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Comparative Evaluation of the VTT Mold Index Model and the DR SIM Model for Moisture Risk Assessment

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ABSTRACT

Hygrothermal simulations are useful in forensic investigations of moisture problems and in design analysis for identifying and mitigating potential risks both in new construction and retrofit of existing buildings. Damage models, including mold growth models, are often used as a means of assessing risk; such models use simulation outputs such as temperature and relative humidity or moisture content. The Finnish mold growth model (or VTT mold index model), a pioneering model used widely by researchers and practitioners, was developed based on laboratory data for a wide range of materials, and several studies have shown qualitative agreement between field observations and model predictions. However, a round-robin study, which evaluated six different models, found that the VTT model was highly sensitive to user input selections and assumptions. Furthermore, under field conditions with considerable variation in temperature and humidity, the VTT model significantly underestimated the extent of mold growth compared with observations using microscopy. To provide more realistic predictions of mold growth over the range of hygrothermal conditions experienced in-situ, the Dose-Response Simple Isopleth for Mold (DR SIM) model was developed. This paper compares the DR SIM model with the VTT model in terms of model structure, statistical goodness of fit to laboratory mold growth datasets from the literature, and accuracy of pass/fail predictions based on mold index thresholds. We find that the DR SIM model is more accurate than the VTT model overall, but the possibility of overfitting needs further investigation. We highlight the advantages and limitations of each model and emphasize the need for further laboratory and field mold growth data on North American materials.

INTRODUCTION

A functional building envelope protects the structure against bulk water intrusion and manages the flows of heat, air, and water vapor between the exterior and interior environments (ASHRAE 2021b, 2021c, 2023a). Moisture levels in buildings can influence the indoor environmental quality by fostering conditions suitable for biological growth. Indoor dampness and microbial growth have been consistently linked with adverse health effects (IOM 2004; WHO 2009; Mendell et al. 2011). Moisture accumulation can lead to deterioration of structural materials and finishes (ASHRAE 2021c, 2023a, 2023b).

Hygrothermal simulation is a useful tool for both forensic investigations of moisture problems in buildings and design analysis for identifying and mitigating potential risks both in new construction and retrofit of existing buildings. Moisture and temperature conditions within a building envelope assembly can be simulated in response to interior and exterior

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environmental conditions (Hens 1996; Trechsel 2001; Straube and Burnett 2005; ASHRAE 2021a; ASTM 2023). Simulation outputs typically include time series of temperature, relative humidity, and moisture content within a multilayered assembly. Various post-processing models can translate simulation outputs into quantitative values representing the extent of specific types of damage such as mold growth (Vereecken and Roels 2012; Gradeci et al. 2017; Lepage et al. 2019).

The Finnish mold growth model (or VTT model), developed through collaboration between the VTT Technical Research Center and Tampere University of Technology (TUT n.d.), is used widely by researchers and practitioners. This pioneering model, originally developed for mold growth on wood (Viitanen 1997; Hukka and Viitanen 1999), was later extended to a broad range of building materials (Viitanen and Ojanen 2007; Ojanen et al. 2010; Viitanen et al. 2010). The model is dynamic in the sense that it considers time-varying inputs, i.e., surface temperature and relative humidity, and provides a time-varying output, i.e., the mold index, which has a numerical rating scale from 0 to 6. Several studies have shown qualitative agreement between field observations and model predictions (Ojanen et al. 2010; Glass et al. 2017), and the model is included in the moisture performance evaluation criteria in ASHRAE Standard 160 (ASHRAE 2021a).

Despite the wide adoption of the VTT model, its sensitivity and accuracy need further investigation. Johansson et al. (2021) reported the results of a study that involved field exposure of building materials in five different environments (crawl spaces and attics), monitoring of the hygrothermal conditions in these environments, periodic rating of the extent of mold growth on the materials using microscopy, and prediction of the extent of mold growth based on the measured hygrothermal conditions by multiple participants using six different models, including the VTT model. The study found that this model was highly sensitive to user input selections and assumptions. Furthermore, in field conditions with considerable variation in temperature and humidity, the VTT model significantly underpredicted the extent of mold growth compared with observations.

