MATHEMATICAL FORMULATION OF THE FINNISH MOLD GROWTH MODEL

The Finnish mold growth model is the current state of the art of dynamic mold growth modelling. The model was originally developed for wood (Hukka and Viitanen 1999) and is based on extensive laboratory experiments with Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). The model is a pure mathematical representation of mold growth, i.e. it does not model real biological processes at microscopic mold domain.

The model predicts the time evolution of the mold index M [–], which is a dimensionless quantity taking values in the interval 0 – 6 (see the definition in Tab. 1). The mold index describes the stages observable only by a microscope ($M < 3$) and the stages observable by naked eyes ($M \geq 3$). The hourly values of temperature Θ [°C] and relative humidity RH [%] serve as model inputs. Temperature and relative humidity at the surface of a hygroscopic substrate material should be used for the calculation of mold development under dynamic boundary conditions (Viitanen et al. 2008). If ambient conditions are used instead, the mold index will be overestimated (Colinart et al. 2017).

TABLE 1. Definition of mold index M according to (Ojanen et al. 2011)

M	Growth stage
0	No growth
1	Small amounts of mold on surface (microscope), initial stages of local growth
2	Several local mold growth colonies on surface (microscope)
3	< 10 % coverage of mold on surface (visual) or < 50 % coverage (microscope)
4	10 – 50 % coverage of mold on surface (visual) or > 50 % coverage (microscope)
5	Plenty of growth on surface, > 50 % coverage of mold on surface (visual)
6	Heavy and tight growth, coverage around 100 %

The intensity of mold growth is modelled by the equation:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \frac{k_1 k_2}{7 \cdot t_{M=1}} \qquad [\text{–/day}] \qquad (1)$$

where M [–] is the mold index, t is time, $t_{M=1}$ [week] is the time required to reach the mold index $M = 1$, which is defined according to (Viitanen 1996):

$$t_{M=1} = \exp(-0.68 \cdot \ln(\theta) - 13.9 \cdot \ln(RH) + 0.14 \cdot W - 0.33 \cdot SQ + 66.02), \qquad [\text{week}] \qquad (2)$$

where Θ [°C] is temperature, RH [%] is relative humidity, W [-] is coefficient depending on wood species (0 – pine, 1 – spruce), SQ [-] is coefficient depending on the quality of the surface (0 – resawn, 1 – original kiln dried).

Parameters k_1 and k_2 are functions of $M(t)$. Parameter k_1 controls the growth rate in the initial stages of growth, whereas parameter k_2 controls the deceleration of growth in later stages of growth. Parameters are defined as:

$k_1 = k_{11}$	for $M(t) < 1$	[–]	(3)
$k_1 = k_{12}$	for $M(t) \geq 1$		
$k_2 = 1 - \exp\big(2.3(M - M_\infty)\big)$	$k_2 \geq 0$	[–]	(4)

where k_{11} and k_{12} are constants listed in Tab. 2 and M_∞ [-] is the maximum mold index for actual environmental conditions. As mold index approaches M_∞, the coefficient k_2 decreases from one to zero and gradually reduces the intensity of mold growth.

The maximum mold index M_∞ is defined as a function of relative humidity and temperature (see Fig. 1):

$$M_\infty = A + Bx - Cx^2 \qquad [–] \qquad (5)$$

where A, B, C are parameters (Table 2), and normalized independent variable x [–] is defined as follows:

$$x = \frac{\varphi - \varphi_c}{1 - \varphi_c} \qquad [–] \qquad (6)$$

where φ [–] is relative humidity and φ_c [–] is critical relative humidity for mold growth.

The critical relative humidity for mold growth φ_c is defined as:

$$\varphi_c = \frac{1}{100}(-0.0267 \cdot \theta^3 + 0.160 \cdot \theta^2 - 3.13 \cdot \theta + 100), \text{ when } \Theta \geq 20\ °\text{C} \qquad [–] \qquad (7)$$

otherwise φ_{min} defined in Table 2.

where Θ [°C] is temperature.

