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A COMPARISON OF DIFFERENT MOULD PREDICTION MODELS

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ABSTRACT

To predict the mould growth risk during the design stage, a mould prediction model can be used. Several models are found in literature (e.g. temperature ratio, isopleth systems, biohygrothermal model, ESP-r mould prediction model, empirical VTT-model). Each of these models includes however different assumptions. Consequently, a different conclusion may be drawn depending on the used prediction model. In the current paper, a comparison between the different mould prediction models is made. To do so, the hygrothermal behaviour of two thermal bridges is simulated and the obtained surface temperature and surface relative humidity are used as an input in the different mould prediction models.

INTRODUCTION

A large part of human beings' time is spent indoors. Hence, a healthy indoor air quality and comfort are of main importance. Whereas nowadays a lot of attention is paid to the improvement of the energy performance of a building, one should also be cautious for a potential loss in the indoor air quality and occupant's comfort. For instance increasing the air tightness of the building envelope without adapting the ventilation strategy, applying interior insulation without paying enough attention to potential thermal bridges or replacing single glazed windows by double glass can result in an increased mould growth risk. To evaluate the mould growth risk during the design stage, a mould prediction model can be used. Several models are found in literature (e.g. temperature ratio, isopleth models, biohygrothermal model, ESP-r mould prediction model, empirical VTT-model). These models are however based on either experiments or assumptions. Morover, in a part of the existing models only the temperature (T) and relative humidty (RH) are included. Though, also the substrate and exposure time can have an important impact in the mould growth process (IEA-Annex 14, 1990; Adan, 1994; Sedlbauer, 2001). Consequently, a different conclusion may be drawn depending on the used prediction model.

In the current paper, the mould growth risk for two thermal bridges is evaluated with the different mould prediction models. To do so, the hygrothermal behaviour of the thermal bridges is simulated and the temperature and relative humidity course on the interior surface are used as an input in the different mould prediction models. The risk on mould growth, the time until growth starts and the mould intensity are compared with each other.

An introductory section reiterates the main mould prediction models. The second section presents the investigated thermal bridges and the simulated temperature and relative humidty courses. Furthermore, the risk on mould growth based on the simulated temperature and relative humidity courses is evaluated with the different mould prediction models. In the third section, the main conclusions are summarised.

MOULD PREDICTION MODELS

Temperature ratio

To evaluate mould risk, the IEA-Annex 14 (1990) proposes a mould growth evaluation based on the temperature ratio τ:

$$\tau = \frac{\theta_{s,\min} - \theta_e}{\theta_i - \theta_e} \tag{1}$$

where $\theta_{s,\min}$ the minimum surface temperature (°C) and θ_i and θ_e respectively the inside and outside temperature (°C). A temperature factor of 0.7 is related to an acceptable mould risk of 5%. A lower temperature factor will introduce an unacceptable high mould risk. This criterion is often used in combination with a critical RH threshold for mould growth, which is according to the IEA Annex 14 recommended to be set at 80%.

VTT model

The VTT model is an empirical mould growth prediction model developed by Hukka and Viitanen (1999), which is based on regression analysis of a set of measured data (Viitanen, 1996; Viitanen et al., 2010). In the measurements different mixed mould species are used. The mould growth development is expressed by the mould index (M), which can range between 0 and 6 (see Table 1). The mould index can be used as a design criterion, e.g. often M=1 is defined as the maximum tolerable value since from this point on the germination process starts.

