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EVALUATION OF HYGROTHERMAL MODELS FOR MOLD GROWTH AVOIDANCE PREDICTION

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ABSTRACT

The most dominant moisture-related problem in building materials is probably mold growth. It occurs as a result of relatively high moisture concentrations. Although recent research has established the causal, physical-biological relationship between moisture content, temperature, material type, and mold growth, we do not have an established set of causal relationships between certain building parameters (such as envelope characteristics) and the risk of mold growth. This indicates a need for a "performance indicator" (PI) that expresses the mold growth risk in existing buildings as the causal effect of certain building parameters. Such a performance indicator should express the relationships between mold growth occurrence and the physical descriptors of building components, HVAC systems and layout, maintenance and cleaning operation, and so forth. This paper will deal with the first stage of research that focuses on the construction of such a PI. In this stage, we will deal with the accurate prediction of mold growth based on the availability of detailed information of the physical state (i.e., temperature and moisture content) of the materials in the building over time. Based on the accurate simulation of these states, these states can be aggregated into a PI value that is meaningful to the actual risk that mold growth will indeed occur under these circumstances. A method for the latter will be presented.

INTRODUCTION

Several international standards identify an upper limit on relative humidity in buildings, such as a range from 60% to 80% (ASHRAE 1992; 1999). The human health is not affected by high humidity levels but rather the growth and spread of biotic agents in high humidity (Baughman 1996). Microbial growth in buildings is a major cause of Indoor Air Quality (IAQ) problems.

Despite intensive research efforts on preventing mold growth in buildings in the last several decades, the relationships between the probability of mold growth and certain values of building parameters have not been fully established yet. While it is easy to associate a building with low energy performance to certain parameters (high U-values of the enclosure, low HVAC efficiency, and others), it is much less obvious how such causalities can be expressed with respect to the building's systems performance in an effort to avoid mold growth. Such performance is influenced by a multitude of parameters with complex physical interactions. The set of relevant "building parameters" will include physical parameters of building components, building usage, building materials, occupants' behavior, HVAC system components, weather data, and so on. When all building situation and use parameters are known for a given building, it should be possible to simulate the physical states of the building accurately, and analyze these states over time to arrive at a prediction of mold growth occurrence in one or more locations in the building.

In order to achieve this goal, we need to:

- be able to simulate physical states (temperature and moisture content) with enough accuracy.
- be able to aggregate these states into a theoretical measure of actual mold growth occurrence.
- ascertain that this theoretical measure can be used as the foundation of the practical PI as introduced earlier (introducing a normalization procedure, correction factors, etc. where needed).

The following sections will present three objectives. The first section will present the first objective, to show that current first principles based energy and mass transport simulation packages can be deployed on a whole building scale. A review of existing models will outline the required features of hygrothermal models to meet this objective.

The next section will present the second objective, to adopt a new measure that tests the severity of combinations of relative humidity and temperature, depending on the length of time that certain conditions were maintained.

The last section will present the third objective, to introduce a set of situational factors that may be used to calibrate the theoretical measure for more practical application.

The next section will evaluate several hygrothermal models that predict the moisture content and temperature in building materials. They will be evaluated in terms of their capability to prepare a quantifiable performance indicator for mold growth (expressed as a so-called "mold growth PI"). In order to use the results from the hygrothermal models for such a PI, we will show that a new mold growth analysis method has to be developed.

REVIEW OF HYGROTHERMAL MODELS

Mold growth is dominated by the relative humidity (or moisture content) on the surfaces of building materials, not the ambient relative humidity. Acquiring surface conditions require calculation of the moisture flow between porous building materials and adjacent air, and moisture flow within multi-layered building materials. For this purpose, many first principles based energy and mass transport models have been developed (Clarke 1997; Hens 1991; Nakhi 1995). The International Energy Agency (IEA) reviewed heat, air, and moisture (HAM) transport models for buildings and identified 37 different models of various complexity. The IEA divided the HAM models into 9 types, ranging from very simple to the most complete, according to the complexity of the model (Hens 1996). Since this classification was not based on the use of the models for mold prediction in existing buildings, it is hard to find appropriate models for our mold growth PI. The review of the existing hygrothermal models, new categories, and the required features of the models that will be used in the mold growth PI are discussed below.

