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Mould Models Applicable to Wood-Based Materials – A Generic Framework

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Abstract

This paper systematically reviews mould models that are applicable to wood-based materials. Both similarities and differences are observed with respect to governing factors and their interrelations, methodology, experimental set-ups, substrate and extensiveness, and how the result is communicated. Therefore, a generic framework, representing the general computation procedure of all models, is developed considering the factors that govern mould behaviour. This framework, adapted to each model, is used to structure, evaluate and compare current models. This outline supplemented with a comparison table, revealing the models' extensiveness and differences, establishes a basis to ensure better adequate application of the selected mould model for the case at hand.

Keywords: Mould, Wood, Timber, Mould Models, Generic Framework, Systematic Review

1. Introduction

Mould can result in financial loss and unfavourable social problems such as discomfort and health risks [1]. Mould prevention is a conventional design stage part; however, the repeated problems in buildings suggest that the representation of this biological phenomenon need clarification [2]. Models have been developed attempting to represent mould growth activity [3-6]. Discrepancies have been found when comparing these models with each other, or when analyzing their validity with results from experimental research [2]. These differences and discrepancies may

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impose challenges for selecting the adequate model. Therefore, this paper's scope is to provide clarity in this field, by offering the end-user basis and background for the selection of the most applicable model to the specific case at hand.

2. Methodology

This article is a complementary work of a systematic literature review [2] investigating the criteria and models representing mould activity in wood-based materials. The review methodology and its application can be found in [2]. The validity and limitation of the models compared to the results from the experimental research review is also discussed in [2]. The scope of the present paper is to extent the previous work by providing a summary and more clarity of the differences between mould models, and therefore improve their applicability, by:

- Identifying and describing current available mould models applicable to wood-based materials.
- Creating a scheme derived from results in [2] that presents the mould governing factors and their features that should be considered when opting the representation of mould growth activity.
- Converting this scheme into a generic framework which can be used: a) to inform and guide researches of the necessary steps and features to be considered when developing new models applicable to building engineering and/or b) to structure, evaluate and compare current models by creating a neat outline.
- Adapting this framework to current models to show in a structured manner their computation procedure.
- Creating an overview table that shows and compares the characteristics of mould models including the governing factors and their extension, experimental basis used and characteristics of the assessment procedure.

3. Results

3.1. Proposed scheme and generic framework

From the review of experimental research [2], mould governing factors are identified and brought schematically in Fig. 1 (a). This scheme is further developed and converted into a generic framework showing the general approach to mould growth assessment (see Fig. 1 (b)) that accounts for these factors and how they are considered in current models.