The VTT model is based on laboratory experiments on pine and spruce sapwood in which the influence of temperature, relative humidity, surface and time is taken into account. In this model a critical relative humidity RH_{crit} (%) can be found, which is defined as the lowest humidity under which mould growth can occur if the material is exposed to it for a long enough period. For wood RH_{crit} is given by:

$$RH_{crit} = \begin{cases} -0.00267\theta^3 + 0.160\theta^2 - 3.13\theta \\ \qquad +100.0, \text{ when } \theta < 20°C \\ RH_{\min} \text{ when } \theta \geq 20°C \end{cases} \tag{2}$$

where RH_{min} is 80% for wood-based materials. The incremental mould index increase or decrease can be calculated by use of a differential equation in which varying temperature and humidity conditions can be taken into account. For pine and spruce the following equation gives the incremental change in mould index:

$$\frac{dM}{dt} = \frac{k_1 k_2}{7 \cdot t_{M=1}} \tag{3}$$

with t the time, in the original model expressed in days due to the long monitoring periods used in the measurements. In the new model (explained below) the time unit used is hours. The factor k_1 defines the growth rate under favourable conditions and is given by:

$$k_1 = \begin{cases} 1, \text{ when } M \leq 1 \\ \dfrac{2}{\dfrac{t_{M=3}}{t_{M=1}} - 1}, \text{ when } M > 1 \end{cases} \tag{4}$$

with $t_{M=1}$ and $t_{M=3}$ respectively the time needed to reach M=1 (start growth) and M=3 (first visual appearance of mould growth after the initial stage). For wood, these response times are in cases of constant temperature and humidity conditions expressed by following regression equations (Hukka and Viitanen, 1999):

$$t_{M=1} = \exp\begin{pmatrix} -0.68 \cdot \ln(T) - 13.9 \cdot \ln(RH) \\ +0.14 \cdot W - 0.33 \cdot SQ + 66.02 \end{pmatrix} \tag{5}$$

$$t_{M=3} = \exp\begin{pmatrix} -0.74 \cdot \ln(T) - 12.72 \cdot \ln(RH) \\ +0.06 \cdot W + 61.50 \end{pmatrix} \tag{6}$$

with W the wood species (0 for pine, 1 for spruce), SQ the surface quality (0 for resawn and 1 for original kiln-dried timber), T the temperature (°C) and RH the relative humidity (%). To implement a moderation of the growth intensity when M approaches the maximum peak value in the range of $4<M<6$, the factor k_2 is added in Eq. (3):

$$k_2 = \max\left[1 - \exp\left(2.3 \cdot (M - M_{\max})\right), 0\right] \tag{7}$$

with M_{max} the maximum mould index level (-), described by:

$$M_{\max} = 1 + 7 \cdot \frac{RH_{crit} - RH}{RH_{crit} - 100} - 2 \cdot \left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \tag{8}$$

Latter equation indicates that the critical RH is besides its dependence of the temperature also connected to the mould growth level. A delay in mould growth caused by unfavourable conditions results in a decline of the mould index given by

$$\frac{dM}{dt} = \begin{cases} -0.00133, \text{ when } t - t_1 \leq 6h \\ 0, \text{ when } 6h < t - t_1 \leq 24h \\ -0.000667, \text{ when } t - t_1 > 24h \end{cases} \tag{9}$$

with $t\text{-}t_1$ (h) the time exposed to unfavourable conditions. Note however, that Eq. (9) is based on a small number of experiments and that no temperatures below 0°C or long periods (> 14 days) have been included.

Updated VTT model

To make the VTT model also usable to evaluate mould growth on other building materials, the original model is expanded (Ojanen et al., 2010).

Since developing a model for each building material is not realistic, four mould sensitivity classes are presented: very sensitive (vs), sensitive (s), medium resistant (mr) and resistant (r) materials. Resawn pine wood (W=0, SQ=0) is used as a reference material to develop the model for these classes. Experiments showed that for some materials a rather high mould growth coverage can already be observed on the

Table 1
Mould index

Index	Growth rate	Description		
0	No mould growth	Spores not activated		
1	Small amounts of mould on surface	Initial stages of growth	Microscopic level	
2	<10% coverage of mould on surface			
3	10-30% coverage mould on surface, **or < 50% coverage of mold (microscope)**	New spores produced		Visually detectable
4	30-70% coverage mould on surface, **or > 50% coverage of mould (microscope)**	Moderate growth		
5	>70% coverage mould on surface	Plenty of growth		
6	Very heavy, dense mould growth covers nearly 100% of the surface	Coverage around 100%		

microscopic level. Therefore, the mould index classification is slightly adapted (see Table 1 (**bold**)). Furthermore, for a more sensitive material, RH_{min} in Eq. (1) can be changed to 85%, the factor k_1 is adapted and new parameters are defined for the determination of M_{max} (Eq. (8)):

$$M_{\max} = A + B \cdot \frac{RH_{crit} - RH}{RH_{crit} - 100} - C \cdot \left(\frac{RH_{crit} - RH}{RH_{crit} - 100} \right)^2 \quad (10)$$

