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A probabilistic-based approach for predicting mould growth in timber building envelopes: Comparison of three mould models

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Abstract

This paper applies a probabilistic-based approach as a methodology to analyze and compare the mould growth computations' results from three different mould models. This approach, instead of the conventional deterministic ones, offers the advantage of accounting for uncertainties concerning prediction of mould growth. The results are able to demonstrate more realistic and conclusive outcomes that can be applicable to real-life situations.

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1. Introduction

Mould is one of the problems in wooden constructions, which can result in financial loss and unfavourable social problems such as discomfort and health risks [1-3]. Mould growth is a very complex phenomenon [4] influenced by variables of stochastic nature such as weather conditions and indoor climate that are characterized by uncertainties in the models representing the phenomena. Uncertainties in predicting mould occurrence are twofold; a) those related to the representation of the biological activity, and b) those related to the representations of climate exposure.

During the last two decades, different mould models have been developed to predict mould growth on the surface of wood-based materials [4]. Many authors have compared the calculated mould growth from different mould models,

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where both agreements and disagreements have been found [4-10]. However, these comparative studies are based on a deterministic approach, and therefore they do not account for the uncertainties involved. By applying the latter methodology, it may lead to inconclusive results for applications in building engineering, where mould models are expected to assess the likelihood of mould germination (onset of mould) on the material surface exposed to natural weather conditions. Plausible comparison between mould models are required in order to deliver directions and guidelines of their applicability. In light of this, this paper proposes to analyse and compare mould models by using the results of mould occurrence in a timber envelope calculated by a probabilistic-based approach. This methodology offers the advantage of providing more overarching results due to the following properties:

- It accounts for uncertainties related to the boundary conditions that affect the hygrothermal conditions on the materials' surface, which are further used as the input to the mould models.
- It considers both favourable, unfavourable conditions and their interrelations as encountered in real-life application, by using a mathematical expression that generates possible patterns of the weather data in a time series containing plausible sequences, frequencies and correlations.
- It consider models' specific parameters that might affect the result of mould growth including time duration, time step, materials dependencies or other individual model parameters.

2. Material and methodology

2.1. Limitations of current approaches and opportunities associated to probabilistic approach

Many studies have compared the mould models' results in order to get an insight of their applicability and to evaluate their accuracy with each other. Generally, these studies share a similar methodology based on a deterministic approach when comparing results across models. Among other studies, are found comparing; a) basic characteristics of models such as minimum requirements for mould growth (ranges of consideration of governing parameters) [4-7], b) mould growth results exposed to specific user-defined climate scenarios [7, 8], c) mould growth compared to results from experimental research with similar exposure [8, 9] and d) mould growth results of building envelopes exposed to specific reference year(s) [10]. Both disagreements with significant deviation and agreements are reported.

The scope of mould models in the field of building engineering (including the comparison studies) is to assess the likelihood of mould growth in building envelopes, which are exposed to potential natural weather conditions and for a reasonable time duration that can reflect the actual performance. While the results of the aforementioned comparison studies might offer a valuable information regarding the differences between mould models, especially comparison studies with experimental results, they might bring inconclusive results regarding the actual application of these models in the building engineering field. These limitations are grouped as the following:

- Mould models are established by using different methodologies based on results derived from different experiments that have specific settings. From these datasets, mould models have been developed to assess mould growth occurrence for these boundary conditions and further extended to other potential boundary conditions. Due to these differences, there is the possibility that a specific climate exposure falls in 'intermitted' domain that is an exposure that may offer limited conditions for mould growth depending on the model and is treated differently based on the methodology used. For example, when using isopleths, such exposure is always treated as favourable, while when using a regression technique, it might fall outside the valid domain of the regression equation. Therefore, a specific combination of the hygrothermal conditions (i.e. change of relative humidity from 90% to 60%) might provide different growth when calculated from different models. However, this type of exposure considers the variation of the weather parameters in a non-realistic way. While user-defined exposure conditions might reveal that these models have specific domains where they contradict each other, this might be misleading and does not give conclusive results as a basis for their building engineering application since these data may not reflect reality.
- Mould growth is communicated by different rating scales or quantities in different models. The results must be carefully evaluated and interpreted when comparing models using different rating scales, even though these scales are described with similar prescriptive characteristics, which however are based on human visual judgement.
- Mould models' results are sensitive to the materials' characteristics being investigated and to its hygrothermal conditions. The latter depend on variables that have a stochastic nature including weather conditions, interior climate and material properties. These variables are also depending on stochastic parameters including the initial

time of the weather exposure and its duration. Consequently, when using the traditional approach (deterministic) to compare different mould models, the results do not account for the aforementioned uncertainties, which leads to inconclusive results and improper recommendations of the models applicability in engineering practice.

