buildings and their hygrothermal properties, and thus also long-term behaviour, are still unclear.

The objective of the present study is to first establish numerical models using WUFI Pro 6.3 and compare their output to data from temperature and RH sensors. Then, mould growth risk predictions are derived from both experimental data and simulation results, and both are compared to lab test results. This way, we verify both our material models (either custom or taken from a certified database), interior climate models and the applicability of the standard Sedlbauer mould growth risk model to local climate [25, 26].

2. The experiment

2.1. Test buildings

The test site houses five buildings, codenamed AER, CER, EXP, LOG and PLY, which stand for different materials used as insulators for wall envelopes. All five variations have identical roof and floor assemblies. Material layer order and thickness values are given in this section, below. A general overview of a test building (shapes are identical) is shown in Figure 1a. Detailed specifications for each building and sensor placement within are given in [27]. For our analysis, only certain temperature and RH sensors were of interest - these are indicated in Figure 2 for wall envelopes, and designated as "FLOOR" and "CEILING" in floor and ceiling assemblies, respectively (Figure 1a). These material layer and sensor arrangements are later translated to numerical models. Material parameters that were known due to our own studies are provided in [27], but some are also provided in section 4 with hygrothermal curves and coefficients that were available in databases (Fraunhofer-IBP, MASEA, University of Technology Vienna) and those deduced over the course of this study (those not showcased are available on-demand).
Figure 1. A layout of the sensor network within a test building (a), where black dots correspond to sensor locations, and typical air flow velocity readings from a sensor in the air gap in PLY (b), where black dots are 1-hour average measured air velocities and the red curve is a 1% length moving average of the dataset. Three types of sensors are installed: air velocity (interior, air gap, attic and outdoors), temperature and RH (at all indicated positions). In (a), "ROOM" represents sensors located within building interior, "LOFT" is the attic sensor, "AIR.FAC" is the flow velocity sensor within the air gap of the wall envelope, "WALL" and "FLOOR" are sensors embedded into walls and floor, respectively.

Figure 2. The five wall insulating assemblies with marked sensor locations (black dots). Here "-" indicates the outdoor side and "+" represents the indoor side of an assembly. "T" stands for temperature sensor, "H" is humidity sensor. "WOOL" means that the sensor is embedded into a soft material, and "CONSTR" are sensors place into hard structural materials.

All 5 wall envelopes have the following first three outer layers: Spruce 40 mm, → Plywood 6.5 mm, → Air gap, 30 mm. Inner layer structure, exterior to interior, is as follows:

- **AER**: Stone wool, 30 mm → Stone wool, 50 mm → Lime-cement plaster, 15 mm → Aerated concrete, 375 mm → Lime-cement plaster, 15 mm
- **CER**: Weather protection board, 3 mm → Stone wool, 120 mm → Lime-cement plaster, 15 mm → Perforated ceramic blocks, 440 mm → Lime-cement plaster, 15 mm
• **EXP**: Lime-cement plaster, 15 mm → Filled ceramic blocks, 510 mm → Lime-cement plaster, 15 mm
• **LOG**: Spruce, 200 mm → Stone wool, 200 mm → Vapour barrier, < 1 mm → Spruce, 40 mm
• **PLY**: Plywood, 20 mm → Stone wool, 200 mm → Plywood, 20 mm → Fibrolite, 75 mm → Cement plaster, 20 mm

Ceiling and floor assemblies have the following layouts:

• **Ceiling**: Plywood, 12 mm → Wood wool, 200 mm → Plywood, 4 mm → Stone wool, 50 mm → Vapour barrier, < 1 mm → Plywood, 6.5 mm
• **Floor**: Plywood, 21 mm → Vapour barrier, < 1 mm → Stone wool, 200 mm → Plywood, 21 mm → Stone wool, 50 mm → Vapour barrier, < 1 mm → Plywood, 21 mm