An overview of the different sensitivity classes together with a description of the corresponding materials, the adapted values for k_1 and RH_{min} and the new parameters of Eq. (10) can be found in Table 2. The adapted factor k_1 can also be defined as follows:

$$k_1 = \begin{cases} \dfrac{t_{M=1,pine}}{t_{M=1}}, \text{ when } M \le 1 \\ \dfrac{2 \cdot \left(t_{M=3,pine} - t_{M=1,pine} \right)}{t_{M=3} - t_{M=1}}, \text{ when } M > 1 \end{cases} \quad (11)$$

where $t_{M=1/3,pine}$ and $t_{M=1/3}$ corresponds to the time till germination/first visual growth for respectively the pine wood and the investigated material occurs. Note that, when comparing the value $k_1=2$ ($M \ge 1$) for the very sensitive class with Eq.(4), (5) and (6), for e.g. 20°C the updated VTT model seems to be developed based on the results obtained by 97% relative humidity.

The material will also have an impact on a potential mould growth decline (Ojanen, 2010). Therefore, a coefficient C_{mat} is introduced for the different materials. By use of this coefficient, the original decline model (Eq. (9)) can be applied in:

$$\left(\frac{dM}{dt} \right)_{mat} = C_{mat} \cdot \left(\frac{dM}{dt} \right)_{pine} \quad (12)$$

where $(dM/dt)_{mat}$ and $(dM/dt)_{pine}$ the mould decline intensity respectively for the investigated material and for pine in the original model. For the *vs*, *s*, *mr* an *r* sensitivity class the coefficient C_{mat} are respectively set to 1, 0.5, 0.25 and 0.1.

Isopleth models

Since the temperature and relative humidity are the main influencing factors for mould growth, several models are based on isopleth systems which indicate the mould potential in function of the temperature and relative humidity combination. The main isopleth models are developed by Clarke and Rowan (ESP-r model) and Sedlbauer.

Clarke and Rowan (Clarke et al., 1999; Rowan et al., 1999) subdivided the mould fungi found in buildings in six categories with respect to relative humidity and temperature. For each of these categories, Clarke and Rowan defined a curve f(T,RH). When the relative humidity and temperature combination exceeds such a curve, a mould risk of the matching fungi exists.

Sedlbauer (Sedlbauer, 2001) developed an isopleth system for different substrate classes: 0 (optimal culture medium), I (biologically recyclable building materials) and II (biologically adverse recyclable building materials). For the critical mould species he developed an extra isopleth system K. The proposed evaluation model consists out of a dual system: isopleths indicating the time until germination occurs and isopleths indicating the growth rate. The conditions below which no mould growth will occur are defined by the LIM (Lowest Isopleth for Mould) - curve. Note however that this isopleth system can be used only if steady-state conditions occur. To make the isopleths also usable in cases of transient conditions, Moon (Moon, 2005; Moon and Augenbroe, 2004) established the ‘mould germination graph method’. This method takes into account the temperature and relative humidity at previous time steps. To do so, each curve is indicated by a group with a certain required exposure time for initiation of mould germination. For each group the associated accumulated exposure time can be recorded. When the accumulated exposure time for a group is equal or larger than its required exposure time, a mould growth risk exists. A possible drying out of the spores is not considered in this model.