The Mold Resistance Design (MRD) model (Thelandersson and Isaksson 2013), another dynamic model, was also evaluated in the study by Johansson et al. (2021). Like the VTT model, the MRD model was found to underpredict the extent of mold growth compared with field observations. Subsequently, Boardman et al. (2022) made several modifications to the MRD model structure that gave modest improvements in predictive performance for European and North American woods and wood-based materials. Building on this work, Boardman et al. (2023) explored more radical changes to the MRD model and developed a new model known as the Dose-Response Simple Isopleth for Mold (DR SIM) model. While the DR SIM model has improved predictive power over the MRD model, it has not been directly compared with the VTT model.

The objective of this paper is to critically evaluate the VTT model and the DR SIM model as part of the development of a moisture risk index (Glass et al. 2025). The next section of the paper compares the basic structure of the models. This is followed by a description of the methods used for evaluating the quality of the models, relative to laboratory mold growth datasets from the literature. We show that the DR SIM model predictions overall are more accurate than the VTT model. We conclude with a summary of the advantages and limitations of each model and recommendations for further research to improve mold risk modeling.

MODEL STRUCTURE

Here we provide an overview of the structure of the two models and highlight similarities and differences. Full descriptions and equations can be found in the original publications (Ojanen et al. 2010; Boardman et al. 2023).

Critical Relative Humidity and Temperature Conditions

Both models define conditions that are conducive to mold growth using a curve for the critical surface relative humidity, RH_{crit}, as a function of the surface temperature (T), as shown in Figure 1. Relative humidity (RH) conditions greater than RH_{crit} are conducive to mold growth. The VTT model groups materials into four sensitivity classes: very sensitive, sensitive, medium resistant, and resistant. The RH_{crit} curves for the very sensitive and sensitive classes are identical, with a minimum of 80%. The medium resistant and resistant clases, in contrast, have a minimum RH_{crit} of 85%. These different critical values are necessary to reflect the empirical observation of reduced fungal growth based on substrate characteristics. On the other hand, the DR SIM model uses a parabola for RH_{crit} as an approximation of empirical mold isopleths (Hens 1999; Johansson and Svensson 2020). The vertex of the parabola is set at 29.1 °C (84.4 °F) for all materials, but the RH value at the vertex and the shape of the parabola can be varied depending on the material. Both models assume that temperatures below 0 °C (32 °F) and above 50 °C (122 °F) are not conducive to growth.

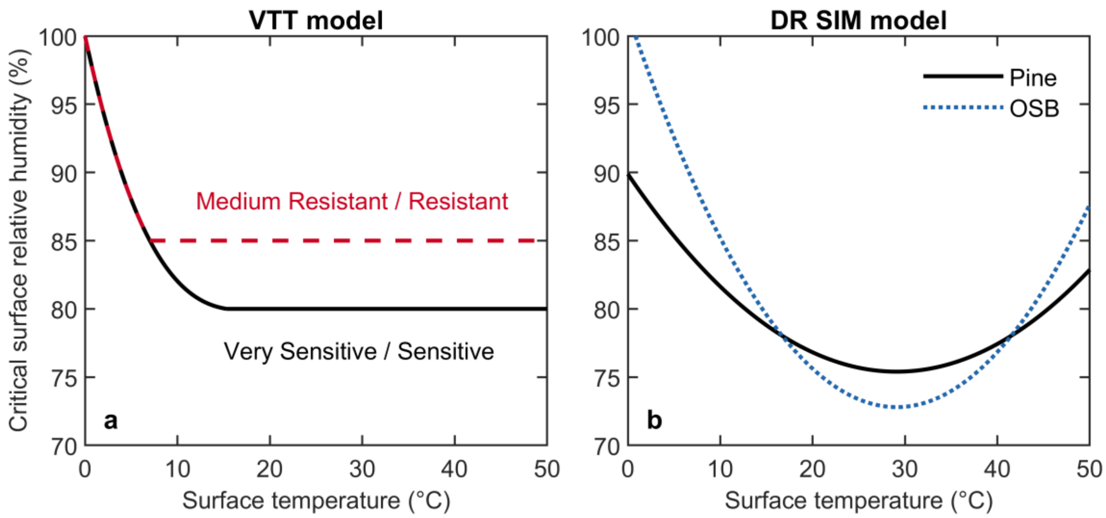

Figure 1 Critical surface relative humidity as a function of surface temperature for the VTT model (a) and DR SIM model (b). The VTT model groups materials into four sensitivity classes. The DR SIM model uses a parabola that can be adjusted for the material. OSB: oriented strand board. 0–50 °C equals 32–122 °F.