2.2. Processing of experimental datasets

Monitoring both buildings and weather conditions at the test site from April 3, 2013 to April 1, 2019 yielded the following data:

- Outdoor temperature, RH, wind direction and speed, solar radiation intensity
- Temperature and RH values from sensors within test building (see Figures 1a and 2) and air flow velocity in wall air gap (Figure 1b)
- At the 5 year mark, building envelopes were opened and samples from key locations (including sensors) were taken to the lab for micro-organism content assessment

Data for outdoor climate was used both for interpretation of experimental results and as input for numerical simulations. In both cases outliers were removed and the remaining values were binned into 1-hour intervals, since characteristic time scales in building physics for these kinds of experiments are days/months/years. Also, in the case of model input, each hour was taken to be the average of the corresponding hours of the five separate yearly cycles, yielding a single year-long interval. This interval was then periodically extrapolated over the entire calculation period. The rationale is that no long term trends other than yearly cycles were present in gathered data, and such simplified representation of outdoor conditions allows one to observe the general behaviour of studied systems more clearly, which makes sense given the many unknown parameters.

Since *WUFI Pro 6.3* is only applicable to parts of assemblies with symmetries that admit 1D models, only data from sensors shown in Figure 2 and wall/floor sensors was used. After removing outliers, temperature and RH time series from these sensors were de-noised using a low-pass frequency filter with a threshold equal to the inverse of the 0.5 % of time series length, which is roughly 10 days.

3. Numerical simulations

The assemblies described in Figures 1 and 2 and in section 2.1 were simulated in *WUFI Pro 6.3*, a finite volume method (FVM) package that solves coupled heat and moisture transport equations under standard building physics assumptions [28]:

\[
\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \left( \lambda \nabla T + \frac{h_v \delta}{\mu} \nabla (\phi_p) \right) ; \quad T = T(\vec{r}, t);
\]

\[
\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \left( D_\phi \nabla \phi + \frac{\delta}{\mu} \nabla (\phi_p) \right) ; \quad \phi = \phi(\vec{r}, t);
\]
where \( T \) is temperature, \( \phi \) is RH, \( \lambda = \lambda(T, \phi) \), \( \delta = \delta(T, \phi) \) and \( p_s = p_s(T) \) are thermal conductivity, vapour diffusivity and vapour saturation pressure, respectively, \( \mu \) is relative vapour diffusion resistance, \( w(\phi) \) is water content density (given by the moisture storage function), \( D_\phi = D_\phi(T, \phi) \) is water diffusivity and \( H(T) \) is enthalpy. The left hand side of Equation (1) includes temperature dependent liquid-ice transition enthalpy and water/ice enthalpy flow, while vapour enthalpy flow is given by the second term on the right hand side of Equation (1). This and other constitutive relations for Equations (1) and (2) are given in [28].

Outdoor and indoor climate are prescribed by Robin boundary conditions for \( T \) and \( \phi \) on the exterior and interior assembly surfaces:

\[ \nabla T \cdot \vec{n} + h_t(T - T_0) = q(t) \]  

\[ \nabla (\phi p_s) \cdot \vec{n} + \beta_v (\phi p_s - (\phi p_s)_0) = 0 \]  