Table 2
Mould sensitivity classes and their corresponding parameters k_1, k_2, M_{max} and RH_{min}

Sensitivity class	Material groups	k_1 (if M<1)	k_1 (if M ≥ 1)	M_{max} (influence on k_2)			RH_{min} (%)
				A	B	C	
vs	Untreated wood; includes lots of nutrients for biological growth	1	2	1	7	2	80
s	Planed wood; paper-coated products, wood-based boards	0.578	0.386	0.3	6	1	80
mr	Cement or plastic based materials, mineral fibers	0.072	0.097	0	5	1.5	85
r	Glass and metal products, materials with efficient protective compound treatments	0.033	0.014	0	3	1	85

Biohygrothermal model

To make a more reliable prediction of the mould risk in cases of transient conditions possible, Sedlbauer extended his isopleth model with the biohygrothermal model (Sedlbauer, 2001; Krus et al., 2007; WTA, 2006). This model makes it possible to calculate the moisture balance of a spore, which has a certain osmotic potential and which can consequently absorb water from the environment dependent on the transient boundary conditions. This means also that even an interim drying out of the fungus spores can be considered. To calculate this process, the spore is characterised by a moisture retention curve and a humidity-dependent s_d-value. The spore is supposed to germinate when a certain moisture content, the critical moisture content, is reached. From this point on metabolic processes and spore growth can start. The critical moisture content can be determined based on the critical relative humidity, which can for a certain temperature be found based on the isopleth system and the moisture retention curve of the spore. The type of substrate can be taken into account by using the substrate dependent isopleth system in the determination of the critical moisture content. By use of this model, the required time till germination and the mould growth (mm/day) can be determined. Note however that the obtained mould growth can only be used as a comparative factor (Krus et al., 2010).

APPLICATION

To investigate the impact of the mould prediction model on the obtained conclusion about a potential mould risk, this section applies the existing models to predict the mould risk for a temperature and relative humidity course obtained on two thermal bridges: a) a connection of an inside wall with an outside wall which is insulated with interior insulation and b) a non-insulated outside corner (Figure 1). Note that the hygrothermal response of the investigated thermal bridges is used only as an input to investigate the impact of the different mould prediction models. An analysis of the hygrothermal response of the thermal bridges is out of the scope of this paper.

Temperature and relative humidity course

The hygrothermal performance of the thermal bridges is simulated with HAMFEM (Janssen, 2002). In the simulation hourly climate data of Essen, Germany, are used. Driving rain is calculated by wind direction, wind speed and rain on a vertical surface area. The inside wall (case A) is connected to the centre of the south-west wall of a 10m x 10m x 10m building. The simulated corner (case B) is located at 5m height on a 10m x 10m x 10m building and points towards the north-west. The catch ratios as determined by Blocken and Carmeliet (2006) are used. The outside heat and moisture transfer coefficient, the short-wave absorptivity, the long-wave absorptivity and the inside heat and moisture transfer coefficient can be found in Table 3. For case A, the inside heat transfer coefficient is assumed to be 8 W/(m²K). Note, that the constant inside heat transfer coefficient is a simplification, since in practice the inside heat transfer coefficient will decrease towards the corner. For case B, the inside heat transfer coefficient is supposed to be a function of the distance from the corner, as proposed in Annex 14 (1990) for an outside corner. The indoor temperature and indoor relative humidity are kept constant at respectively 20°C and 50%. The initial temperature and relative humidity in the walls is set at respectively 20°C and 50%. The simulation is started from July 1st. Figure 1 shows one half of the simulated thermal bridge A (a) and thermal bridge B (b) with the obtained temperature. The temperature and relative humidity in function of the time for location A and B are given in Figure 2.

