Research Article

Monte Carlo Simulation to Evaluate Mould Growth in Walls: The Effect of Insulation, Orientation, and Finishing Coating

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Mould growth can have severe consequences both on the health of occupants and on constructions' durability. Mould growth is a very complex process that depends on many factors such as temperature and relative humidity, presence of nutrients, and exposure time. Several mould prediction models, which allow estimating mould growth in building components and performing risk analysis, are available in the literature, such as the updated VTT model or the Biohygrothermal model. A Portuguese typical wall configuration was used for a sensitivity analysis. The importance of insulation (with and without insulation), orientation (north and south), and finishing coating (gypsum-based rendering, medium density fibreboard (mdf), and untreated wood) for the mould growth phenomenon was tested using both the updated VTT model and the Biohygrothermal model. A total of 12 case studies were investigated. The influence of indoor climate was evaluated by simulating 200 scenarios previously generated using the Monte Carlo method. Each of the scenarios has been applied to the 12 case studies, and 2400 hygrothermal simulations were carried out. Initially, the case studies were simulated using WUFI 1D since both mould growth models require the superficial temperature and relative humidity as input. Simulations were carried out for a one-year period. The updated VTT model produced results (mould index— M) ranging between 0.4 (gypsum-based rendering, insulated, and south oriented wall) and 5.9 (untreated wood, noninsulated, and north oriented wall) and the Biohygrothermal model (mould growth) between 10.1 and 406.4 mm for the same case studies. Despite that the effect of the orientation of the wall could be identified, the importance of insulation and nature of substrate was more evident. Although the two models produced overall comparable results, some differences could be found, creating the opportunity to discuss their strengths and weaknesses as well as their sensitivity to the input parameters.

1. Introduction

Mould growth is a very common problem in dwellings and has been steadily increasing in the last decades due to the growing concerns about energy efficiency of buildings. In fact, higher airtightness of the envelopes and lower ventilation rates provide favourable conditions to enable mould growth. On the other hand, new materials used as interior coatings may also increase the problem [1].

Several studies performed by the scientific community pointed that mould growth affects not only the durability and performance of the materials but has also a main impact

on the health and well-being of occupants. Respiratory infections, asthma, allergies, and cough are reported by several authors as respiratory diseases related to inhalation of mould spores. Coating detachment, materials deterioration, and decrease of thermal, hygric, and mechanical performance are the most common drawbacks of mould growth from the building point of view [1–4].

Although more than 100,000 mould species can be found in nature, only about 200 occur inside buildings. In dwellings, the transmission by air is the one that plays a relevant role on the health of occupants. Critical concentrations in rooms have been defined, although the information available in different

legal directives/guidelines often differs among them. In addition, no accurate and widely applicable information exists about which concentrations do represent a hazard to health [2]. According to the World Health Organization (WHO), pathogenic and toxic mould species are not acceptable indoors and a maximum concentration of 150 CFU/m³ of a mixture of not very common different mould spores is considered to be acceptable, and if mould belongs to common species that usually occur in the outside air, a maximum concentration of 500 CFU/m³ is satisfactory [5].

For mould growth to occur, certain conditions are required. Although these conditions depend on the species, it is possible to generally state that temperature, relative humidity (and the combination of these two), the existence of nutrients and oxygen, and exposure time play a major role in mould development [1, 2, 6]. Krus et al. pointed other parameters that also influence mould growth, like pH value, light, surface roughness, and biotic interactions [7].

In the last decades, several models have been developed in order to assess mould growth in buildings [1, 2, 4, 6–13]. These models are very interesting tools as their correct application can help prevent damage in buildings. However, it is important a deep knowledge of the models in order to understand their strengths and limitations and to learn how to interpret their results.

The VTT model [11] was developed in the Technical Research Centre of Finland (VTT) by Hukka and Viitanen. It is an empirical model based on visual findings of mould growth in pine and spruce sapwood under controlled conditions (laboratory tests). This model quantifies the mould growth through a mould index (M) that varies from 0 (no growth) to 6 (visually detected coverage 100%). In order to apply this model to other materials rather than wood, new tests were performed in collaboration between VTT and the Tampere University of Technology (TUT), and the mould index was related with other substrates in the updated VTT model also called the Finnish mould growth model. Temperature and relative humidity of the surface, together with the exposure time and the surface characteristics, are the key input parameters considered by the model. The complete formulation of the model can be found in [11, 14, 15].