Mold Growth Rating Scale

Both models give a numerical output that can be compared with experimental mold growth ratings. The VTT model was developed using an index that goes from 0 to 6 (Viitanen and Ritschkoff 1991; Viitanen and Ojanen 2007; Ojanen et al. 2010; Viitanen et al. 2010) as described in Table 1. The DR SIM model, on the other hand, was developed using the rating scale of Johansson et al. (2012), which goes from 0 to 4. A method for converting between these two rating scales (Table 1) was proposed by Boardman et al. (2023).

Table 1. Mold Index (0–6) Scale and Johansson (0–4) Scale

Mold Index	Description of Growth Rate	Microscopy	Naked Eye	Approximate 0–4 Rating
0	No growth; spores not activated	None	None	0
1	Initial stages	Small amounts of mold	None	1
2	—	Several local colonies	None	2
3	New spores produced	≤ 50% coverage	< 10% coverage	3
4	Moderate growth	> 50% coverage	10–50% coverage	3.5
5	Plenty of growth	—	> 50% coverage	4
6	Heavy and tight growth	—	About 100% coverage	4

Rate of Mold Growth

The VTT model is based on empirical relationships between the time needed to reach a certain mold index and the surface temperature and RH conditions, under constant or cyclic conditions. These relationships are incorporated into a series of equations (Hukka and Viitanen 1999; Ojanen et al. 2010).

The DR SIM model has a dose–response structure. The dose represents how conducive the conditions are to mold growth at a given time step and is a function of the difference between the current surface RH and RH_{crit}, or ΔRH, as shown in Figure 2a. The dose is calculated for each time step and then summed to give a cumulative dose. The response is a predicted mold growth rating. The cumulative dose is transformed into a mold rating using a sigmoidal curve (Figure 2b) to represent the non-linear biological growth curves of fungi (Brischke and Rapp 2008). The DR SIM model also includes a threshold parameter Z that allows the mold rating curve to shift left or right, depending on the specific material's resistance to mold growth.

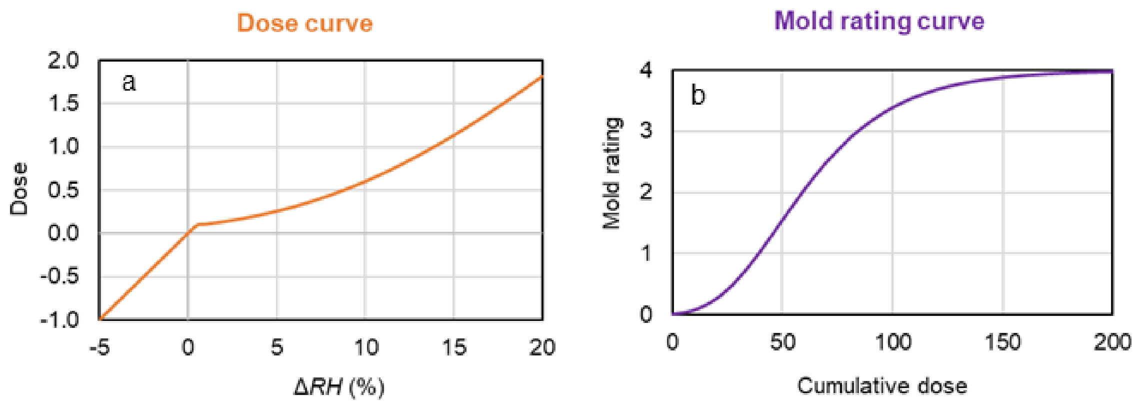

Figure 2 Dose curve (a) and sigmoidal mold rating curve (b) for the DR SIM model.

Unfavorable Conditions

As living organisms, fungi can be negatively affected in inclement environmental conditions, which can include low humidity and both extremes of temperatures. Both models consider conditions to be unfavorable when T ≤ 0 °C (32 °F), T ≥ 50 °C (122 °F), or RH < RH_{crit}. The VTT model decreases the mold index at a rate that depends on the length of time when conditions have been unfavorable and a coefficient specific to the material. The decline and subsequent increase in mold index were intended to mathematically represent empirical observations of the delay in growth, rather than any change in the appearance of the surface (Hukka and Viitanen 1999). The DR SIM model, on the other hand, does not decrease the predicted mold rating when conditions are unfavorable. Instead, it delays the increase once favorable conditions resume. To accomplish this, the model defines a negative dose for unfavorable conditions at a given time step. Negative doses do not contribute to the cumulative dose. If the average dose over the previous 13 days is positive and the dose for the current time step is positive, it is added to the cumulative dose; otherwise, the cumulative dose is unchanged. This 13-day lookback and the negative dose were based on fitting laboratory data with RH conditions cycling above and below RH_{crit} (Boardman et al. 2023).