General overview of hygrothermal models

Research efforts to improve the accuracy of the hygrothermal models have continued with different purposes in mind. This section reports on an investigation of six hygrothermal models that were recently developed or improved. We attempted to classify them into two categories in terms of the target at which the model aims.

Some of the hygrothermal models predict moisture behavior within a building material, especially as part of the building envelope. These models help researchers or practitioners to identify the moisture transport behavior of building components. Other researchers have incorporated moisture transfer modules into existing thermal models that operate mostly on a whole building scale. The purpose of these models is to simulate accurate whole building performance by calculating thermal and moisture behavior simultaneously.

These two distinctly different models for moisture transfer simulation lead to the classification of "hygrothermal envelope models" and "hygrothermal models within a whole building energy simulation." The features and limitations of the hygrothermal models in both categories are discussed below. Table 1 summarizes the models.

Hygrothermal envelope models

Hygrothermal envelope models target a particular building envelope in order to predict the moisture behavior within the materials and suggest ways to improve the performance of the envelope system. They focus on moisture and heat flow within a multi-layered building material, delivering moisture contents within each layer, relative humidity and temperature variation over time inside the construction, as well as the heat and moisture transfer rates at each side of the surfaces. The models can also be customized for specific functions such as, condensation risk calculation, dew point calculation, moisture accumulation risk assessments, and so on.

The model uses different moisture flows, which depend on the complexity of the models. Full models consider heat flow (e.g., conduction, enthalpy, latent heat), moisture flow (e.g., vapor diffusion, vapor convection, liquid transport) and air flow together. These models typically generate accurate results that are verifiable with empirical data obtained from small scale experiments.

Boundary conditions on both sides of the envelope are specified in terms of weather and indoor air conditions. The type of weather data varies depending on the features of the model. For example, WUFI considers wind driven rain as another driving force of liquid transport on an exterior surface. Since the models in this category use long duration weather data, the moisture flow can be monitored from the fluctuating outside condition to the exterior surface of the envelope. For the indoor boundary condition, one has to assume plausible indoor air states (temperature, humidity) over time, because indoor air temperature and relative humidity cannot be calculated from a heat/mass balance of the building zone. However, the indoor air states affect the moisture content on the interior surfaces and vice versa. At the same time, indoor air conditions are also affected by heat and moisture sources as well. These thermal and moisture sources include occupants' behavior, HVAC system operation, furniture, equipment in a room, and so on. The hygrothermal envelope models are not able to represent this reciprocal moisture flow since the models in this category do not consider these sources or simplify the effect of the source terms. This leads to non-realistic results of surface conditions over time. In mold growth analysis, which focuses on surface conditions in existing buildings, the fluctuating indoor conditions are important for an accurate simulation that obtains realistic surface conditions on a specific building material surface. The lack of this capability can be a serious limitation for mold growth analysis. 1-D HAM, WUFI, MOIST are examples of hygrothermal envelope models.

Hygrothermal models within a whole building energy simulation

With the ground work done in the 1960s and 1970s, advanced simulation packages for many aspects of building performance has been established over the last two decades (Augenbroe 2002). Energy consumption and cooling/heating load calculation in buildings were one of the mainstream developments in building simulation research. These models have integrated HVAC system simulations for selecting appropriate size of equipment and predicting the performance of these systems. In order to acquire more accurate predictions of thermal building performance, some building energy simulation models have incorporated moisture transfer modules into their packages. These models fit into the category of "hygrothermal models within a whole building energy simulation", as they deal with a building as a system, that is composed of one or multi-zones. Each zone is made up of several spaces bounded by envelope elements. In order to deal with all building components simultaneously and keep complexity manageable, the applications typically simplify the moisture flow models. For example, vapor diffusion may be the only mechanism that is considered for moisture flow within the building structure.

However, the advantages of these approaches are that indoor air temperature and moisture contents are simulated from heat and mass balance equations so that information about fluctuating interior surface conditions is more reliably available for mold growth analysis. In their mass balance approach, they take into account moisture flows from outside, occupants' activity, humidification for a zone (or multi-zone). Some applications also offer the capability of airflow calculation so that moisture transportation by infiltration, ventilation (between zones) is also available. The models in this category are contained in applications such as ESP-r, BSIM2002, and EnergyPlus. These applications deliver the physical states as a function of time at the interior surfaces. As discussed before, they are the determining factor for assessing the risk of mold growth. In order to use these results as the basis of the proposed mold growth PI, we need a method that aggregates variable state information at the surface into an averaged mold growth risk.