These reasons may be an explanation of the large discrepancies found in studies when comparing different models under specific climate exposure. A more plausible comparison can be developed through a probabilistic approach [11] since it offers the possibility to account for these uncertainties related to model predictions and additionally, reduce the possibility of providing results that might fall in the ‘intermittent’ domain. Moreover, by running sensitivity analysis or parametric studies, the influence of different parameters associated to the models can be investigated, which forms a more overarching comparison basis of the models.

2.2. Building envelope construction and simulation set-up

During recent years, there has been increasing interest in the use of OSB (Oriented Strand Board) as wind retarders instead of more traditional membrane solutions, even though issues concerning water resistance and air-tightness remain the subject of some discussion [12]. For this reason, this paper investigates a configuration where an OSB board is the wind retarder (see Fig. 1).

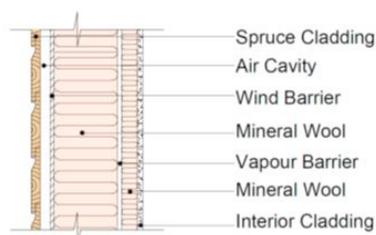


Fig. 1. The cross-section of the timber-building envelope

The calculation of the mould growth is performed by using a probabilistic-based approach as introduced in [11]. The heat and moisture simulations are performed using the hygrothermal building simulation software WUFI® [13]. The initial conditions inside the envelope are set at RH=80% and T=20°C. The indoor climate is represented by a sine wave derived from a single year period representing medium moisture load according to WUFI. Ten-year hourly-based records data (relative humidity and temperature) in Blindern, Oslo are used as input to represent the outdoor weather data. Time series analysis using ARMA (Autoregressive-Moving Average) [14] models are applied to construct 300 outdoor weather simulations as explained in [11]. These time series are derived from mathematical expressions that generate possible patterns of the weather data containing plausible sequences, frequencies and correlations and, consequently favourable and unfavourable conditions for mould growth as encountered in reality. The mould growth is assessed between the OSB and insulation layer.

2.3. Mould models

During the last two decades, different mould models have been developed to predict mould germination on the surface of wood-based materials [4]. The VTT-model [15], MRD-model [16] and m-model [17] are among them, which also consider the most governing factors affecting mould behaviour [4]. The mould computation framework for each of these models is shown in Fig. 2. One similarity that enables the comparison between them is that they communicate mould growth with the same quantity, *VTT index I* [15]. In addition, these models are originally derived from the same experimental results; however, they are developed with different methodologies and have been further modified through additional different experimental results. Consequently, differences exist, especially in regard to how the fluctuating conditions are considered. The aforementioned reasons are the basis for selecting these models for this comparative study. Additional information regarding these three models can be found in [4, 15-18].