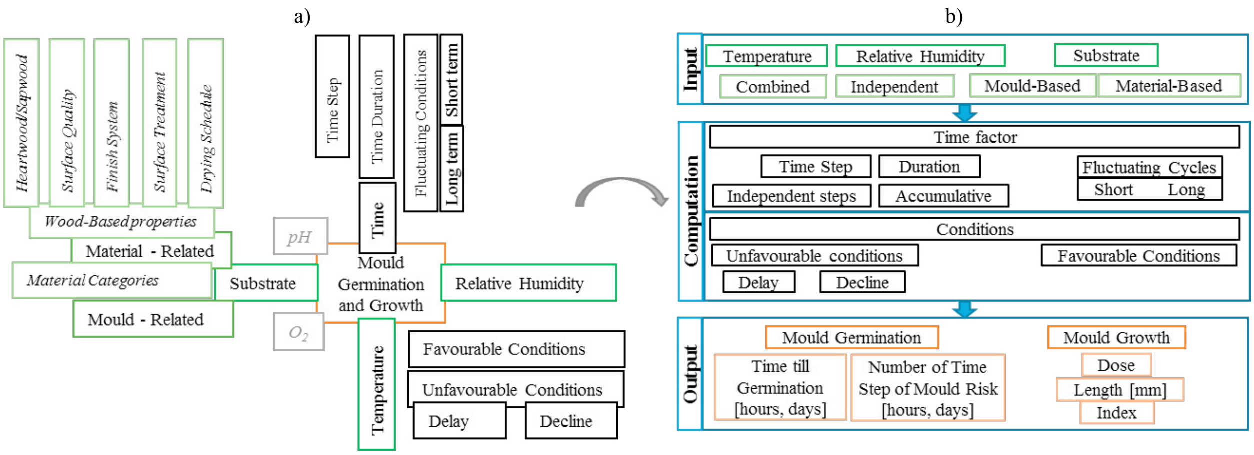

Fig. 1. Proposed scheme presenting mould governing factors and their features (a) and generic framework (b).

Three main parts are categorized; input (governing parameters that depend on the material and its exposure, temperature T and relative humidity RH), computation procedure and output (how results are communicated). Models are established as mould-based or material-based. Mould-based models are developed considering either the most common mould fungi, and thus excluding potential others; or as the mould fungi with the lowest requirements for growth, and thus considering the worst-case scenario; or several categories of mould fungi. Material-based models may create a more realistic basis for mould computation as in real-life situations. Materials' variation consideration are based on mould growth susceptibility, varying from broad categories up to specific materials with specific properties. Consideration should be put while defining the range of categories, since unrealistic mould computation may result due to the incorrect assumed substrate class or broad categorization. Small differences in material properties may provide different mould growth result [2]. Additionally, these models are fitted based on measurement of specific materials or mould fungi and therefore attention is required when using them outside the domain and conditions they were derived from. The computation procedure and methodology used to establish the model are two other crucial characteristic. Careful attention should be put on modelling the fluctuating condition, on the assessment duration and on a time-step that considers the variation of the hygrothermal properties. Two main mould outcome are calculated, mould germination (the onset of the fungi) and/or its growth (expressed in different levels or units). The outcome should be clearly defined, expressed in realistic unit and applicable to real-life situation and if categorized, a clear distinction of the categories should be available. Complementary to this framework, Table 1 provides suggestion when developing or improving mould model and Table 2 gives an overview of how current mould models (identified below in 3.2) consider these characteristics of the three main parts.

Table 1. Suggestions regarding what to consider when developing or improving mould models.

Input	The ranges of T (both low T<5ºC and T>30ºC) and RH (70 - 80 %) should be carefully considered. These two variables should be considered as joint contribution to mould growth [2].
	Material variation is very important and clear distinguishment of materials or groups of materials should be available, since different material own different mould growth susceptibility. Wood-based properties that affect mould growth should be also considered.
Computation	Time step should be sufficiently short to consider the variation in time of temperature and relative humidity. One hour is suggested.
	The assessment duration should account for the total service life of the construction which is checked for mould occurrence.
	Fluctuating condition must be carefully modeled, accounting for both long and short cycles.
	A delay and a decrease of mould growth should be both considered depending on the encountered unfavourable conditions.
Output	Clear ranges of mould germination and growth should be available, where it is possible to derive the consequences of the specific range. It is suggested to use the standard available scales, used for inspection as in the guidelines, for example as in EN 927-3.
Method	Consideration when extending the model from the measurements and domain that were considered during the experimental set-ups. Isopleth considers the worst-case scenario, while regression technique might not include potential scenarios of mould growth.
	Model should account for uncertainties, both for the data retrieved from the experiments and when modeling the computational equations.
	Calibration of models with real-life situation should be an ongoing update project.

3.2. Identification of mould models and individual application of generic framework

VTT Model **-** The VTT model [7] consists of a differential equation based on laboratory studies in [8-10]. The model is improved [11] by investigating the variation of different materials. Four sensitivity classes are considered based on different coefficients and minimum requirements of RH. The mould growth is quantified by the mould index varying from zero to six where mould index 1 indicates germination. The model accounts for long seasonal cycles (> 24 hours), where during unfavourable conditions growth is modeled with a linear decrease.