where \( T_0 \) and \( (\phi p_s)_0 \) are exterior/interior temperature and water vapour pressure, respectively, \( \vec{n} \) is the surface normal, \( h_t \) is heat transfer coefficient and \( \beta_v \) is moisture transfer coefficient (related to \( h_v \) via the Chilton–Colburn analogy). Exterior \( T_0 \) and \( \phi_0 \) are given by the processed time series from the meteorological station, while interior conditions are given by ISO 13788 or EN 15026/DIN 4108/WTA 6-2 standards (herefrom referred to as simply ISO or EN) with variable mean temperature and RH class (moisture load) - the reason is that it is not yet entirely clear to what extent sensor data from within test building rooms are trustworthy and representative of actual inner surface conditions. No records of precipitation dynamics were available, so rain and snow were not accounted for. Solar radiation is accounted for by a heat source \( q(t) \) added to Equation (3) at the outer boundary (\( q(t) = 0 \) at the inner boundary) and a set of transfer coefficients. Initial conditions for simulations were defined based on sensor measurements and construction/maintenance logs. Cloud index is unknown, so a standard coefficient suggested by WUFI for atmospheric counter-radiation is used. All of the above parameters and functions must be defined with care, since Equations (1) and (2) are highly non-linear. Establishing the unknowns among these is one of the primary concerns of this study. Note that in some cases initial conditions RH, to which Equations (1)-(4) are sensitive, were known only up to an interval.

Equations (1) and (2) were solved in a 1D approximation. Regarding the air gap in wall assemblies (Figure 1a and 2) and attic spaces (Figure 1a), data from a velocity sensor relocated into the PLY assembly air gap (Figure 1b) allowed to perform dimensional analysis and estimate the degree of ventilation. It was found that Grashof \( (Gr) \), Rayleigh \( (Ra) \), Reynolds \( (Re) \) and Richardson \( (Ri) \) numbers are \( Gr \in [10^8; 10^{10}] \), \( Ra \in [10^8; 10^{10}] \), \( Re \in [10^3; 10^4] \), \( Ri \in [0.1; 24] \) and on average \( Ri < 1 \), implying that highly turbulent forced convection dominates within the gap, homogenising air temperature and leading to temperature and RH that should be close to exterior conditions. Since the attic is ventilated and connected to the air gap in each building, we infer that the topmost layer of ceiling assemblies is also exposed to near-outdoor conditions. This allows one to eliminate the outer weather protection layer from numerical models of wall assemblies and ceiling envelope (and thus set \( q(t) = 0 \) in Equation (3)), provided that an appropriate effective heat transfer coefficient is specified. The floor insulation assembly is essentially an inverted roof (Figure 1a) and is directly exposed to outdoor air. The air gap below is sufficiently wide to disregard grass (periodically trimmed) and shading nullifies the effect of solar radiation. Thus, floor outer boundary is treated as an external wall with \( h_t = 0.0588 \, W/(m^2 \cdot K) \), while external boundaries of other assemblies are treated as interior walls and are assigned \( h_t = 0.125 \, W/(m^2 \cdot K) \).

Optimized numerical mesh consists of 750 cells over the assembly length with refinement at material and model boundaries (expansion factor 1.05). Time stepping is adaptive, with a...
maximum step of 1 \( h \) (exterior climate time step) and recursive refinement of up to 20x, each refinement level splitting the current time step level into 10 smaller steps, until step convergence is achieved.

4. Results and analysis

Sensor data and simulation results (temperature and RH time series from April 3, 2013 to April 1, 2019) were processed and compared. Virtual sensors were placed in WUFI Pro 6.3 models in corresponding locations (1a and 1b) and output was processed in the same way as experimental values. Here, several representative results are be shown.

Starting with the ceiling envelope, one can see the results of WUFI modelling versus the experiment in Figure 3: Figures 3a and 3c, clearly show that temperature curves align nearly ideally for LOG, but there are considerable discrepancies in case of PLY starting with roughly the second half of 2018 (dashed red lines in Figures 3b and 3d).

![Figure 3](image_url)

**Figure 3.** Experimental (light blue) and numerical (yellow) results for the ceiling envelope for temperature (a,c) and RH (b,d) dynamics over the entire monitoring period at the outer stone wool sensor location. Figures (a,b) correspond to LOG, data for PLY is shown in (c,d). Note the "flatlined" areas encircled with dashed red lines (a,b) - there, sensors have temporarily malfunctioned, resulting in data loss. Similarly, in (d) a RH sensor initially indicated unrealistic dynamics, so starting RH was chosen based on the further interval of the curve. For precise sensor locations, please refer to Figure 1.