MOLD GROWTH ANALYSIS

Although it may be reasonable and conservative to use the moisture content of a material at 80% RH as a threshold level for preventing mold occurrences in buildings, it must be acknowledged that the actual threshold level varies with temperature, relative humidity, length of time that certain conditions were maintained (i.e., exposure time), types of building material, and so on. The first principles-based models (as discussed in the previous section) generate surface states over time that can be analyzed by taking the effects of exposure time, hysteresis, and other conditions into account. The existing approaches for such mold growth analysis will be reviewed below.

Mold growth analysis methods have been introduced to predict the mold occurrences or growth rates of molds on the surfaces of a building material. Table 2 presents an overview of some state-of-the-art mold growth analysis methods. Most of the existing methods have attempted to establish mold growth limitation curves. These curves are called "critical relative humidity" in LATENITE or "Lowest Isopleth for Mold (LIM)" in the biohygrothermal model. One limitation of these curves, however, is that they have been established for constant temperature and relative humidity in lab experiments without considering the required "exposure time" to initiate mold germination. In fluctuating indoor air conditions in existing buildings, the "exposure time" becomes a more important factor than in constant indoor conditions.

To solve these issues, we have developed a new mold growth analysis method based on hygrothermal models and a mold germination graphs. This method keeps track of the environmental conditions at previous time steps so that the effect of the fluctuating conditions can be considered. It is assumed that once molds have germinated, the risk of mold growth is already present. Another assumption is made for the unfavorable conditions of mold growth. In fluctuating humidity conditions, the cumulative time in high-humidity conditions can be used to quantify the exposure time needed for the initiation of mold germination. However, if the environmental conditions fall out of the favorable range, some delay in the rate of mold growth will occur if it is already germinated (Hukka 1999). For the germination condition, it is assumed that germination will not occur once the environmental conditions are out of the favorable range. In this case, the accumulated exposure time is set to zero. To obtain reliable data, more experimental research needs to be done to observe mold growth in fluctuating conditions.

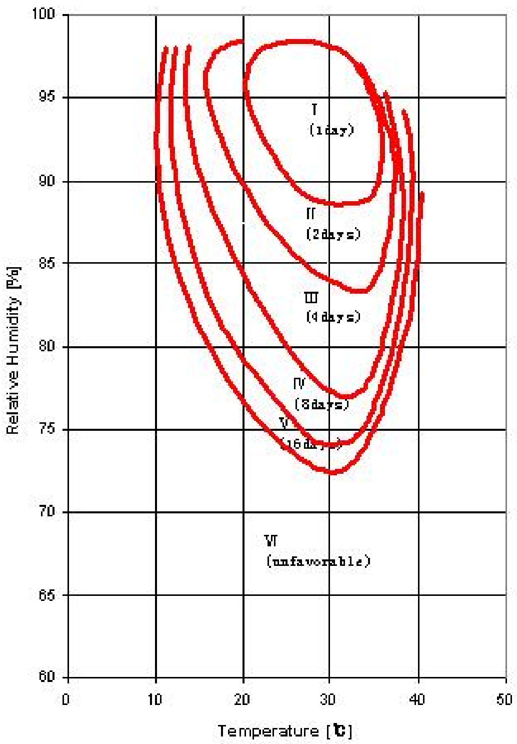

Figure1. Mold germination graph showing each group with temperature, relative humidity and required exposure time for the initiation of mold germination.

Growth conditions, ranging from optimum condition to unfavorable condition can be categorized in terms of surface relative humidity, surface temperature, and required exposure time for germination of mold. These isopleths for mold spores (mold germination graph) were developed from experiments by (Ayerst 1969; Smith 1982). These isopleths were also introduced in the biohygrothermal model underlying LIM (Krus 2001).

Figure 1 shows a mold germination graph of Aspergillus restrictus with favorability groups. If the surface condition is assigned into Group 1, this condition should be maintained at least one day to initiate the mold germination.