To classify the materials, the model establishes four mould growth sensitivity classes: (a) very sensitive, which includes pine sapwood; (b) sensitive, which includes glued wooden boards, PUR with paper surface and spruce; (c) medium resistant, which includes concrete (aerated and cellular concrete), glass wool, and polyester wool; and (d) resistant, which includes PUR polished surface. The model also considers a decrease function in the mould index, when relative humidity and/or temperature are unfavourable for mould growth, as a function of materials characteristics [14].

The Biohygrothermal model was developed by Sedlbauer et al. [7, 16, 17] based on the isopleth system proposed by Sedlbauer [2]. The model allows calculating the moisture balance in a spore considering transient boundary conditions comprising temperature and relative humidity of the surface. Biological growth is directly dependent not only on the hygrothermal boundary conditions but also on the

substrate. For that reason, four different substrate classes are considered: (a) Class 0, which corresponds to the optimal biologic culture medium; (b) Class I, which includes biologically recyclable building materials like wall paper, paper facings on gypsum board, building materials made of biologically degradable raw materials, and materials for permanent caulking; (c) Class II, which includes building materials with porous structure such as renderings, mineral building materials, and certain wood species as well as insulation material not covered by I; and (d) Class III, which corresponds to building materials that are neither biodegradable nor contain any nutrients and for which no isopleth system was developed as it is considered that mould growth is not possible on their surface [17]. The model also includes an additional Class K that was created to differentiate mould species pointed as critical to health considering the optimum culture medium [18].

According to the Biohygrothermal model, if the course of the moisture content within a spore, which depends on ambient relative humidity, achieves the critical water content inside the spore, which depends on temperature and moisture retention curve for each substrate, mould growth will begin. The growth is expressed in millimetres and, in the beginning of the simulation, it describes the increase of the mycel length. However, this model allows continuous growth as long as there are suitable boundary conditions and, with ongoing growth, unrealistic values of several hundred millimetres can be reached. Therefore, these values can only be regarded for a comparative assessment of the risk of mould development, but not as a realistic growth [19].

Some studies about the comparison of these two models are available in the literature [19–24]. Both models traduce the influence on mould development of surface temperature, relative humidity, and substrate, but while in the updated VTT model, a decrease in the mould index exists under unfavourable conditions, in the Biohygrothermal model growth is assumed equal to zero in those circumstances. On the other hand, updated VTT model limits mould index to a climate specific maximum value, while the Biohygrothermal model allows continuous growth as long as there are suitable boundary conditions. Although their outputs are different (mould index (–) for the updated VTT model and mould growth (mm) for the Biohygrothermal model), a correlation between them was proposed based on hygrothermal calculations [19].

These models have recently been applied in mould risk evaluation. The risk of mould growth when adding interior thermal insulation to a log wall in a cold climate was analysed by Alev and Kalamees [25]. Almeida and Barreira [26] selected critical locations of a gymnasium envelope and monitored superficial temperature and relative humidity during 4 months. The results were used as inputs for comparing the mould growth models. Gradeci et al. [27] proposed a probabilistic-based methodology to assess the performance of façade constructions against mould growth. The methodology takes into account uncertainties related to the biological phenomenon, the climate exposure, and the material properties and integrates several mould growth models in a combined outcome.

TABLE 1: Selected materials and their classification according to the updated VTT and biohygrothermal models.

Material	Sensitivity class (updated VTT model)	Substrate class (Biohygrothermal model)
Gypsum-based rendering (M1)	Medium resistant	II
Medium density fibreboard (mdf) (M2)	Sensitive	I
Untreated wood (M3)	Very sensitive	I

FIGURE 1: Typical fluctuation of the interior air (black line) and indoor climates used in the hygrothermal simulations: (a) temperature; (b) relative humidity.

Although there are existing studies that use and compare the updated VTT and the Biohygrothermal models, no detailed information exists about their application to Mediterranean countries. In fact, in southern European countries, not only the exterior climate has specific particularities but also the interior climate is much more dependent on exterior conditions as no heating habits exist and “adventitious ventilation” is a common strategy. The main objective of this paper is to present the results of a sensitivity analysis to evaluate mould risk in a wall, using a probabilistic approach based on Monte Carlo simulation.