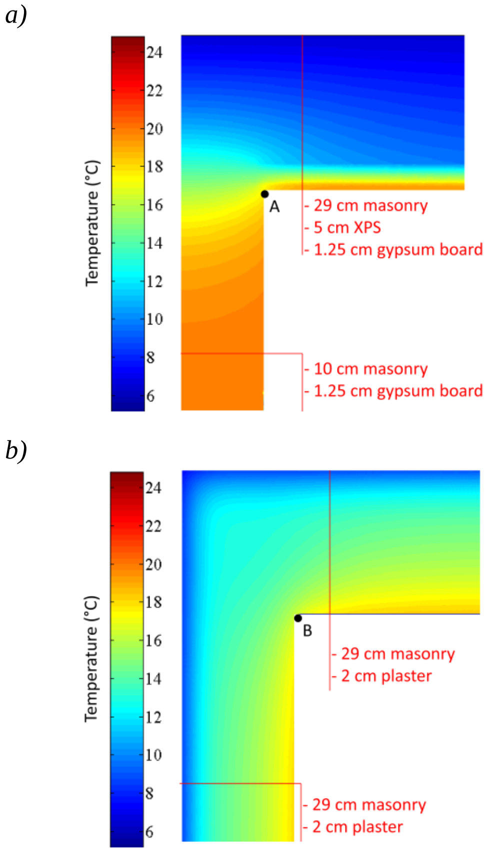
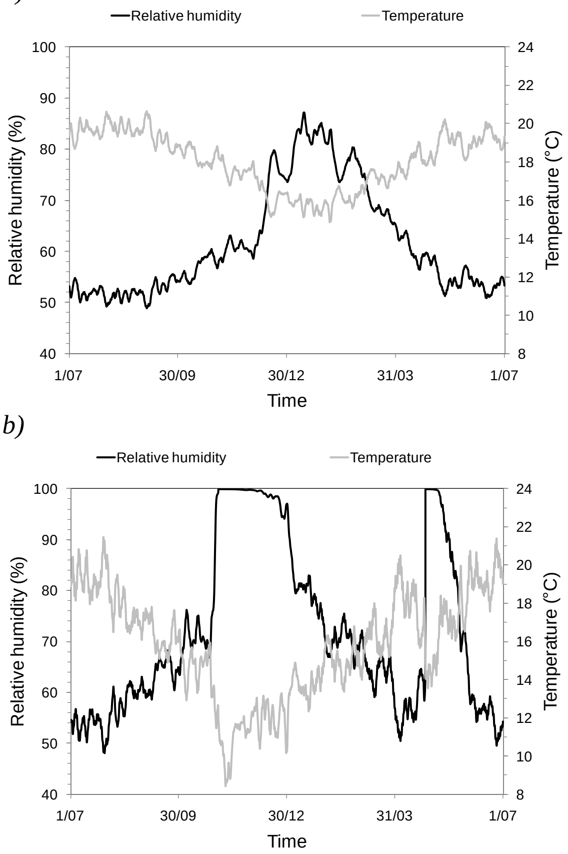


Figure 1 Thermal bridges (December 28): a) inside wall connected to an outside wall insulated with interior insulation (one half), b) outside corner of a non-insulated massive wall

Table 3
Boundary conditions

h_e	20 W/(m²K)
β_e	$20*7.7*10^{-9}$ s/m
α_s	0.6
α_L	0.9
h_i	Case A: 8 W/(m²K) Case B: Eq. (13)
β_i	$(8/2)*7.7*10^{-9}$ s/m

$$h_i = 8\cdot\left(1-\left(1-\frac{6}{8}\right)\exp\cdot\left(-3\cdot\frac{\text{distance from the corner (m)}}{0.31}\right)\right) \qquad (13)$$


a)

b)

Figure 2 Surface temperature and relative humidity course during the second year (hourly data): a) location A, b) location B

Mould growth evaluation

In the mould growth evaluation hourly data for the surface temperature and surface relative humidity at location A and B are used. The first year of the simulation results is not taken into account in the mould growth evaluation. The second year obtained in the simulation is used and is assumed to occur also in the next years in the mould growth analysis. The evaluation is performed for a period of four years, starting from July 1st. Figure 3 shows the critical isopleths from the ESP-r model together with the simulated hourly temperature and relative humidity combinations. As can be observed, for position A a mould risk exists only for the xerophilic mould species. For position B for all the mould species mould growth is indicated. Note that a single excess of a curve will result in a mould risk for the investigated mould species in the ESP-r model.

