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Development of climatic damage predictive tool for timber façade moisture-related damage

K Ostapska[1], **G B A Coelho**[2], **J Brozovsky**[1], **D Kraniotis**[2], **A Loli**[1]

[1] SINTEF Community, Pb 4760 Sluppen, Høgskoleringen 7b, 7465 Trondheim
[2] Department of Built Environment, Faculty of Technology, Art and Design, Oslo Metropolitan University, PO box 4 St. Olavs plass, Oslo, NO-0130, Norway

E-mail: katarzyna.ostapska@sintef.no

Abstract. Development of the method for automated and adaptive assessment of mould growth in the timber frame facade is presented. A heat, air, and moisture (HAM) transport simulation using the open-source Python library HAMOPY is validated against a well-established software (WUFI Pro 1D). Climate input of the reference year in Norway, Oslo is used in validation. The material parameters of the 1D numerical model that influence mold growth conditions most are identified via a parametric study. The increased water vapor permeability and thermal conductivity of the outside envelope as well as the critical relative humidity threshold are selected as the model updating parameters to account for the risk of the thermal bridge, moisture leakage, and mold growth conditions variation in the model. The example of the automated parametric computation of the mold growth conditions in the facade is presented for a reference climate based on the developed and validated HAM model.

1. Introduction

This research aims at developing a method for an automated prediction of the hygrothermal performance of the building facade. The focus is put on the prediction of mold-driving conditions in timber-based facade systems, where wood is protected against direct exposure. Current mold prediction models are based on the temperature and moisture conditions on a given substrate over time and provide a categorical assessment of the mold growth risk. Mold growth models for materials are commonly developed in laboratory settings on small clear material specimens and subjected to controlled spore application and growth. Conditions of mold growth in the building facade differ substantially from the laboratory settings. Therefore, multiple uncertainties are present in the mold growth prediction models that can be accredited to the lack of accurate temperature and moisture (weather) data, insufficient or inaccurate material specification, wrong model assumptions, and inherent model simplifications [1]. Organic materials like wood absorb moisture from the air and contain extractives enhancing mold growth and bio-degradation. A better understanding of the mold growth conditions in modern timber building facades is necessary to assure their durability and reliability. The performance of the mold growth models can be improved with data from sensors installed in the facade and the use of the most accurate weather input. A physics-based model of the heat, air, and moisture (HAM) transfer through the facade based on real weather data input can be calibrated against the facade sensor data and used for generic mold growth predictive tools based on available mold growth models. Furthermore, the model can be verified over time via facade maintenance inspections and sensor data against mold occurrence and can be updated with the new data to develop more accurate methods, e.g. by using linear regression or other machine learning algorithms. This article presents a method integrating the HAM and mold models in the open-source script for the facade predictive maintenance system (PMS).

2. Methodology

2.1. Timber facade sections

The facade structure is based on a wooden frame made from glued laminated timber beams and columns that are connected in the corners with steel plates and screws. The frame is attached to the building with steel plates bolted to the timber frame. The frame has an orthogonal layout and allows for different envelope mounting on the outside: a 3-layer glass pack, insulation with zinc sheet panels, and insulation-glass panels. The secondary structure supporting the envelope panels is made from aluminum profiles screwed to the timber frame. The typical cross-sections through the facade panels and timber frame are shown in Figure 1. The two typical sections A1, and A2 are the internal panel sections and the timber frame-aluminum frame section respectively. The A2 section is at risk of a thermal bridge since it contains a lot of cavities and joints that could be a source of moisture leakage and accumulation. Therefore section A2 was chosen as a case study for a numerical model and is further referred to as risk spot (RS). The materials used in the sections are explained in the caption of Fig 1. The structural timber elements are of glued-laminated timber consisting of 160x60mm cross-section beams glued from four 60x40mm lamellas.