2. Methodology

In this work, a sensitivity analysis of the updated VTT and the Biohygrothermal models was made. Three parameters were assessed, coating material, orientation, and the existence of a layer with thermal insulation characteristics, resulting in 12 cases analysed (3 coatings, 2 orientations, and existence or not of thermal insulation). The main aim of the analysis was to evaluate the influence of these three parameters on mould growth. Additionally, a comparison between the results produced by each model was attempted.

The coating materials were selected according to the most common Portuguese construction practices and taking into account the substrate classes in the Biohygrothermal model (Classes I and II) and the sensitivity classes in the updated VTT model (very sensitive, sensitive, and medium resistant), in order to obtain at least one material representative of each group. Table 1 describes the sensitivity class and type of substrate in which each coating material is included.

Surface hygrothermal conditions are also fundamental for mould growth. These conditions depend essentially on

the interior climate, whose variability is highly dependent on the actions and behaviours of the users [28, 29]. In this work, a probabilistic approach was used to evaluate the effect of indoor climate (air temperature and relative humidity). The base case for the interior climate was established in accordance with the typical fluctuation of the interior air temperature and relative humidity on a Portuguese dwelling (black line in Figure 1).

After defining a base case, the Monte Carlo method was used to generate 200 new scenarios (Figure 1) assuming a normal distribution for the air temperature and relative humidity and a standard deviation of 20%. The Latin hypercube sampling (LHS) algorithm was selected for the number generation because it provides good convergence of parameter space when compared to the simple random sampling. Each of the scenarios was then applied to the 12 case studies (wall configurations), and a total of 2400 one-dimensional hygrothermal simulations were carried out using WUFI 1D, since both mould growth models require the superficial temperature and relative humidity as input. The simulations were carried out for a one-year period. Figure 2 presents schematically the methodology that was used and the cases Id.

The exterior climate was the one of Porto (Portugal), generated by the commercial software Meteonorm in an hourly base [30] (Table 2). Table 3 presents the materials' main properties used in the hygrothermal simulations, where e is the layer thickness (m), γ is the bulk density (kg/m^3), ξ is the porosity (m^3/m^3), C_{dry} is the specific heat capacity of the dry material ($\text{J}/\text{kg}\cdot\text{K}$), λ_{dry} is the thermal conductivity of the dry material ($\text{W}/\text{m}\cdot\text{K}$), and μ is the water vapour diffusion resistance factor (–). A schematic representation of the wall section can be found in Figure 3.

FIGURE 2: Methodology and cases Id.

TABLE 2: Porto climate (generated by Meteonorm 6.0).

Climatic parameter	Annual average	Annual accumulated
Temperature	14.8°C	—
Relative humidity	78%	—
Global radiation emitted by the sun	343 W/m ²	—
Wind velocity	2.6 m/s	—
Wind direction (north: 0°; east: 90°; south: 180°; west: 270°)	195°	—
Rain	—	779 mm

TABLE 3: Material properties used in the hygrothermal simulations.

Material	e (m)	γ (kg/m ³)	ξ (m ³ /m ³)	C_{dry} (J/kg·K)	λ_{dry} (W/m·K)	μ (—)
Exterior rendering	0.02	1219	0.3	850	0.25	10.8
Concrete	0.2	2200	0.18	850	1.6	92
XPS (extruded polystyrene insulation)	0.06	30	0.95	1500	0.04	50
Gypsum-based rendering (M1)	0.015	850	0.65	850	0.2	8.3
Medium density fibreboard (mdf) (M2)	0.015	508	0.66	1700	0.12	15
Untreated wood (M3)	0.02	550	0.66	1700	0.18	70

3. Hygrothermal Simulations

The first step of this research was simulating the interior superficial temperature and relative humidity for the 2400 scenarios. As an example, Figure 4 shows the results of the hygrothermal simulation for the scenario M1_NI_N using the base case as indoor climate (black line in Figure 1). Figure 5 synthesizes the results for the entire dataset, including the average, maximum, and minimum values.

Results reveal that the presence of an insulation layer is the most important factor as a clear difference between I and NI cases can be observed. As expected, NI cases present lower temperature and higher relative humidity (differences of 1°C and 5%, approximately). Moreover, a larger variability can be found in NI cases, confirmed by an average coefficient of variation of 13.8% and 15.9% in temperature results, for I and NI cases, respectively, and of 10.3% and 12.5% in the relative humidity results.