For the evaluation based on Sedlbauers isopleth system the finishing layer is supposed to belong to the substrate group I. Figure 4 shows the germination and growth rate isopleths. For both locations the LIM-curve is exceeded. Note however, that these isopleths are defined for steady-state conditions.

The mould growth obtained with the biohygrothermal model is defined by using the 'WUFI-Bio'-software (WUFI, 2005). Also in this model class I is assumed. Figure 5 shows the

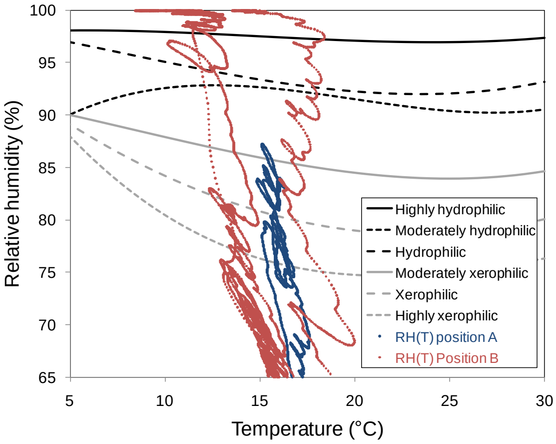


Figure 3 Simulated RH-T combinations and critical ESP-r isopleths

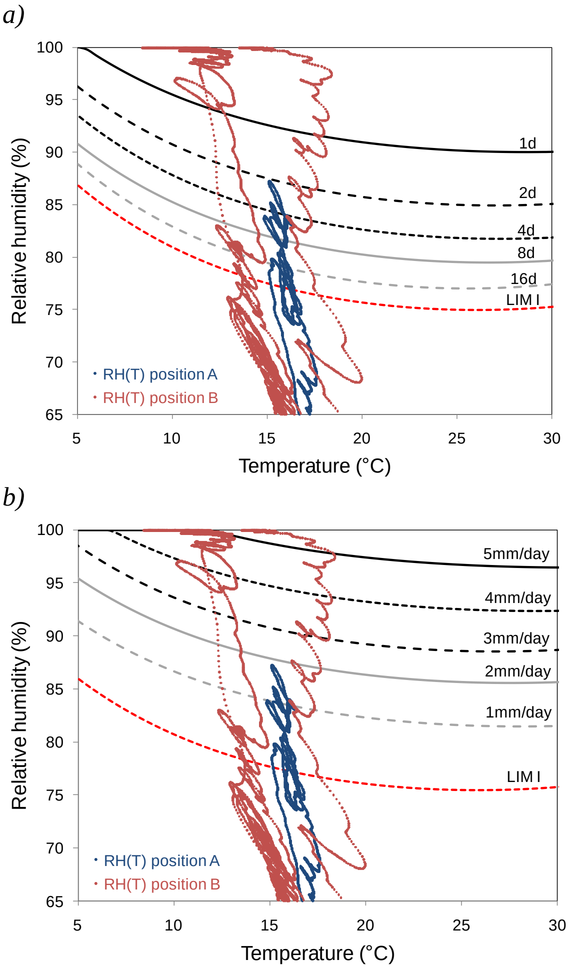

a)

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Figure 4 Simulated RH-T combinations and Sedlbauers isopleth system for substrate group I: a) germination iopleths, b) growth rate isopleths obtained critical and spore moisture content for both cases. For both cases, the spore moisture content exceeds the critical moisture content. Consequently, the germination process will start. To make a comparison between the biohygrothermal model and the isopleth system of Sedlbauer for non-steady-state conditions, Moons mould germination graph method is used and a linear interpolation between the growth curves is made. The results for the mould growth are shown in Figure 6. Note that for both cases the mould growth course obtained based on the isopleth system is lower compared to the results obtained with the biohygrothermal model. This can be attributed to a prolongation of the favourable spore conditions during unfavourable periods in the biohygrothermal model.