MODEL EVALUATION METHODS

Laboratory Data

The VTT model and the DR SIM model were developed based on laboratory measurements. Here we test these models against the pine and spruce sapwood datasets on which the VTT model was originally developed and additional datasets from the literature, as summarized in Table 2.

We previously compiled a comprehensive database of laboratory mold growth ratings over time for a range of European and North American wood species and wood-based materials (Boardman et al. 2022, 2023). We extracted T and RH conditions and mold growth ratings from tables and figures in various publications. A rating represents the mean or median of multiple specimen observations at the same environmental conditions at a point in time. The laboratory studies used different inoculation techniques with different mixtures of fungal species that were intended to represent the most common species of concern in wood-frame construction. Given that different rating systems were used to characterize mold growth, for this paper we translated all mold ratings to the mold index scale (0–6) developed by Viitanen and coworkers rather than the 0–4 Johansson scale (Table 1).

Table 2. Literature Sources for Laboratory Mold Growth Ratings[a]

Shorthand Label	References	Materials[b]	Duration, Weeks	Cyclic Conditions?
Viitanen	Viitanen and Ritschkoff (1991) Viitanen and Bjurman (1995) Viitanen and Ojanen (2007)	Pine sw, spruce sw	4–24	Yes
Johansson	Johansson et al. (2012, 2013)	Pine sw, spruce sw	6–32	Yes
Nielsen	Nielsen et al. (2004)	Pine sw	17–30	No
Yang	Yang (2005)	OSB, plywood, aspen sw/hw, jack pine sw, white spruce sw	8	Yes

[a] Available online; see supplementary data from Boardman et al. (2023)
[b] sw, sapwood; hw, heartwood; OSB, oriented strand board

Modeling and Analysis

Both the VTT model and the DR SIM model were run using a one-hour time step. The VTT model was run separately for the Very Sensitive class and the Sensitive class, abbreviated here as VTT/VS and VTT/S, respectively. The DR SIM model parameters were taken from Boardman et al. (2023). The predicted mold rating from the DR SIM model, which uses the Johansson et al. (2012) rating scale (0–4), was converted to a predicted mold index (0–6) using the method proposed by Boardman et al. (2023). For each different material and model, the root mean square error (RMSE) and mean bias error (MBE) between model predictions and measured mold growth ratings were calculated.

In addition to these fitting statistics, the models were evaluated using binary pass/fail assessments based on the mold ratings for each laboratory measurement condition. These categories were defined by the mold index value M in relation to a threshold value X, where "fail" corresponds to $M \geq X$ and "pass" corresponds to $M < X$. A model assessment for a given condition was correct if it gave the same binary result as the measured data. Threshold values of $X = 2$ and $X = 3$ were considered. The latter ($X = 3$) is based on the mold index value at which growth can be detected visually without magnification (Viitanen and Ritschkoff 1991) and coincides with the evaluation criterion in ASHRAE Standard 160 (ASHRAE 2021a). The former ($X = 2$) is investigated as a stricter alternative based on the MRD model (Thelandersson and Isaksson 2013).

RESULTS AND DISCUSSION

Measurement and Modeling Examples

Several examples of laboratory mold ratings over time are compared with model predictions in Figure 3. These represent a selection of four cases out of 145 total cases analyzed. A "case" is a series of mean or median mold ratings over time for multiple samples of a material under a set of temperature and relative humidity conditions (constant or cyclic). The VTT model, using the Very Sensitive class (dashed curves), closely fits the data for pine sapwood, both for constant (Figure 3a) and cyclic RH conditions (Figure 3c). This is expected because the model was originally developed using these datasets. The VTT model, using the Sensitive class (dotted curves), generally underpredicts the measurements for pine sapwood (Figure 3a and 3c). This is merely for illustration; pine sapwood is classified as very sensitive rather than sensitive. The VTT/VS model considerably overpredicts for the OSB example case (Figure 3b) and slightly underpredicts for the plywood example case (Figure 3d). The DR SIM model (solid curves) gives similar results to the VTT/VS model for pine sapwood and plywood, while overpredicting for OSB but less so than the VTT/VS model.