In the I scenarios, the effect of finishing coating and orientation is almost imperceptible. On the contrary, in the

NI cases, the effect of the finishing coating is more obvious in the north oriented scenarios.

4. Results

4.1. VTT Model. Figure 6 shows the maximum mould index obtained for each case study considering only the base case as indoor climate. Although only slight differences in the superficial hygrothermal conditions were found among the dataset, the application of the VTT model exposed a completely different scenario as the mould index ranged from 0.4 (M1_I_S) to 5.9 (M3_NI_N). These differences justified a detailed sensitivity analysis to establish the relative importance of each parameter under this study: finishing coating material, insulation layer, and orientation (Figure 7). Only the base case as indoor climate was considered in this analyses.

Figure 7(a) highlights the effect of the finishing material using the north oriented, noninsulated set-up as example. The maximum mould index was 2.98, 4.41, and 5.86 for the

FIGURE 3: Schematic representation of the wall section.

FIGURE 4: Superficial temperature and relative humidity for the scenario M1_NI_N using the base case as indoor climate.

FIGURE 5: Average, maximum, and minimum for the entire dataset: (a) temperature; (b) relative humidity.

FIGURE 6: Maximum mould index, considering the base case as indoor climate.

FIGURE 7: VTT model: sensitivity analysis (base case as indoor climate): (a) finishing coating material; (b) insulation layer; (c) orientation.

gypsum-based rendering, the medium density fibreboard (mdf), and the untreated wood, respectively. For the three materials, the maximum mould index occurred approximately in the same instant, around 2600 hours. Figure 7(b) uses the north oriented set-up with the gypsum-based rendering, to expose the effect of the insulation layer. A significant difference between the two cases can be observed as the maximum mould index increases from 0.54 up to 2.98. Furthermore, a time lag between the maximum values is now distinguishable. The maximum mould index in the insulated case occurs around the 3400 hours, but when there is no

insulation, it occurs about 1000 hours before. Finally, in Figure 7(c), it can be confirmed that orientation is the less important parameter. In the gypsum-based rendering, noninsulated set-up, the maximum mould index varies between 2.63 and 2.98. As expected, the higher value occurs in the north oriented case due to the lower incident solar radiation. Despite the small difference in the maximum mould index value, a time lag between the instants is also visible in this scenario as in the south oriented, it occurs at the 3350 hours, approximately, and about 1000 hours after the north oriented.

FIGURE 8: Maximum value of mould index cumulative relative frequency: (a) case studies with insulation layer; (b) case studies without insulation layer.

FIGURE 9: Maximum mould growth, considering the base case as indoor climate.

The introduction of variability in indoor climate has confirmed the importance of this parameter in the evaluation of the risk of mould growth. Figure 8 shows, as

a cumulative percentage, the results of the maximum value of the mould index obtained in the 2400 simulations, separately for the 12 case studies. In Figure 8(a) are the cases

(a)

(b)

(c)

FIGURE 10: Biohygrothermal model: sensitivity analysis (base case as indoor climate): (a) finishing coating material; (b) insulation layer; (c) orientation.

FIGURE 11: Maximum value of mould growth cumulative relative frequency: (a) case studies with insulation layer; (b) case studies without insulation layer.

with an insulation layer, while in Figure 8(b) are the ones without insulation.

In addition to the already known importance of the sensitivity class of the coating material, it is observed that in cases with insulation layer, the importance of the variability of the interior climate is more evident. In fact, in the cases without thermal insulation, the value of the mould index has a much lower dispersion, that is, the introduction of the layer reduces the impact of the exterior climate, thus maximizing the importance of the indoor climate. It is also worth noting that the cases with an untreated wood coating and without insulation layer are clearly limited by the model itself ($M=6$).

4.2. Biohygrothermal Model (Wufi Bio). The Biohygrothermal model was applied to the entire dataset using

Wufi Bio, and the maximum growth was used as the comparison output. The same approach used in the VTT model was applied and Figure 9 shows the maximum growth for the 12 case studies considering only the base case as indoor climate. Once again, large differences between the different case studies can be observed. The lower mould growth value occurred in the M1_I_S case (10.1 mm) and the highest in the M3_NI_N case (406.4 mm). These results are in line with the ones obtained with the VTT model, which also pointed out these two cases as the extreme scenarios. Figure 10 depicts the results of the sensitivity analysis.