The new mold growth analysis method ("the germination graph method") uses the isopleths for mold spores in order to establish a standard "mold germination graph." According to the calculated surface RHs and surface temperatures, the conditions can be assigned into one group. Once this occurs, one can start to record the accumulated exposure time for each group. If the accumulated exposure time is greater or equal to the required exposure time, mold growth risk exists. At least one group has to display the mold growth risk in order to determine a risky day. If the group on the next day goes higher than that on the previous day (e.g., Group Ⅲ -> Group Ⅱ), the accumulated exposure times of the lower groups (Group Ⅲ) are recorded and compared with the required exposure time. However, in the reverse cases (e.g., Group Ⅱ -> Group Ⅲ), the exposure times of upper groups (Group Ⅱ) are set to zero because in this case germination will not occur in the upper group.

Table 3. Example of the application of the germination graph method

Day	Surface		Group	Accu. exposure time	Req. exposure time	Mold growth risk	
	Temp	RH					
1	20	70	Ⅵ	-	-	x	x
2	25	80	Ⅲ	1	4	x	x
3	23	85	Ⅲ	2	4	x	x
4	26	90	Ⅱ	1	2	x	x
			Ⅲ	3	4	x	
5	30	95	Ⅰ	1	1	o	o
			Ⅱ	2	2	o	
			Ⅲ	4	4	o	
6	22	85	Ⅲ	5	4	o	o
7	18	97	Ⅱ	1	2	x	o
			Ⅲ	6	4	o	
8	25	80	Ⅲ	7	4	o	o
9	18	97	Ⅱ	1	2	x	o
			Ⅲ	8	4	o	
10	20	70	Ⅵ	-	-	x	x
11	25	80	Ⅲ	1	4	x	x
12	18	97	Ⅱ	1	2	x	x
			Ⅲ	2	4	x	

Table 3 illustrates the use of the germination graph in the mold growth analysis method. The surface temperature and RHs are assumed to be available. In the example, our mold growth analysis method generated 5 risky days out of 12 days.

Different building materials have different critical humidity and exposure time for the initiation of the fungal growth. For example, wood-base materials require a lower critical humidity level and exposure time than stone-based materials (Ritschkoff 2000). The effect of different building materials as substrates can be taken into account by modifying the mold germination graph for each group. An alternative solution is the introduction of a substrate correction factor. Parallel research is underway to develop such substrate correction factors for different building materials.

Comparative Studies

Two case studies have compared the results from the mold germination graph method with two other methods, the embedded mold prediction method in ESP-r and the simple RH=80% threshold approach.

A one-zone building model was made in ESP-r. The building model includes a simple HVAC plant with a specified humidity ratio, heating coil, and a supply fan. The HVAC system runs with an on-off control law and the zone temperature set points are set at 20 ~ 24℃ during working time (8:00 – 18:00). The simulation was implemented for one week in winter season with Atlanta weather data. The results of temperature and relative humidity on the interior surface of the south facing wall are shown in figure 2.

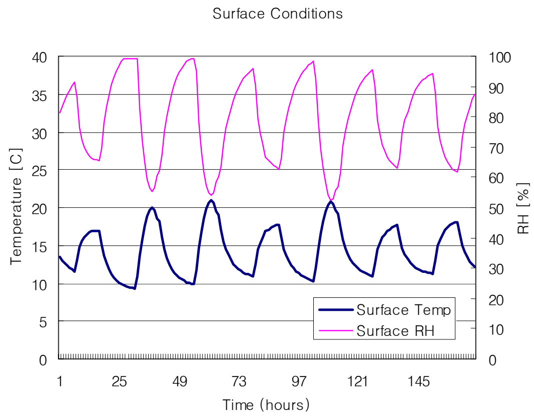

Figure 2. Results for interior south surface temperature and relative humidity in ESP-r

As a consequence of the zone temperature set points, the surface temperature reaches 20℃ occasionally (leading to low RH in a 60% range at the surface). On the other hand, the relative humidity on the surface can reach values close to 100% at night. Variations in surface conditions in response to fluctuating indoor conditions are shown in the figure 2.