Model Statistical Quality

The RMSE and MBE values are summarized in Table 3 and discussed below for each model.

VTT/VS. The RMSE is 0.9 for the Viitanen pine and spruce sapwood datasets. The MBE values are positive (0.4 and 0.5), indicating that the model gives a slightly higher prediction of mold growth in general than the laboratory data. It should be noted, however, that a given individual case could be overpredicted or underpredicted. For the Nielsen pine sapwood dataset, the RMSE is the same (0.9) with a slightly smaller MBE (0.2). In contrast, for the Johansson pine/spruce sapwood dataset, the RMSE is larger (1.4); moreover, the MBE (–0.7) is negative with a large magnitude, meaning that the model appreciably underestimates the extent of mold growth. The reason for this discrepancy for the same type of material is unclear. There are several methodological differences between these laboratory studies including the way specimens were conditioned, the scale used to rate mold growth (though we have translated the ratings for direct comparison), and the reporting of mean values vs. median values. The RMSEs for North American materials (Yang data) are larger than for the Viitanen data (1.1–2.1), and the MBEs are all positive (0.4–1.3). The VTT/VS model statistics are better for aspen sapwood, jack pine sapwood, and white spruce sapwood than OSB, plywood, and aspen heartwood.

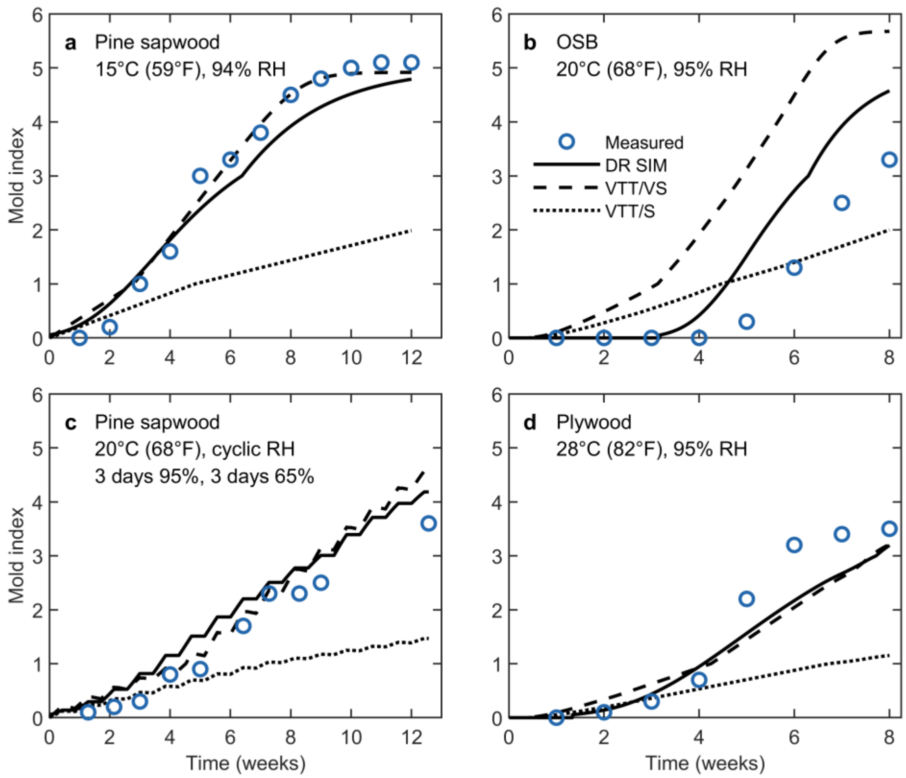

Figure 3 Model predictions compared with laboratory data for select examples: (a) pine sapwood (Viitanen and Ritschkoff 1991), (b) oriented strand board (Yang 2005), (c) pine sapwood (Viitanen and Ojanen 2007), and (d) plywood (Yang 2005).