The effect of the finishing coating material is shown in Figure 10(a) using, once again, the north oriented, non-insulated set-up as an example case. The maximum mould growth was 255.7 mm, 325.0 mm, and 406.4 mm for the gypsum-based rendering, the medium density fibreboard

FIGURE 12: Mould growth versus mould index (2400 simulations).

(mdf) and the untreated wood, respectively. Since the Biohygrothermal model does not include a decrease factor to take into account unfavourable growth conditions, the first instant in which the maximum mould growth value occurred was used as the “time indicator.” In this way, only slight differences can be found between the cases as in the three, the instant was at 5800 hours, approximately. Figure 10(b) uses the north oriented set-up, with gypsum-based rendering, to expose the large differences found in the mould growth due to the presence of an insulation layer. The maximum mould growth decreases from 255.7 mm in the noninsulated case to 19.4 mm in the insulated one. Furthermore, this value is reached earlier in the insulated case (4000 hours). Compared with the VTT model, the Biohygrothermal model is more sensitive to the effect of orientation as exposed in Figure 10(c). The maximum mould growth was 163.2 mm in the south oriented and 255.7 mm in the north one. Both occurred around the same instant.

The importance of variability of the indoor climate is shown in Figure 11, where the cumulative percentage of the maximum value of mould growth obtained in the 2400 simulations is depicted, separately for the 12 case studies. In Figure 11(a) are the cases with an insulation layer, while in Figure 11(b) are the ones without insulation.

In this model, unlike the VTT model, the dispersion of the distribution is not much affected by the presence of the insulation layer. Using as example case the untreated wood (the material with the highest risk of mould growth), it is verified that for both north and south oriented cases, 80% of the maximum values (percentiles between 0.1 and 0.9) are within a range of about 100 mm. For the remaining case studies, an equivalent range is observed.

4.3. Discussion. The results previously presented showed some agreement between the two models as both pointed the same cases as the extreme scenarios. Nevertheless, some

differences were also identified such as the highest sensitivity to wall orientation found in the Biohygrothermal model and the more evident effect of the variability of indoor climate in the VTT model. Figure 12 illustrates the relationship between maximum mould index and maximum mould growth in the entire dataset (2400 simulations). The agreement between the two models was already tested and reported by previous researchers, suggesting the use of a BET function to mathematically describe this relationship [19–21]. In this work, in addition to the previously mentioned BET function, two approximations were tested: a third degree polynomial function and an exponential function. The attained coefficient of determination was 0.66 and 0.59, respectively. Although better than the BET function, these coefficients indicate that these functions seem unsuitable to describe the relationship.

Analyzing the results, it is possible to verify that the BET function tends to overestimate the mould growth value when the mould index is high. In addition, this function presents a more interesting performance in the case studies without the insulation layer. The two approximation functions presented in this research (polynomial and exponential), for the same values of mould index, suggest lower values of mould growth. One should also stress that the high number of results with maximum mould index ($M=6$) may overestimate the importance of these points and thus bias the functions.

Interesting findings can be drawn if one compares the instants at which the maximum mould index and the maximum mould growth occur as illustrated in Figure 13. The main conclusion is that the maximum value occurs earlier when the VTT model is used. This is an obvious consequence of the reduction function included in the model to take into account unfavourable hygrothermal conditions, while in the Biohygrothermal model, the mould growth function can only increase or be stable.

Additionally, clear patterns can be identified on the results of the VTT model. In the noninsulated cases, besides

FIGURE 13: Comparison of the results calculated by both models.

the evident effect of the finishing material, a time lag due to orientation can also be observed. The south oriented scenarios reached the maximum mould index, approximately, 800 hours after the corresponding north oriented cases. This situation disappears when the insulation layer is added. A more random configuration can be observed in the results of the Biohygrothermal model. Nevertheless, a trend for an earlier maximum mould growth in the insulated scenarios can be pointed out.