Figures 3b and 3d indicate very good agreement for RH dynamics for PLY, but there is a considerable and systematic overshoot in case of LOG. Also note that radically different RH curves are predicted for PLY, again, from around the second half of 2018.

Interestingly, inspecting maintenance logs reveals that strong deviations in Figures 3c and 3d correspond to a prolonged series of conditioning system and phase change material (PCM) tests that lasted throughout the remainder of the time interval in question. The reason for RH deviations in LOG are not presently obvious. The established (or current best) initial and interior conditions for LOG and PLY are, respectively: \( \varphi_0 = 0.5 \) globally and the EN interior climate conditions.
with a high moisture load (HML): $\phi_0 = 0.9$ within the wood chip wool, $\phi_0 = 0.6$ elsewhere and EN-HML interior climate. In this and other cases, we are willing to share the established material and climate models and initial conditions on demand (corresponding author). For AER, CER and EXP, ceiling temperature sensors indicate excellent agreement with WUFI, but RH sensor data is, unfortunately, ripe with artefacts, which preclude analysis.

Temperature and RH dynamics for the PLY wall assembly are shown in Figure 4 - note the very good temperature curve fit. However, RH time series exhibit overshoots during winter and a deviation near the beginning. Although in Figure 4b initial conditions may look different, here $\phi_0 = 0.9$ was indeed set for stone wool and $\phi_0 = 0.6$ elsewhere, as per sensor data, but these initial values were removed during automatic data filtering. The EN-HML interior climate model was used.

![Figure 4. Temperature (a) and RH (b) dynamics for the PLY wall assembly at the stone wool sensor location.](image)

Results obtained for the AER assembly wall are presented in Figure 5, wherein Figures 5a

![Figure 5. Temperature (a,c) and RH (b,d) dynamics for the AER wall assembly at the stone wool (a,b) and aerated concrete (c,d) sensor location.](image)
and 5b represent temperature and RH dynamics at the stone wool sensor, while 5c and 5d correspond to the sensor within the concrete slab. Concrete and wood are some of the more challenging materials to model in WUFI, often exhibiting hysteresis in sorption curves. Given that WUFI provides no means of accounting for this, it is pleasantly surprising that, as seen in Figures 5b and 5d, the general trends are captured successfully. While the undershoot seen in 5b could be explained by a higher true initial RH value, it is not yet clear why there is a delay in drying seen in 5d. The likely explanation is that the sorption curve is incorrect within the high RH interval. The interior climate also very strongly affects drying. The initial conditions established thus far are $\phi_0 = 0.95$ for aerated concrete and $\phi_0 = 0.5$ elsewhere. Again, the EN-HML interior climate seems to best fit the experimentally observed dynamics.

Figure 6 displays the comparison between mould growth risk assessment derived from sensor readings (Figure 6a) and predicted by WUFI (Figure 6b) for the PLY wall at the location of the sensor placed within the stone wool layer. Note the very similar pattern in both cases. Both experimental and simulation data suggest moderate risk for biodegradable materials such as wood wool and minor risk for more resilient materials, such as the stone wool in question, with very little organic content.

![Figure 6](image-url)

**Figure 6.** Mould growth risk assessment from April 3, 2013 to April 1, 2019 for the PLY wall at the location of the sensor placed within the stone wool layer. Temperature and RH pair (event) density is color coded and normalized to maximum (see the color bar to the right). White contours are event density isolines. LIM (lowest isopleth for mould) curves are due to the standard Sedlbauer mould growth risk model. Higher density above the LIM curves implies greater risk of mould growth.