MRD (Mould Resistance Design) model **-** This dose-response model [12] predicts mould germination (corresponding to VTT Index 1) based upon the results of experimental data [8, 10]. The model is originally based on daily averages of RH and T, however later is modified with 12 hour averages [4]. The total dose $D(t)$ for n days is the sum of the 12-hour averages doses D. It is further calibrated with new laboratory data for wooden materials by [13]. The model considers results from [14] for unfavourable conditions, and [13] for the effect of cyclic RH and T. The difference between wood-based materials is considered from the factor μ_x.

m-model **-** The m-model calculates the 'accumulated risk time' until germination (VTT Index 1) based on hourly-data [5]. The model is based on the laboratory studies [8, 9, 15, 16], where six mathematical expressions of the critical humidity are calculated for six duration. The total accumulated risk is the sum of all time steps where the parameter $m \geq 1$ considering unfavourable conditions. This model has similarities regarding the concept of 'm' as in [17].

Biohygrothermal IBP **–** This model combines Lowest Isopleth Model (LIM) model that determines germination time for spores and mycelium growth rate, and a transient biohygrothermal model that considers the influence of varying conditions [3, 18]. Four substrate categories are used. The LIM curves for each category represent minimum requirements assuming worst-case scenario. Mould growth is modeled as a non-declining and expressed in mm.

Johansson et al. Model **-** The model is based on results from house façades exposed in outdoor conditions over a 20-month period, investigating the influence of the thermal inertia, surface colour and compass directions [19]. Three different indices are used to express mould growth. The first index is based only on the RH at room T. In the second index, two functions are introduced to account for the interaction between RH and T, derived from literature data for

Cladosporium spp. The third index includes a delaying function when the organism has been outside its growth limits (when either both or one of functions equals zero), however the duration of this time is not provided.

Gobakken et al. Model **-** A cumulative logit model is developed from extensive experimental studies investigating large variation of wood substrates, surface structure, paint system, coating typology in [20-22]. The latest model is a function of wood substrate, coating typology, exposure time, RH higher than 80 % and T higher than 5 ºC.

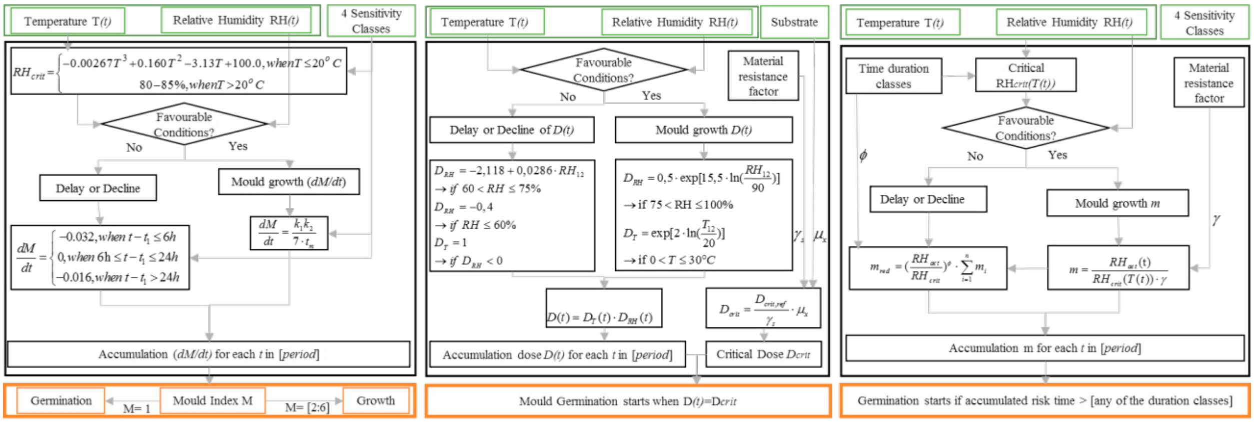

Fig. 2. Individual Generic Framework for VTT- (left), MRD- (middle) and m-model (right).