Figure 3 presents the results of mold growth conditions as used in the ESP-r mold growth prediction module. The surface temperature and relative humidity points are superimposed on the generic mold growth curves that are embedded in a database within ESP-r. As can be seen, the distribution of data points affects all growth curves. On this basis it can be concluded that mold infestation would have occurred in all growth categories. This analysis method does not generate any quantitative results, so it is difficult to compare the results of this method with those of other methods.

Table 4 shows daily surface temperature and relative humidity as presented by the ESP-r simulation. It also shows the result of a mold growth risk analysis based on our germination graph method. Although the simulation ran for only one week, interestingly, it showed that there was only two days in a favorable range (Group 5), which requires 16 days for the initiation of mold germination. The result indicated that no mold growth would occur during that period.

This conclusion would not have been reached by using the ESP-r module as presented in Figure 3.

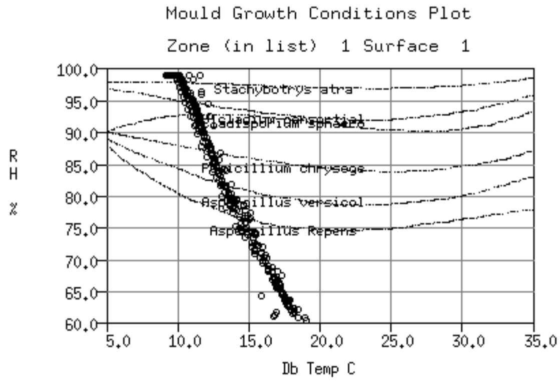

Figure 3. Mold growth prediction using ESP-r

Table 4. Mold growth risk analysis using a germination graph method

Day	Surface		Group	Accu. exposure time	Req. exposure time	Mold growth risk	
	Temp	RH					
1	13.9	79.5	Ⅵ	-	-	x	x
2	13.8	84.7	Ⅴ	1	16	x	x
3	14.7	78.0	Ⅵ	-	-	x	x
4	14.0	85.1	Ⅴ	1	16	x	x
5	14.9	76.8	Ⅵ	-	-	x	x
6	14.0	79.9	Ⅵ	-	-	x	x
7	14.3	78.7	Ⅵ	-	-	x	x

A second case study for the same one-zone building was conducted for a one-year simulation using EnergyPlus. This study used a conservative mold prevention criterion, which was 80% of relative humidity as a threshold for mold germination. The purpose was to compare the results of this study with those using the germination graph method. Figure 4 gives the simulation results for interior surface conditions.

Figure 5 shows the results from both analysis methods. The mold germination graph method generated 117 mold growth risky days during a one year period, less than the result of the 80% criterion (131 days). The difference is not dramatic as this is clearly a case with high mold growth risk (due to high internal moisture production assumed in the zone). In less obvious cases, it is believed that the germination graph method will can eliminate spurious days, leading to more reliable predictions.

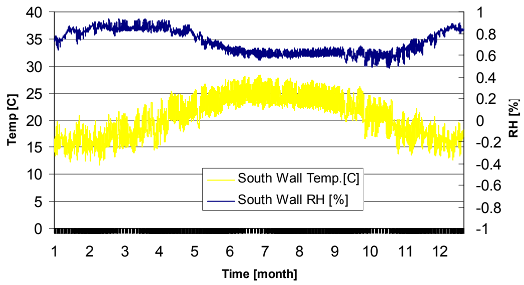

Figure 4. Results for interior south surface temperature and relative humidity in EnergyPlus

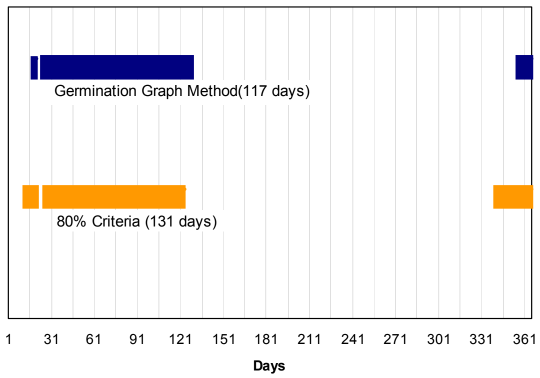

Figure 5. The mold growth analysis results from the germination graph method and 80% criterion