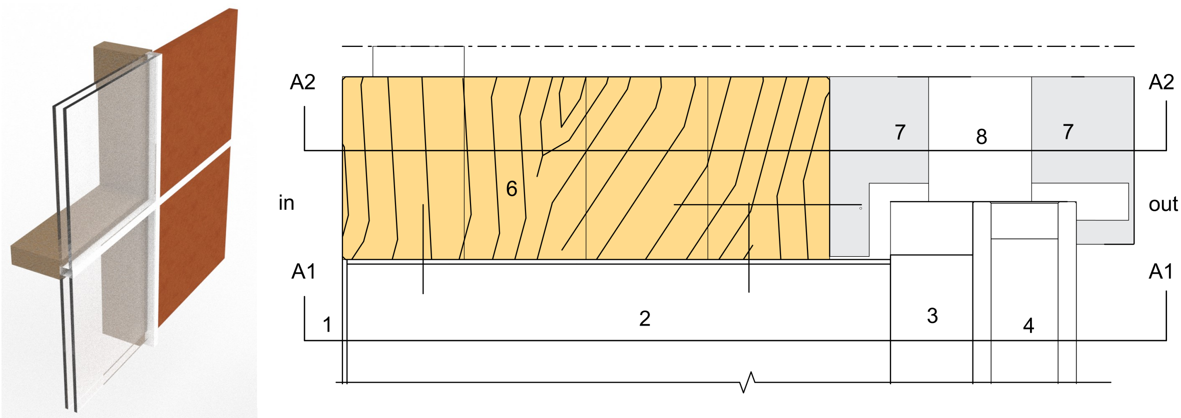

Figure 1. Facade view (left) and cross-sections (right) A1 and A2. Facade materials are 1- zinc sheet, 2- soft mineral wool, 3- semi-hard mineral wool, 4- integrated glass unit, 5- tin sheet, 6- glued laminated timber (GLT) from spruce, 7- aluminum profile, and 8- polyisocyanurate insulation foam.

2.2. Climate model

The hourly weather data (e.g., temperature, relative humidity, air pressure, global radiation, precipitation, wind direction, and wind speed) was downloaded from the "Norwegian Centre for Climate Services" website [2] for Oslo (Blindern station) for a period of 30 years (1990-2019). However, due to hourly data unavailability, this period was in fact shorter (i.e. 27 years) as it also occurred to Geving and Torgersen [3]. The Bird model [4] was used, by means of the solrad.xls [5], to fill the global radiation data gaps. Some other data unavailability was also detected for Blindern (SN18700) stations, i.e. in terms of precipitation. To overcome these gaps, data from the nearest weather stations were used, i.e. Blindern – Blindern Plu station (SN18701).

Finally, the multi-year weather datasets were transformed into representative one-year weather files through the procedure described in standard ISO 15927-4 [6]. This two-step procedure selects the most representative month of the whole period for each year's twelve months [7]. The procedure uses air temperature, relative humidity, global radiation, and wind speed, and then smooths the transition between the different months through linear interpolation [7]. Figure 2

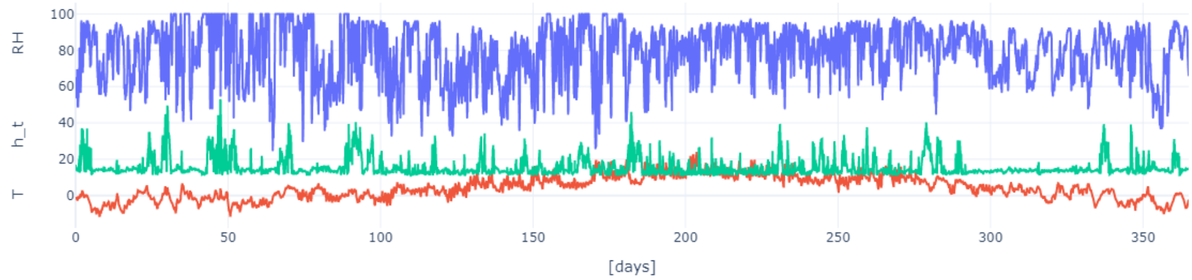

Figure 2. Test reference year (TRY) weather data for OSLO, Norway.

presents the air temperature, relative humidity, and the exterior surface heat transfer coefficient across one year in Oslo. In addition, the model for surface heat transfer coefficient h_t and surface moisture transfer h_m was assumed in equations 1, where k is wind direction coefficient (equal to 0.33 for leeward and 1.6 for windward facade), $\alpha_c = 4.5$ is a convective and $\alpha_r = 6.5$ is a radiative component. Climate data are depicted in figure 2.