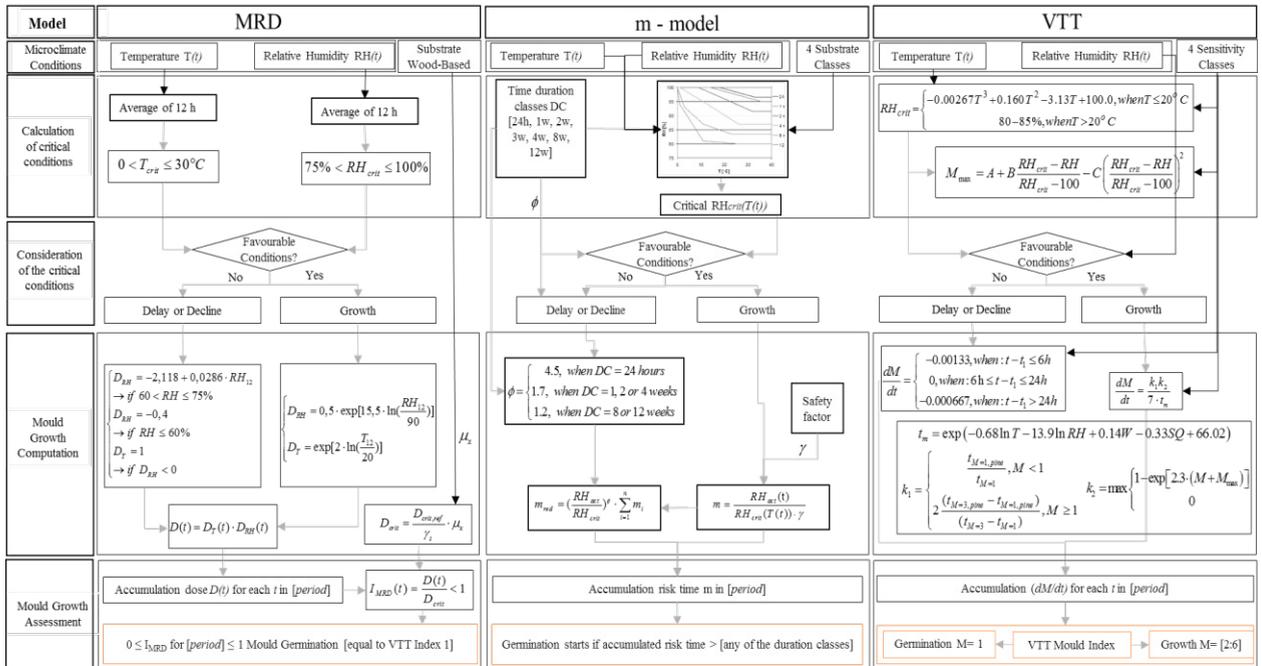


Fig. 2. Mould computation framework for MRD , m-model and VTT as adapted from [18]

3. Results and discussion

Different models’ parameters are accounted in this paper. Four different wood substrates are considered for VTT and MRD model (Spruce Planed *SP*, Pine Planed *PP*, Spruce Kiln-Dried *SK* and Pine Kiln-Dried *PK*). The m-model does not offer a clear difference within wood-based materials and the reference model assesses mould growth on spruce planed surface. For this model, the safety factor $\gamma = [1; 0.99; 0.98]$ is considered.

When considering a time duration of 10 years for Oslo climate, starting in October and ending in September, it is observed that the final mould growth output from each model is zero due to the unfavourable climate condition of the last period. However, higher levels of mould growth are observed during several periods within the 10 years. Fig. 3 shows the mould growth computation of one realization.

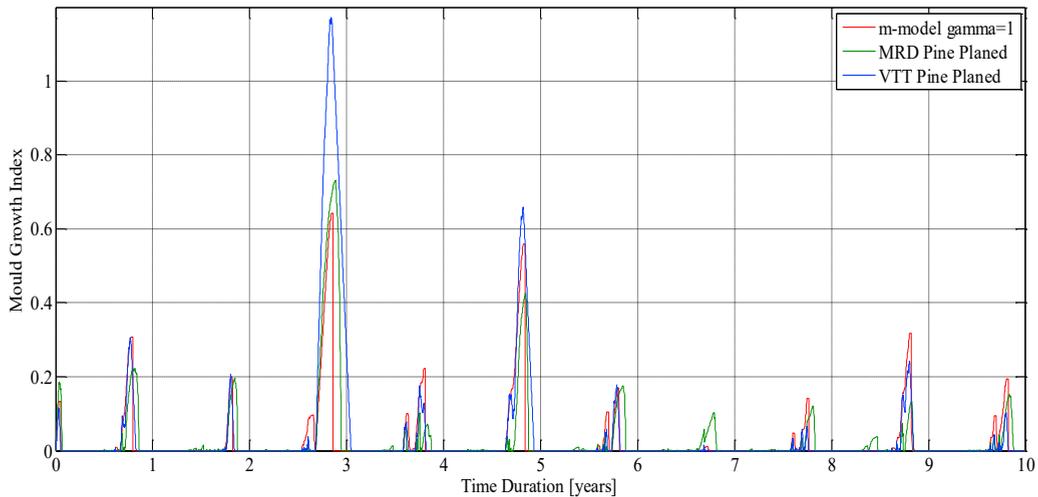


Fig. 3. Mould growth assessment based on VTT, MRD and m-model for time duration=10 years.

The three models show relatively the same behaviour and comparable response to exposure. Nevertheless, conflicting results can also be found, especially during unfavourable conditions. This can be explained from the different methodologies used to establish these models and specific parameters that each model considers. Consequently, comparing the results only by a deterministic approach, these differences might be amplified and lead to unrealistic or inconclusive guidelines for engineering application.