Since the mould growth obtained by the isopleth system of the biohygrothermal model is not a reasonable unit, Krus et al. (2010) developed a conversion function to transform the calculated mould growth into the mould index. A comparison of the mould index obtained based on the results of the biohygrothermal model together with the mould index obtained with the VTT model (original model and sensitivity class s) is given in Figure 7. The mould index determined based on the results obtained with the biohygrothermal model differs from the mould index obtained with the VTT model. Using the VTT model, a decline of the mould index is obtained during the unfavourable conditions. In WUFI-Bio however, the mould index remains constant during unfavourable conditions.

Table 4 shows for both cases if a mould risk exists, the time till germination and mould growth and the obtained mould intensity. For both cases the standard mould prediction rule based on the temperature factor indicates a potential mould problem. Due to the period of high relative humidity found for case B, for this case also the more advanced models indicate a mould risk. For case A however, the more advanced models do not always indicate mould growth. An evaluation with the ESP-r model results only in a mould risk for the xerophilic species. When using the VTT model no mould risk is obtained, since in the VTT model a decline in mould index during the unfavourable conditions is included. This decline is not included in the determination of the mould index based on the results of the biohygrothermal model. Consequently, when using the mould index determined in WUFI-Bio for case A a mould risk is obtained. In the biohygrothermal model a spore moisture content higher than the critical moisture content indicates the start of germination. This start of the germination process is found for case A. Though, in the biohygrothermal model the start of germination is not used as an indication of a mould risk. Instead, the mould growth per year is determined and the risk on mould growth is evaluated based on the ‘signal light’ rule (WUFI, 2005):

- Mould growth > 200mm/year: ‘red light’, not acceptable
- 50 mm/year < Mould growth < 200 mm/year: ‘yellow light’: additional evaluation is necessary
- Mould growth < 50 mm/year; ‘green light’: usually acceptable

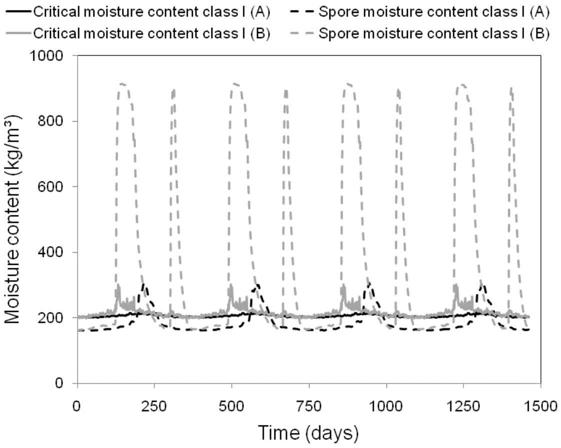

Figure 5 Moisture content in the model spore and critical moisture content determined with the biohygrothermal model

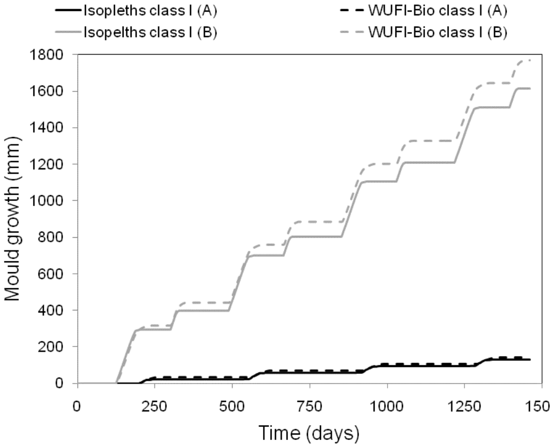

Figure 6 Mould growth determined based on the mould prediction graph method and determined with WUFI-Bio