$$h_t = k \cdot v_{wind} + \alpha_c + \alpha_r \ [W/m2K], \ h_m = 7 \cdot 10^{-9} \cdot \alpha_c \ [W/m2K] \tag{1}$$

2.3. Numerical HAM transfer model

A heat and moisture transport model in the facade section was created using the open-source Python code HAMOPY [8]. HAMOPY allows for one-dimensional finite element simulations of transient coupled heat and moisture transport in materials with user-defined thermal and hygric properties. The applied material model has a constant density and specific heat capacity, and thermal conductivity depends on the temperature and water content, see equation 2, where w is water content in [kg/m3] and T is the temperature in [$°C$].

$$\lambda = \lambda_0 + \frac{w}{1000} \cdot \lambda_m + T \cdot \lambda_t \tag{2}$$

The moisture transport properties, i.e., water sorption isotherm and water vapor permeability are defined in the function of relative humidity via a polynomial interpolation curve. All material properties are listed in table 1.

2.4. Numerical model validation

To ensure proper performance and accurate simulation results, a comparison with WUFI Pro v5.3 [9] software was made, which is a commercial HAM software that has been extensively validated against experimental data, other HAM software, and standard EN 15026, EN 137888 and ASHRAE 160P. The resulting temperature and RH history over one year with the hourly resolution was compared for several points in the facade A2. A root mean square error (RMSE) was calculated with the formula in equation 3.

$$e_T = \sqrt{\frac{\sum_1^N (T_{i,WUFI} - T_{i,HAMOPY})^2}{N}}, e_{MC} = \sqrt{\frac{\sum_1^N (MC_{i,WUFI} - MC_{i,HAMOPY})^2}{N}} \tag{3}$$

Table 1. Constant facade material properties: ρ - density, c - specific heat capacity, and thermal/moisture dependent: conductivity constants and coefficients- λ, moisture sorption isotherm W- water content in the function of RH, and δp - water vapor permeability in the function of RH.

Material	ρ $[\frac{kg}{m3}]$	c $[\frac{kJ}{kgK}]$	λ_0 $[\frac{W}{mK}]$	λ_m [-]	λ_t [-]	RH [-]	W [kg/m3]
Spruce GLT	390	1.6	0.128	0.32	2e-4	[0, 0.33, 0.55, 0.94]	[0, 27.3, 37.1, 74.1]
Alum.	2700	0.9	200.0	0.0	0.0	[0, 0.1, 0.5, 0.8]	[0, 1e-13, 1e-12, 4e-12]
Glue	1200	1.8	0.24	0.0	1e-3	[0.25, 0.5, 0.95]	[1e-16, 1.0e-15, 1.0e-9]
PE foam	32.5	1.47	0.024	0.52	2e-3	[0, 0.8, 0.9, 1.0]	[1e-10, 16e-9, 17e-9, 17e-9]

	RH [-]	δp [perm inch]
Spruce GLT	[0.0, 0.3, 0.4, 0.6, 0.7, 1.0]	[1.36e-10, 1.36e-10, 1.74e-10, 3.8e-8, 5.2e-8, 5.2e-8]
Alum.	[0.0, 1.0]	[1.5e-15, 1.5e-14]
Glue	[0.0, 1.0]	[1.2e-20, 1.2e-20]
PE foam	[0.0, 0.8, 0.9, 1.0]	[1.0e-10, 1.6e-10, 1.7e-10, 1.7e-10]

2.5. Framework for sensor-based updating of numerical model
Sensors measuring, e.g., surface temperature, relative humidity in cavities, and wood moisture content will be located in a mock-up in Lithuania at the STATICUS factory. Sensor type and placement were selected based on the risk spots identified in a separate study. A risk spot is understood as a thermal bridge and moisture/water leakage that would result in a higher humidity and moisture content in the wood than is expected from the 1D simplified hygrothermal FEM analysis. Therefore, the material properties that could lead to increased mold growth are identified via a parametric study and sensitivity analysis. Those material properties are subsequently used as parameters to be updated for adjusting the facade model performance to match the measured temperature and relative humidity (or surface moisture) from the sensors placed in the test mock-up.