A very important point is that this correlates with both visual inspection (no mould was detected) and lab tests conducted for samples taken from the stone wool surface. The latter revealed that micro-organisms concentrations of $13400 \pm 3454 \text{ CFU} \cdot \text{g}^{-1}$ (colony forming units per unit sample mass). Compared to $\sim 50 \text{ CFU} \cdot \text{g}^{-1}$ for visually clean surfaces and $\sim 55000 \text{ CFU} \cdot \text{g}^{-1}$ for mould covered surfaces, this suggests that mould growth risk was indeed only mild to moderate throughout the monitoring period. Interestingly, by far the greatest contributor to mould growth was the mesophilic it Cladosporium, which is typically found when $\text{RH} \in [0.8, 0.9]$ - this fits very well with the density maxima seen in Figures 6a and 6b.
Several material models were verified or validated. **Plywood board**: density $\rho = 500 \text{ kg/m}^3$, porosity $f = 0.5$, specific heat capacity $c = 1500 \text{ J/(kg} \cdot \text{K)}$, $\lambda = 0.1 \text{ W/(m} \cdot \text{K)}$, $\mu = 700$. **Wood wool (blowing birch)**: $\rho = 230 \text{ kg/m}^3$, $f = 0.999$; $c = 2100 \text{ J/(kg} \cdot \text{K)}$; $\lambda = 0.053 \text{ W/(m} \cdot \text{K)}$; $\mu = 4$. **PAROC eXtra (stone wool)**: $\rho = 28 \text{ kg/m}^3$, $f = 0.95$; $c = 850 \text{ J/(kg} \cdot \text{K)}$; $\lambda = 0.034 \text{ W/(m} \cdot \text{K)}$; $\mu = 1$. **Fibrolite board**: $\rho = 400 \text{ kg/m}^3$, $f = 0.74$, $c = 2100 \text{ J/(kg} \cdot \text{K)}$, $\lambda = 0.068 \text{ W/(m} \cdot \text{K)}$, $\mu = 44$. For hygrothermal curves, please see Figures 7, 8, 9 and 10.

Due to the article page limit, we are unable to provide the verified material model for cement lime plaster - however, the corresponding author will provide data on demand (values, data files). While it is tempting to showcase material models for the AER wall, as evident from Figure 5d, the hygrothermal model for aerated concrete must be further improved before the data is ready to be made public. This is also true for CER, EXP and Floor models. Once these are improved, we plan to publish the rest of established material models.

**Figure 7.** Hygrothermal curves for plywood board. Thermal conductivity plots (a) and (c) correspond to $\lambda(T, w) = \lambda_{dry}(T) \cdot (1 + c_1 w(\phi))$, where the dependency in (a) gives $c_1$ and (b) gives $\lambda_{dry}(T)$. Normalized water content is the ratio of water content to saturation value.
Figure 8. Hygrothermal curves for blowing birch wood wool. Note that both liquid suction and redistribution mechanism contributions to $D_\phi(w)$ are specified.

Figure 9. Hygrothermal curves for PAROC eXtra.
5. Conclusions and outlook
Numerical models have been established for all buildings within the Botanical garden (University of Latvia) test site. Many of these models showed very good agreement with experimental data in terms of RH dynamics, especially for PLY, AER, Ceiling and Floor insulating envelopes. In most cases temperature time series were in excellent agreement. It was found that both numerical models and processed sensor data correctly predict mould growth risks and growth onset most of the time, but especially so for PLY and Floor assemblies. The fact that three independent mould growth risk assessment methods agree very well leads to the conclusion that our numerical models are on the right track.

As a result of cross-verification, many of the previously unknown material parameters and dependencies, as well as initial conditions were established (see section available on demand). The applicability of LIM critical curve models under local climate conditions was ascertained. Numerical models for CER, EXP and LOG envelopes currently show quite strong deviations from the experiment, indicating that respective material models are thus far incorrect. It was found that assemblies are much more sensitive to indoor conditions than initially anticipated. For this reason, sensor readings for interior temperature and RH will be incorporated into current models. Outdoor climate dataset with no 1-year cycle averaging will also be used instead of the current boundary condition.

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