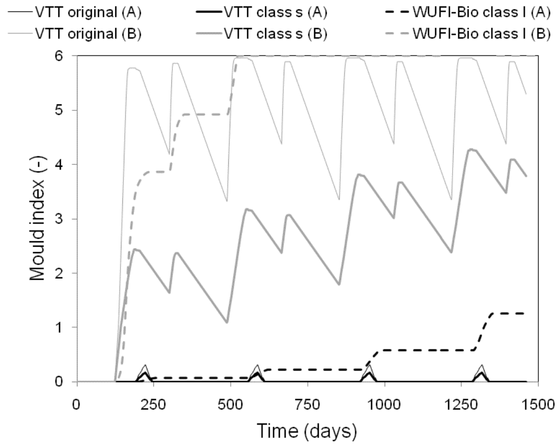

Figure 7 Comparison between the mould index determined with the VTT model and WUFI-Bio

Table 4
Results obtained with the different mould prediction models (GERM = germination, 'SL' = 'Signal light'-rule, HX = highly xerophilic, X = xerophilic, MX = moderately xerophilic, H = hydrophilic, MH = moderately hydrophilic, HH = highly hydrophilic)

	CASE A			**CASE B**		
Model	**Mould risk**	**Start time (h)**	**Mould intensity (max after 4th year)**	**Mould risk**	**Start time (h)**	**Mould intensity (max after 4th year)**
Temperature factor + 80% rule	Yes	-	-	Yes	-	-
VTT original	No	-	-	Yes	3209 $(M \geq 1)$	M = 5.3
VTT class s	No	-	-	Yes	3395 $(M \geq 1)$	M = 4.28
ESP-r	Yes if xerophilic species	4041 (HX) 4531 (X) 4703 (MX) - (H) - (MH) - (HH)	-	Yes	2905 (HX) 2922 (X) 2931 (MX) 2943 (H) 2946 (MH) 2959 (HH)	-
Mould germination graph method with linear interpolation (LIM I)	GERM: Yes 'SL': No	GERM: 4763	132 mm	GERM: Yes 'SL': Yes	GERM: 2970	1615 mm
Biohygrothermal model	> w_{crit}: Yes 'SL': No	w_{cit}: 4641	141 mm	> w_{crit}: Yes 'SL': Yes	w_{cit}: 2959	1772 mm
Mould index based on biohygrothermal results	Yes	3173 $(M \geq 1)$	1.26	Yes	2959 $(M \geq 1)$	M = 6

Consequently, for case A no mould risk is obtained with the biohygrothermal model. Note however that, if a mould index equal to 1 is used to indicate a mould risk, a different conclusion is drawn between the biohygrothermal model and the mould index in WUFI-Bio. For example, for location A the obtained mould growth is lower than 50 mm/year, which results according to the 'signal light' criterion in no mould growth. However, when we look at the mould index obtained with WUFI-Bio a mould index higher than 1 is obtained in the fourth year, which results according to the VTT model in a mould risk.

DISCUSSION AND CONCLUSIONS

Different mould prediction models can be found in literature. Each of these models is developed based on other experiments and makes other assumptions. Consequently, a different result can be obtained when using another mould prediction model in the evaluation.

In this paper, the different existing mould prediction models have been used for the mould risk evaluation of two thermal bridges. For one of the thermal bridges sharply divided conclusions about the mould risk, mould growth and mould intensity have been obtained with the different prediction models. When using the isopleths of the ESP-r model a single exceed of the curve for the investigated mould species results in a mould risk indication. Moons mould determination graph method is used to predict the mould risk based on Sedlbauers isopleth system for the non-steady-state conditions. Note that the mould growth obtained with the isopleth system is lower than the growth obtained with the biohygrothermal model, although the latter model includes an interim drying out of the spore.

Furthermore, the mould index determined based on the results obtained with the biohygrothermal model differ from the mould index obtained with the VTT model. Using the VTT model, a decline of the mould index is obtained during the unfavourable conditions. In WUFI-Bio however, the mould index remains constant during unfavourable periods. Note that this paper includes only a first investigation of the impact of the mould prediction model based on the simulated surface temperature and relative humidity for two thermal bridges. In cases of other temperature and relative humidity courses another sequence of e.g. the start of mould growth could be obtained for the different models. Nevertheless, the investigated cases give an indication that the mould prediction model and the risk criterion used in the mould evaluation can have an impact on the obtained conclusions.

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