2.6. Mould prediction modeling and update
Mold growth conditions can be evaluated based on the history of the dry and wet periods. Those periods are computed assuming a parameter of a critical relative humidity that can be updated later based on the mold inspection report. The mold growth model is based on the VTT model [10].

3. Results and discussion
3.1. Validation: comparison of HAMOPY and WUFI
Temperature and humidity curves obtained with WUFI and HAMOPY for the reference year in different section positions are depicted in figure 3. RMSE between results from WUFI and HAMOPY for different sections are within $e_T = 0.06 - 1.11°C$ and $e_{RH} = 0.1 - 5.6$ ppt.

3.2. Model sensitivity and mold growth periods: parametric study
The moisture and temperature transfer in the simplified 1D model does not take into account the possibility of water leakage and thermal bridge. Thus, the parametric study was performed to identify the sensitivity of the output to changing values of different material parameters and

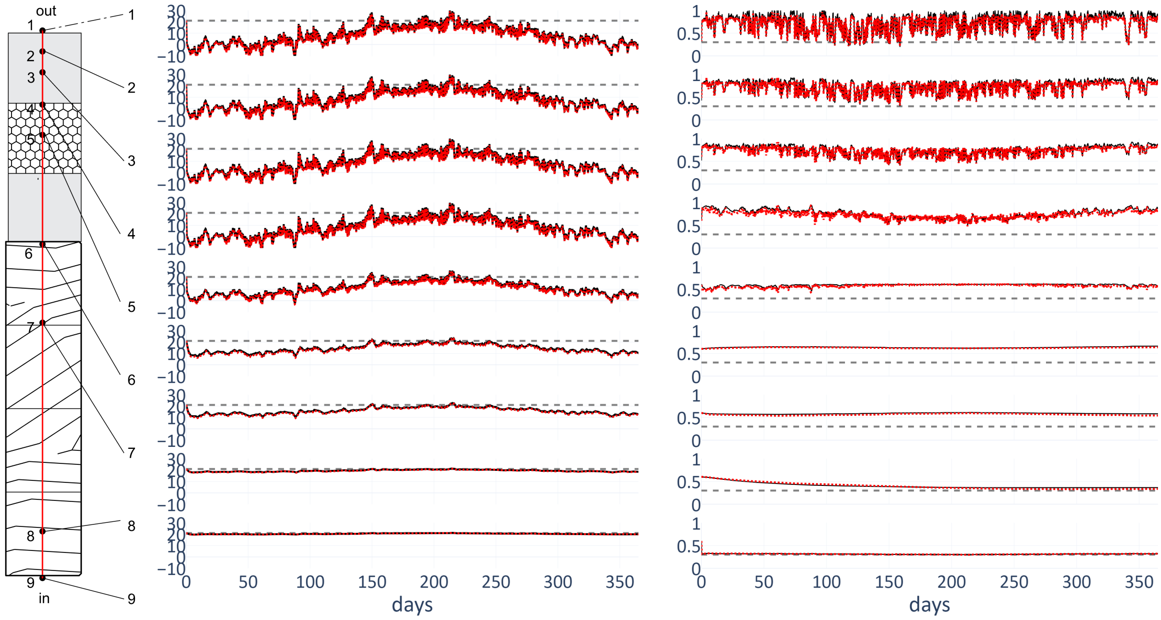

Figure 3. Simulated temperature [$°C$] (middle) and relative humidity [-] (right) from WUFI (black curves) and HAMOPY (red curves) in different section points (shown on the left) for TRY in OSLO, Norway.

identify the best way to model the risk spot and update the model with the data from the sensors that will be located in the facade. The most sensitive parameter modifications and the associated RMSE for the temperature and relative humidity are shown in table 2. The resulting RH curves are used for corresponding mold growth periods calculation assuming different critical RH (e.g., 0.7 and 0.75). The total time when RH exceeds e.g. 70% in point 6 in wood is around 15% for both v1+v2 and v2+v3 versions during the reference year. An effect of modifying the

Table 2. Sensitivity of the temperature and relative humidity in pt 6 of the facade(wood) to aluminium and foam parameter variation, a root mean square error (RMSE) for the TRY year.