Table 3. Model Fitting Statistics

Dataset	Material[a]	Cases	Root Mean Square Error			Mean Bias Error		
			VTT/VS	VTT/S	DR SIM	VTT/VS	VTT/S	DR SIM
1	Viitanen pine sw	41	0.9	1.5	0.8	0.4	–0.8	0.0
2	Viitanen spruce sw	29	0.9	1.5	0.9	0.5	–0.8	0.0
3	Johansson pine/spruce sw	14	1.4	1.9	1.0	–0.7	–1.2	0.0
4	Nielsen pine sw	7	0.9	1.2	0.9	0.2	–0.8	0.3
5	Yang OSB	9	1.8	1.3	0.8	1.1	–0.2	0.0
6	Yang plywood	9	2.1	1.0	0.4	1.3	0.0	0.0
7	Yang aspen sw	9	1.4	1.6	0.9	0.6	–0.7	0.0
8	Yang aspen hw	9	2.0	1.1	0.8	1.3	0.0	0.1
9	Yang jack pine sw	9	1.1	1.9	0.9	0.4	–0.9	–0.2
10	Yang white spruce sw	9	1.4	1.5	1.0	0.8	–0.5	–0.1

[a] sw, sapwood; hw, heartwood; OSB, oriented strand board

VTT/S. This model gives larger RMSE values than the VTT/VS model and negative MBE values of large magnitude for Viitanen pine and spruce, Nielsen pine, and Johansson pine/spruce. These materials would be classified as very sensitive rather than sensitive; the results illustrate the impact of a user selecting the wrong sensitivity class. The VTT/S model also has larger RMSE values than VTT/VS for aspen sapwood, jack pine sapwood, and white spruce sapwood. On the other hand, it has lower RMSE values for OSB, plywood, and aspen heartwood, with MBE values near zero. Although the sensitivity classes are based on measurements using European materials, a user would most likely select the sensitive class for OSB and plywood because they are "wood-based boards" (Ojanen et al. 2010).

DR SIM. This model gives similar or lower RMSE values than the VTT/VS model for the Viitanen, Johansson, and Nielsen datasets. Moreover, the MBE values for the DR SIM model are relatively close to zero, indicating that it does not generally overpredict or underpredict. For the North American materials, the DR SIM model gives considerably lower RMSE values than the VTT/VS and VTT/S models. This observation needs to be qualified by the fact that the material-specific parameters of the DR SIM model were separately optimized for each material type, whereas the VTT/VS and VTT/S models are based on a material classification that was developed for a wide range of materials (no parameters were changed in this study). The DR SIM model might be over-fitting the data in some cases. For example, the critical RH would not be expected to differ much across the various woods and wood-based materials considered here, but the shape of the parabolic RH_{crit} curve of the DR SIM model does show wide variation (Boardman et al. 2023). For the North American materials, this might reflect the influence of a limited temperature range; the data from Yang (2005) had one measurement condition at 10 °C (50 °F) with most conditions at 20–28 °C (68–82 °F).

Model Accuracy for Pass/Fail Assessment

Model accuracy is plotted in Figure 4 for each dataset listed in Table 3 for the two threshold values used to discriminate between pass and fail. The VTT/VS model has an accuracy of 90% or better for the original Viitanen pine and spruce datasets (datasets 1 and 2, respectively). However, this drops to 57% and 71% for the Johansson and Nielsen datasets (labels 3 and 4, respectively). The VTT/VS model accuracy for the Yang datasets is in the range 56–100%. In contrast, the VTT/S model is considerably less accurate than VTT/VS. As mentioned previously, untreated wood should be considered very sensitive rather than sensitive. The VTT/S model accuracy is similar to VTT/VS for OSB and plywood (labels 5 and 6, respectively), consistent with the better RMSE and MBE values in Table 3 for these materials.

The DR SIM model accuracy is in the range 67–100% across all datasets. It is on average more accurate than VTT/VS. The only cases where VTT/VS is more accurate than DR SIM are the original Viitanen pine and spruce datasets using a threshold value of 3, and even here the differences are only 2–3%.