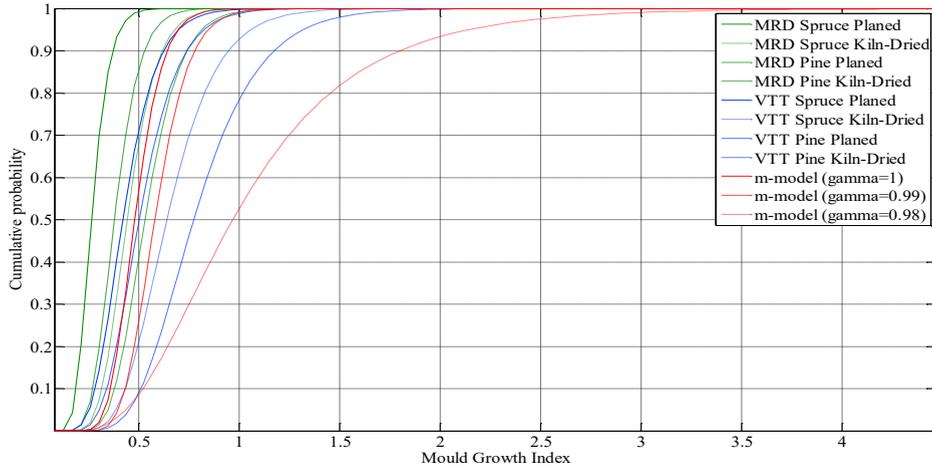


Fig. 4. Cumulative probability distribution of the maximum mould growth occurrence for three models for ten years.

Table 1. The probability of non-exceeding the mould germination. Comparison of three models considering several parameters.

	Spruce Planed	Pine Planed	Spruce Kiln-Dried	Pine Kiln-Dried
MRD model	1.0000	0.9999	0.9991	0.9925
VTT Model	0.9975	0.9886	0.9273	0.7838
m-model	$\gamma=1$	$\gamma=0.99$	$\gamma=0.98$	
	0.9994	0.9911	0.5256	

Table 2. Correlation coefficients of point in time between three models considering several parameters

		MRD model	VTT model				m-model		
		<i>SP, SK, PP, PK</i>	<i>SP</i>	<i>SK</i>	<i>PP</i>	<i>PK</i>	$\gamma = 1$	$\gamma = 0.99$	$\gamma = 0.98$
MRD model	<i>SP, SK, PP, PK</i>	-	0.72	0.69	0.71	0.67	0.45	0.29	0.16
VTT model	<i>SP</i>	0.72	-	0.98	1	0.96	0.69	0.49	0.26
	<i>SK</i>	0.69	-	-	0.99	0.99	0.73	0.52	0.27
	<i>PP</i>	0.71	-	-	-	0.97	0.71	0.50	0.26
	<i>PK</i>	0.67	-	-	-	-	0.74	0.53	0.26
m-model	$\gamma = 1$	0.45	0.69	0.73	0.71	0.74	-	0.74	0.23
	$\gamma = 0.99$	0.29	0.49	0.52	0.50	0.53	-	-	0.38
	$\gamma = 0.98$	0.16	0.26	0.27	0.26	0.26	-	-	-

In light of this, the cumulative probability distributions (see Fig. 4) of the maximum mould growth occurrence are computed. Lognormal distributions are fitted to the data. Table 1 shows that the probabilities of reaching at least the mould index 1 in ten years can be considered comparable to each other. In addition, similar behaviour is observed for some of the results between the models, even though not for the same material across models. When another mould growth level is selected (lower than index 1), high scatter of results is observed and the gap between the probabilities is significantly different. Mould growth behaviour is sensitive to the parameters considered, and thus attention is

required when analysing and interpreting the outcome, especially in comparative studies. Table 2 shows the correlation coefficients of the points in time between the computed mould growths. The correlation between the VTT and MRD model varies from 0.67 to 0.72, while between m-model ($\gamma=1$) and VTT or MRD is 0.69 and 0.45 respectively. Decreasing the safety factor γ , less correlation is observed. The safety factor in the m-model $\gamma=0.98$ provides very conservative results when compared to other models.

4. Conclusion

This paper applies a probabilistic-based approach as a methodology to analyse and compare the mould growth computation results from three different mould models. This approach accounts for uncertainties concerning mould growth prediction, and therefore the outcomes are able to demonstrate more realistic and conclusive results, applicable to real-life engineering applications. While several similar results from the three mould models are observed, disagreements between each other remain substantial. The mould growth behaviour is very sensitive to the decision of which parameters are considered, and consequently attention is required when analysing and interpreting the outcomes, especially in comparative studies.

Mould growth assessment should be considered as an attempt to predict the likelihood of mould occurrence rather than the exact growth. Current mould models can be applied in influence or sensitivity analysis. Solutions on how to further account for and reduce uncertainties related to modelling mould behaviour are proposed by:

- Improving and/or validating current mould models through additional experimental studies.
- The development of a new mould model.
- Another solution, which can be more cost- and time- effective, is the integration of different models into one.

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