variant	material	property	scaling factor	$RMSE_{RH,6}$	$RMSE_{T,6}$
v1	aluminium	δp	10e4	-18 ppt	-0.08 $°C$
v2	PE foam	λ_0	10	+1.6 ppt	-6.18 $°C$
v3	aluminium	δp	10e10	-21 ppt	-0.43 $°C$
v1+v2				-8.2 ppt	-2.95 $°C$
v2+v3				+7.1 ppt	-6.19 $°C$

identified sensitive material parameters on the simulation of RH in wood at section point 6 is presented in figure 4. Despite the RH value decreasing on average, the peaks are higher when the water vapour is allowed through aluminium and the foam is less insulating. These changes in material properties are made to account for moisture coming from nearby zones, which cannot be simulated in the 1D-HAM model.

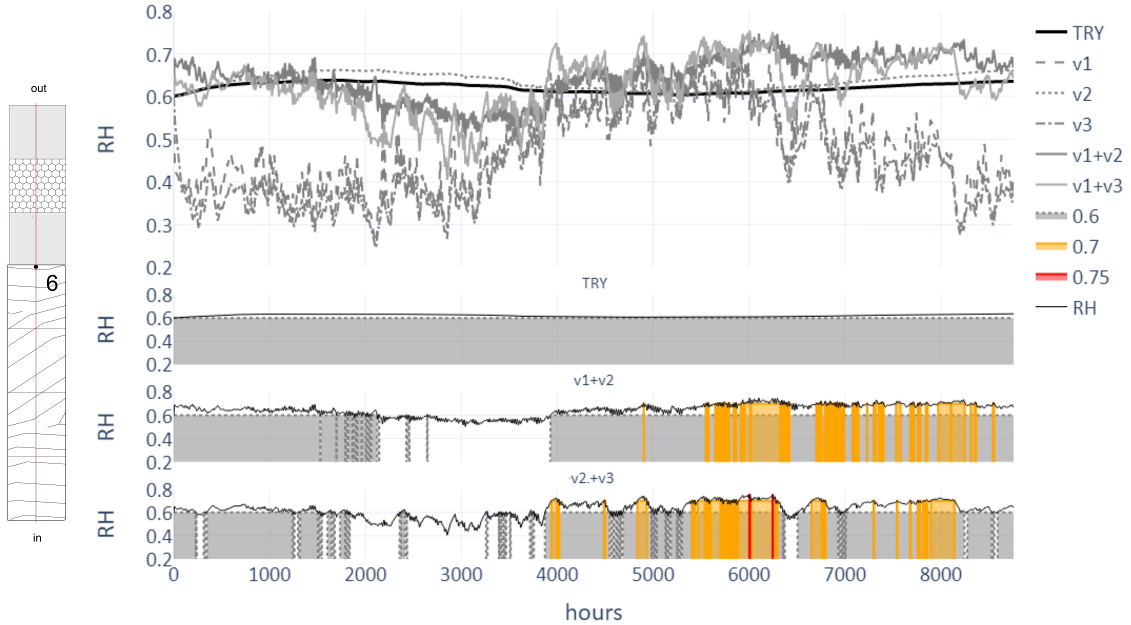

Figure 4. Simulated RH (top) for reference (TRY) and altered (v1,v2,v3,v1+v2,v2+v3) material properties, and corresponding mold growth risk periods for different potentially critical RH(0.6- grey, 0.7- yellow, 0.75 - red) in section point 6 for OSLO, Norway.

4. Conclusions

The study shows an implementation of an automated HAM transfer evaluation for estimating mold growth periods in wood, which can be easily integrated into the predictive maintenance system of the building facade. Sensitive material properties were identified and utilized in the script as parameters for adaptive mold growth prediction in the risk spots of the facade in a simplified 1D model. The method is validated against commercial software and based on an open-source code HAMOPY and existing mold growth models. The method will be developed further based on the facade sensor measurements to test its practicality and calibrate with sensor data, especially to compare against the mold growth conditions over time in real building facades as opposed to laboratory conditions. In the future, the method can be used for mold prediction for different geographical locations, geometry, and material parameters of the calibrated facade.

Acknowledgments

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