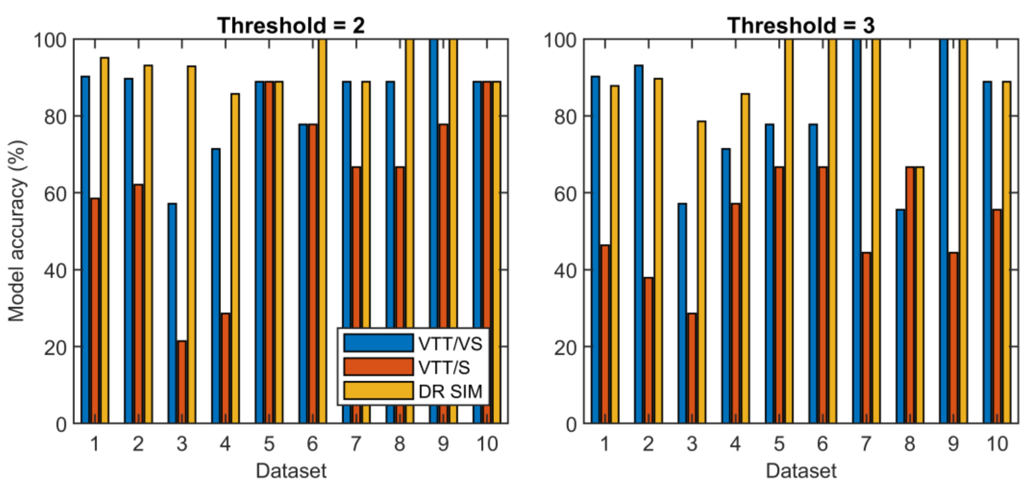

Figure 4 Accuracy of the models for pass/fail assessment compared with laboratory data (see dataset numbering in Table 3) using threshold mold index values of 2 (left) and 3 (right).

Model Advantages and Limitations

The VTT model was built on a large database of measurements for a broad range of building materials. This study shows that it gives good fitting statistics and pass/fail assessments for the original pine and spruce datasets as well as other laboratory datasets from the literature. However, in some cases the model predictions are less accurate. The minimum RH_{crit} value of 80% (see Figure 1) can be critically examined by reference to laboratory data. Certain fungal species are known to have critical RH values as low as 75% (IEA 1991). Although Viitanen and coworkers did not observe mold growth over a period of 12 weeks for RH conditions below 80%, other groups have made such observations over extended conditioning periods. Nielsen et al. (2004) reported mold growth on pine sapwood at 25 °C (77 °F) and 78% RH after 30 weeks. Johansson et al. (2012) reported mold growth on pine sapwood at 22–23 °C (72–73 °F) and 75–76% RH after 26–32 weeks. These datasets indicate that mold growth is marginally favorable under these conditions, although it takes a long time for germination and growth. However, the VTT model sets the minimum RH_{crit} at 80% and thus dictates that the mold index declines rather than increases when RH is slightly below 80%.

The DR SIM model has an RH_{crit} curve that can be adjusted depending on the material, so it may be able to overcome this limitation of the VTT model. The DR SIM model structure is more transparent and easier to modify if sufficient data are available for the material in question. Two features more closely resemble the biology of fungal growth: the sigmoidal mold rating curve and the delay in growth (rather than decline) when conditions are unfavorable. The DR SIM model predictions overall are more accurate than the VTT model in terms of RMSE and MBE as well as pass/fail accuracy. However, this might be partly attributable to over-fitting as discussed previously. Further work is recommended to examine the effect of using a set of material class RH_{crit} curves instead of allowing the shape to vary for each individual material. Additional work is recommended to investigate whether the DR SIM model can be used for materials that are more resistant to mold growth than wood and wood-based materials.

Both models assume that relative humidity at the substrate surface is the relevant moisture metric for mold growth. However, this simple assumption is not generally correct, as independent effects of relative humidity and material moisture content were observed for growth of *Penicillium rubens* on gypsum (van Laarhoven et al. 2015). Furthermore, the material microclimate and the three-dimensional nature of fungi are more complex than what is measured by RH sensors or simulated by one-dimensional hygrothermal models.

CONCLUSION

This paper critically evaluates the VTT model, a pioneering model used widely by researchers and practitioners, and the Dose-Response Simple Isopleth for Mold (DR SIM) model, which was recently developed. Structural differences between the models include the critical relative humidity curve, the mold growth rating scale, how the rate of mold growth is calculated, and how unfavorable conditions are treated. Specifically, the VTT model decreases the mold index, whereas the DR SIM model pauses and delays the increase in predicted mold rating when favorable conditions resume.

Experimental evidence suggests that the minimum critical RH of 80% in the VTT model may be too high. The DR SIM model allows for setting a material-specific critical RH and more closely simulates the biology of fungal growth using a sigmoidal mold rating curve and a delay in growth (rather than decline) when conditions are unfavorable.

Analysis of laboratory mold growth datasets from the literature indicates that the DR SIM model overall has similar or better fitting statistics than the VTT model and is generally more accurate at pass/fail assessments. However, these results depend on optimizing the DR SIM model to the same laboratory datasets, and the possibility of overfitting needs further investigation. Further laboratory and field mold growth data on North American materials would be valuable for improving models that assess risk of mold growth on building materials.

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