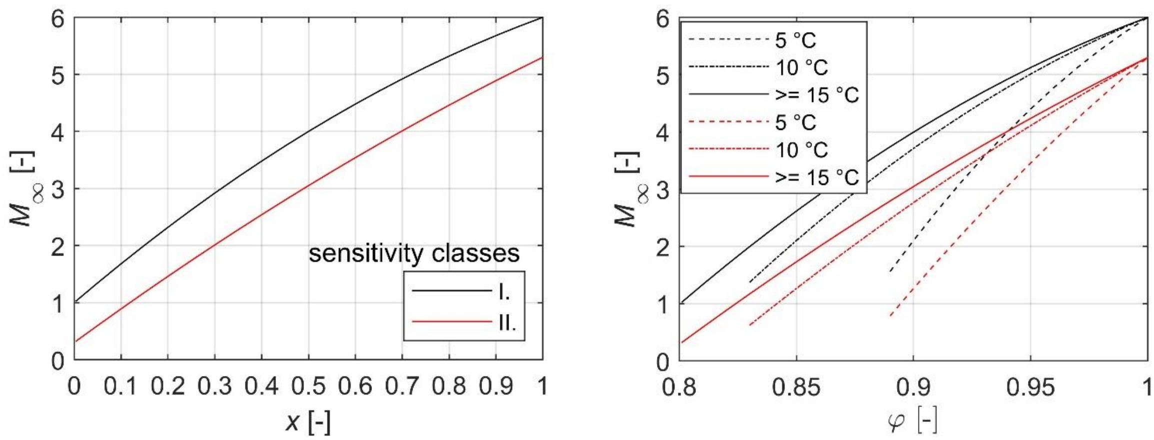

FIGURE 1 (in color). Maximum mold index M_∞ for two sensitivity classes depicted as a function of variable x (left) and as a function of relative humidity and temperature (right).

The original formulation of the model was later extended with a definition of mold sensitivity classes to incorporate other materials than wood. Parameters to distinguish between sensitivity classes (see Table 2) are based on relatively limited experimental data and were set to some extent by expert guess (Ojanen et al. 2011). The classification of building materials in mold sensitivity classes is the subject of some uncertainty. Pine sapwood is used as the reference (Ojanen et al. 2011).

TABLE 2. Parameters of the Finnish mold growth model (Ojanen et al. 2011)

Sensitivity classes	k_1		k_2			
	k_{11}	k_{12}	A	B	C	φ_{min}
Very sensitive	1	2	1	7	2	0.8
Sensitive	0.578	0.386	0.3	6	1	0.8
Medium resistant	0.072	0.097	0	5	1.5	0.85
Resistant	0.033	0.014	0	3	1	0.85

The definition of M_∞ provided by equation (5) does not consider the type of wood and the characteristics of the surface which could also have an impact on the maximum mold coverage, e.g. see results of mold growth experiments published in (Johansson et al. 2013). It also specifies that M_∞ reaches the maximum value at $\varphi = 1$ (see Fig. 1). This assumption could be questionable, since a too moist substrate may not be optimal for mold growth. The optimal environmental conditions also differ between mold species.

(Hukka and Viitanen 1999) also formulated the mathematical description for the decrease of mold index for pine during non-favorable growth conditions:

$$\begin{aligned} \frac{\mathrm{d}M}{\mathrm{d}t} &= -0.032 \qquad \text{when } t_\mathrm{d} < 6\ \mathrm{h} \\ \frac{\mathrm{d}M}{\mathrm{d}t} &= 0 \qquad \text{when } 6\ \mathrm{h} \le t_\mathrm{d} \le 24\ \mathrm{h} \qquad [\text{–/day}] \qquad (8) \\ \frac{\mathrm{d}M}{\mathrm{d}t} &= -0.016 \qquad \text{when } t_\mathrm{d} > 24\ \mathrm{h} \end{aligned}$$

where t_d is the time that passed from the beginning of the dry period. For longer dry periods, equation (8) leads to a linear decrease of M. The absence of mold decline in $t_\mathrm{d} \in$ <6, 24> h seems unrealistic (Vereecken and Roels 2012). The decrease of mold index should not be interpreted as indicating that mold necessarily decline during dry conditions. The model instead defines a delay of mold growth under favorable growth conditions, possibly occurring after the dry period. It is explicitly mentioned in (Hukka and Viitanen 1999) that equation 8 is based on a limited number of laboratory experiments. In practice, the error associated with mold decline could lead to accumulation of errors (Colinart et al. 2017).

(Ojanen et al. 2011) suggests a change of equation 8 to incorporate different building materials:

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{\mathrm{mat}} = C_{\mathrm{mat}}\frac{\mathrm{d}M}{\mathrm{d}t} \qquad [\text{-/day}] \qquad (9)$$

where $\mathrm{d}M/\mathrm{d}t$ is the decrease of mold index for pine (according to equation 8), $(\mathrm{d}M/\mathrm{d}t)_{\mathrm{mat}}$ is the decrease of mold index for other materials, and C_{mat} [-] is an empirical coefficient for mold decline specific for the material.

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