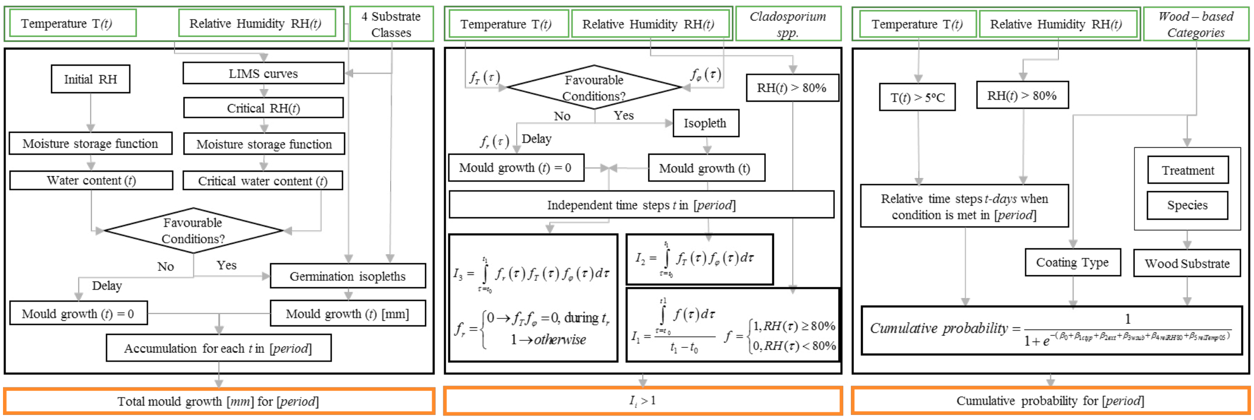

Fig. 3. Individual Generic Framework for Biohygrothermal- (left), Johanson et al. - (middle) and Gobakken et al.-model (right).

Mould Germination Graph Method **–** The model [23] accounts for previous time steps of RH and T to consider the effect of the fluctuating conditions. Mould growth is expressed as the number of mould risky days over a simulation period. During unfavourable conditions, the exposure time is set to zero. The graph is based on the isopleths of *A. Restrictus* [24, 25]. Each state condition is assigned into one of the groups presented at the mould germination graph. The effect of different building materials is not considered, however a correction factor can be used.

Max-days Model **-** The Max-days model [26, 27] assesses the mould growth based on weekly averages of hygrothermal properties. The mould growth potential 'Max-days' is calculated for one-year period. The relative growth rate is calculated for each week and is summed for a year and the result is expressed as the number of days with maximum conditions for germination. The model is derived using the experimental results from [8].

ESP-r Model **-** A literature review [28] investigated mould species affecting UK dwellings, which were grouped in six categories possessing similar growth requirements in terms of T or RH [29]. For each category, growth limit curves are generated from experimental data. The effect of exposure time and transient conditions is neglected.

Other models [24, 25, 30-34] are no further discussed due to restricted applicability or the same principles and data are advancements by other authors. Studies suggesting ergosterol as an indicator of mould growth, are not intended to use for prediction of mould germination and therefore are not treated any further in this article.