5. Conclusions

In this study, the importance of insulation (with and without insulation), orientation (north and south), and finishing coating (gypsum-based rendering, medium density fibre-board (mdf), and untreated wood) for the mould growth phenomenon was tested using the two most well-known models to assess mould growth: updated VTT and Biohygrothermal. Taking into account the importance of interior climate in the phenomenon and due to its highly variable nature in Mediterranean countries, a probabilistic approach based on Monte Carlo simulation was also implemented. A typical external wall configuration was used as the case study. From the results, the following main findings can be stated:

- (i) Although only slight differences among the dataset were found in the superficial hygrothermal conditions, the application of the updated VTT and Biohygrothermal models exposed great differences between the simulated scenarios (mould index ranged from 0.4 to 5.9 and mould growth ranged from 10.1 mm to 406.4 mm).
- (ii) From the three parameters that were assessed, the thermal insulation is the more relevant (relative differences are on average 78%), followed by the coating materials (relative differences are on average around 57%) and, finally, the orientation (relative differences are on average around 18%). The Biohygrothermal model is more sensitive to the effect of

orientation than the updated VTT model (relative differences are, on average, 11% for the updated VTT model and 25% for the Biohygrothermal model).

- (iii) The importance of the variability of indoor climate was confirmed by the results of the Monte Carlo simulation. In the VTT model, in cases with insulation layer, the importance of this variability was more evident. This finding was not so obvious in the Biohygrothermal model.
- (iv) An agreement between the two models (mould index versus mould growth) was searched. A polynomial and an exponential function were tested to approximate the results of the 2400 simulations, and a coefficient of determination of 0.66 and 0.59, respectively, was attained.
- (v) The maximum mould index (updated VTT model) occurs earlier than the maximum mould growth (Biohygrothermal model). Maximum mould index occurs on average at 2900 hours and maximum mould growth occurs on average at 5155 hours. This is a consequence of the reduction function included in the updated VTT model to take into account unfavourable hygrothermal conditions that are not considered in the Biohygrothermal model.
- (vi) Clear patterns can be identified on the results of the VTT model when analysing the instants at which the maximum mould index occur. On the contrary, a more random configuration can be observed in the results of the Biohygrothermal model.

The future research will include the use of real data to compare the results provided by the two models and assess which one is the most interesting for modelling mould growth in the Mediterranean climate.

Data Availability

The data are available on request from the corresponding author. The datasets generated during and/or analysed