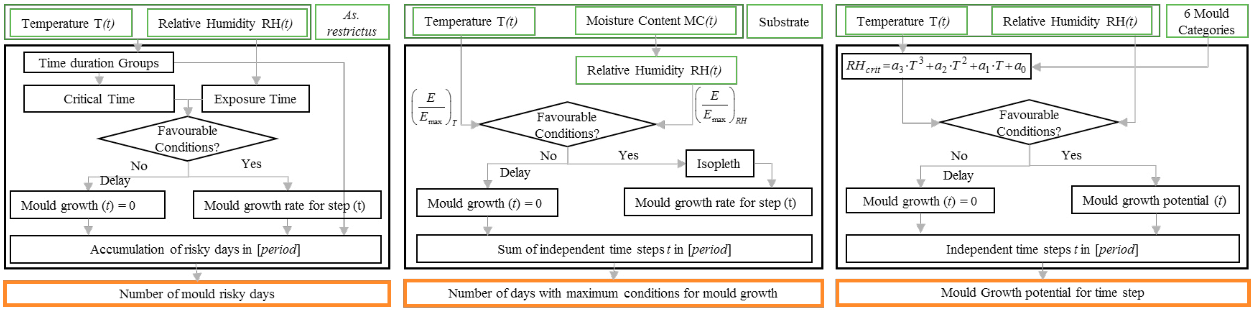

Fig. 4. Individual Generic Framework for Mould Germination Graph- (left), Max Days- (middle) and ESP-r model (right).

Table 2. Overview of characteristics of mould models (symbol '✓' stands for 'accounted or covered in the model', symbol '-' stands for 'not accounted or not covered', symbol 'Y/N' stands for Yes/No).

Factor	Model	ESP-r (1996)	Max days – Model (1997)	VTT Model (1999)	Biohygro-thermal (2001)	Mould Germination Graph (2004)	Johansson et al. Indices (2001)	MRD Model (2010)	Gobakken et al. model (2010)	m - model (2011)
RH	<75 %	-	-	-	✓	✓	-	-	-	-
	75 % - 80 %	✓	✓	-	✓	✓	-	✓	-	-
	>80 %	✓	✓	✓	✓	✓	✓	✓	✓	✓
T	<0 ºC	-	-	-	✓	-	✓	✓	-	✓
	0 ºC – 5 ºC	-	✓	✓	✓	-	✓	✓	-	✓
	5 ºC - 30 ºC	✓	✓	✓	✓	✓	✓	✓	✓	✓
	>30 ºC	✓	✓	✓	-	✓	✓	-	✓	✓
Experi-ments	Agar	✓	-	-	✓	✓	✓	-	-	-
	Laboratory	✓	✓	✓	✓	-	-	✓	-	✓
	Exposed	✓	-	-	-	-	✓	-	✓	-
	Visual	✓	✓	✓	✓	-	✓	✓	-	✓
	Microscope	✓	-	✓	✓	✓	✓	✓	✓	-
Assess-ment	Germination	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Growth	-	✓	-	✓	-	✓	-	✓	-
	Unit to express	Y/N	Y/N	VTT Index	mm, Index	Time	Mould Indices	Time, Index	logit ratio	Time, Index
Comp-utation	Delay	-	-	✓	✓	✓	✓	✓	implicit	✓
	Steps	hourly	weekly	hourly	hourly	daily	hourly	12 hours	daily	hourly
	Decrease	-	-	✓	-	-	-	✓	implicit	✓
	Ass. Period	no limit	one year	no limit	no limit	no limit	no limit	no limit	12 years	4 years
	Mould-based	Six mould categories				*A. Versicolor*	*Cladosporium spp.*			
	Material-based		Wooden materials	Four classes	Four classes		Wooden materials	Variation of wooden materials	Wooden materials & properties	Four classes
Methodology		Equation & Isopleths	Equation	Equation	Isopleths & Equation	Isopleths & Equation	Indices & Isopleth	Dose & Isopleths	Probabilistic model	Equation

4. Conclusions

Current mould models possess different characteristics and assumptions that contradict each other. They differ with respect to governing factors and interrelations, methodology, experimental set-ups, substrate and extensiveness, and how they express mould. In order to assure better adequate applicability, a clear overview of mould models accompanied with a sound comparison revealing characteristics, limitation and extensiveness is provided by:

- Identifying current mould models applicable to wood-based materials by conducting a systematic literature review.
- Proposing a generic framework which can be used: a) to inform and guide researches of the necessary steps and what to be considered when developing new models and/or b) to structure, evaluate and compare current models

by creating a neat outline. Through adapting this framework to each mould model, a clearer overview of the individual computation procedure of each model is provided, and therefore the comparison is clearer and simpler.
- Creating an overview table of comparison showing clearly the differences between mould models.

Acknowledgements

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