during the current study are available from the corresponding author on reasonable request. The large amount of data justifies this option.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] H. J. Moon, *Assessing mold risks in buildings under uncertainty*, Ph.D. thesis, Georgia Institute of Technology, Atlanta, GA, USA, 2005.
- [2] K. Sedlbauer, *Prediction of mould fungus formation on the surface of and inside building components*, Ph.D. thesis, Stuttgart University, Fraunhofer Institute for Building Physics, Stuttgart, Germany, 2001.
- [3] C. A. Robbins, L. J. Swenson, M. L. Nealley, B. J. Kelman, and R. E. Gots, "Health effects of mycotoxins in indoor air: a critical review," *Applied occupational and environmental hygiene*, vol. 15, no. 10, pp. 773–784, 2000.
- [4] O. Adan, *On the fungal defacement of interior finishes*, Ph.D. thesis, Technische Universiteit Eindhoven, Eindhoven, Netherlands, 1994.
- [5] C. Y. Rao, H. A. Burge, and J. C. S. Chang, "Review of quantitative standards and guidelines for fungi in indoor air," *Journal of the Air and Waste Management Association*, vol. 46, no. 9, pp. 899–908, 1996.
- [6] G. Ayerst, "The effects of moisture and temperature on growth and spore germination in some fungi," *Journal of Stored Products Research*, vol. 5, no. 2, pp. 127–141, 1969.
- [7] M. Krus, K. Sedlbauer, W. Zillig, and H. M. Künzle, *A New Model for Mould Prediction and its Application on a Test Roof*, Fraunhofer Institute for Building Physics, Stuttgart, Germany, 2001.
- [8] S. L. Smith and S. Hill, "Influence of temperature and water activity on germination and growth of *Aspergillus restrictus* and *A. versicolor*," *Transactions of the British Mycological Society*, vol. 79, no. 3, pp. 558–560, 1982.
- [9] H. Hens, "Fungal defacement in buildings: a performance related approach," *HVAC and R Research*, vol. 5, no. 3, pp. 265–279, 1999.
- [10] J. Clarke, C. Johnstone, N. Kelly, R. McLean, N. Rowan, and J. Smith, "A technique for the prediction of the conditions leading to mould growth in buildings," *Building and Environment*, vol. 34, no. 4, pp. 515–521, 1999.
- [11] A. Hukka and H. A. Viitanen, "A mathematical model of mould growth on wooden material," *Wood Science and Technology*, vol. 33, no. 6, pp. 475–485, 1999.
- [12] H. Viitanen, J. Vinha, K. Salminen, T. Ojanen, R. Peuhkuri, and L. Paajanen, "Moisture and bio-deterioration risk of building materials and structures," *Journal of Building Physics*, vol. 33, no. 3, pp. 201–224, 2010.
- [13] S. Johansson, L. Wadsö, and K. Sandin, "Estimation of mould growth levels on rendered façades based on surface relative humidity and surface temperature measurements," *Building and Environment*, vol. 45, no. 5, pp. 1153–1160, 2010.
- [14] T. Ojanen, R. Peuhkuri, H. Viitanen, K. Lähdesmäki, J. Vinha, and K. Salminen, "Classification of material sensitivity—New approach for mould growth modeling," in *Proceedings of the 9th Nordic Symposium on Building Physics NSB*, pp. 867–874, Tampere, Finland, May 2011.
- [15] K. Lähdesmäki, K. Salminen, J. Vinha, H. Viitanen, T. Ojanen, and R. Peuhkuri, "Mould growth on building materials in laboratory and field experiments," in *Proceedings of the 9th Nordic Symposium on Building Physics NSB*, Tampere, Finland, May 2011.
- [16] WUFI®, <https://wufi.de/en/2016/04/19/wufi-bio/>, 2018.
- [17] K. Sedlbauer, "Prediction of mould growth by hygrothermal calculation," *Journal of Building Physics*, vol. 25, no. 4, pp. 321–336, 2002.
- [18] M. Krus, R. Kilian, and K. Sedlbauer, "Mould growth prediction by computational simulation on historic buildings," in *Proceedings of the Conference on Preventive Conservation*, pp. 185–189, Milan, Italy, 2007.
- [19] H. Viitanen, M. Krus, T. Ojanen, V. Eitner, and D. Zirkelbach, "Mold risk classification based on comparative evaluation of two established growth models," *Energy Procedia*, vol. 78, pp. 1425–1430, 2015.
- [20] E. Vereecken, D. Saelens, and S. Roels, "A comparison of different mould prediction models," in *Proceedings of Building Simulation: 12th Conference of International Building Performance Simulation Association*, pp. 1934–1941, Launceston, TAS, Australia, August 2011.
- [21] M. Krus, M. Saidler, and K. Sedlbauer, "Comparative evaluation of the predictions of two established mold growth models," in *Proceedings of the Buildings XI*, Eindhoven, Netherlands, August 2010.
- [22] T. Ojanen, H. Viitanen, R. Peuhkuri, K. Lähdesmäki, J. Vinha, and K. Salminen, "Mold growth modeling of building structures using sensitivity classes of materials," in *Proceedings of the Buildings XI*, Eindhoven, Netherlands, August 2010.
- [23] E. Vereecken and S. Roels, "Review of mould prediction models and their influence on mould risk evaluation," *Building and Environment*, vol. 51, pp. 296–310, 2012.
- [24] E. Vereecken, K. Vanoirbeek, and S. Roels, "A preliminary evaluation of mould prediction models based on laboratory experiments," *Energy Procedia*, vol. 78, pp. 1407–1412, 2015.
- [25] U. Alev and T. Kalamees, "Avoiding mould growth in an interiorly insulated log wall," *Building and Environment*, vol. 105, pp. 104–115, 2016.
- [26] R. M. S. F. Almeida and E. Barreira, "Condensation and mold risk evaluation in a gymnasium: in situ measurements and numerical simulation," *Journal of Performance of Constructed Facilities*, vol. 31, no. 5, p. 04017049, 2017.
- [27] K. Gradeci, N. Labonnote, B. Time, and J. Köhler, "A probabilistic-based methodology for predicting mould growth in façade constructions," *Building and Environment*, vol. 128, pp. 33–45, 2018.
- [28] N. M. M. Ramos, A. Curado, and R. M. S. F. Almeida, "Analysis of user behavior profiles and impact on the indoor environment in social housing of mild climate countries," *Energy Procedia*, vol. 78, pp. 561–566, 2015.
- [29] D. H. Gutierrez-Avellanosa and A. Bennadji, "Analysis of indoor climate and occupants' behaviour in traditional Scottish dwellings," *Energy Procedia*, vol. 78, pp. 639–644, 2015.
- [30] Meteotest, *Meteonorm—Version 6.0*, Meteotest, Bern, Switzerland, 2007.