A PRACTICAL MOLD GROWTH PERFORMANCE INDICATOR

We demonstrated how simulation results can be aggregated into a mold growth analysis. However, simulations are only idealized representations of reality. Actual surface conditions will vary across a wall, due to local effects and potential anomalies (i.e., situations that are not "as-designed"). TenWolde claims that "service conditions," including building design and operation, should be considered in mold growth analysis (TenWolde 2000). Hens combined substrate nutrient values with the threshold relative humidity and incubation time (Hens 1999). This leads to the conclusion that the theoretical mold growth risk, determined from simulations and post-aggregations, cannot be used straightforwardly as a mold growth avoidance indicator (PI). Rather, it should be used as the foundation of a more practical PI by including a set of additional factors (situation factors) that account for effects that are not represented in idealized simulations.

From the literature review on building pathology, the authors found various causes of mold and moisture problems in residential, commercial and school buildings (Moon 2003). It proved possible to link these causes to four particular "situation factors" described in Table 5. The suggested situation factors are as follows:

a: the building usage factor, which considers building usag as relavant to the origin of spores (e.g., as resulting from dust accumulating on paper materials)

b: the substrate correction factor. The mold germination method is based on the results of lab experiments with fixed temperature and relative humidity on agar for a specific fungi spore. This factor corrects the substrate effects for different building materials.

c: the maintenance/operation factor, which considers the effects of building maintenance and HVAC system operations, particullary the effect of filters, and dust and mold accumulation in ducts.

d: the building details factor, which takes into account that molds prefer to grow where insulation materials are improperly designed or installed, causing thermal bridge effects. Possible places for condensation are window sills, behind wallpaper, and under carpet. This factor considers these types of design mistakes and defects in buildings.

A practical PI can now be formalized as a combination of the outcome of idealized simulations and the additional factors.

$$\text{Mold growth PI} = a \times (b \times PI^*) \times c \times d, \quad (0 < a,b,c,d < 1)$$

where,

PI*: idealized mold growth risk based on simulated and aggregated surface environmental conditions (i.e., using the germination graph method)

After the calculation of aggregated surface envirionmental conditions, the practical mold growth PI results in mold growth risks depend on building specific situation factors. Detailed calculations and aggregation methods for the four situation factors are now underway.

CONCLUSIONS AND FUTURE WORK

Because mold growth in existing buildings is such a complex phenomenon, no simple prediction method works for all cases. One has to consider the physical properties of the buildings as well as case dependant building related factors in order to understand and predict the risk of mold growth.

In this paper, we reviewed several state-of-the-art heat and mass transfer simulation packages to calculate surface environmental conditions. Hygrothermal models within whole building energy simulations generate more realistic physical states at the surfaces in existing buildings by simultaneously calculating the indoor air conditions. It was shown how a new mold growth analysis method based on mold germination graph can generate more accurate, although "idealized," mold growth risk. This approach is believed to eliminate spurious mold growth risk days found with simpler methods, but more validation has to take place.

It was articulated that the idealized measure could be used as the foundation of a practical PI by introducing a set of additional building related situation factors, which are specific to each building case.

The detailed development and aggregation of the four situation factors will be researched in the next stage of research. An extensive database of mold growth occurrences and data from existing buildings will be used to identify correlations between building parameters and actual mold occurrences. Once the correlations are established, the ultimate step is then to use the known correlations to calibrate the postulated performance indicator for mold growth (i.e., calibrate a, b, c and d).

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Table 1. Characteristics of hygrothermal models in the two categories

Category	**Hygrothermal envelope models**	**Hygrothermal models within a whole building energy simulation**
Target	One building envelope	One or multi- building zones
Features and Limitations	• Detailed moisture transfer (vapor diffusion, vapor convection, liquid diffusion, rain penetration, etc.) • Predefined indoor boundary conditions • Non reciprocal moisture transfer from/to an interior surface and indoor air • Limitation of the fluctuating surface conditions	• Whole building simulation • Multi-zone simulation • Ability to calculate fluctuating surface conditions • Various moisture sources • HVAC operation and control • Moisture transport between zones by airflow (infiltration, ventilation) • Simplified moisture flows within the building envelopes (vapor diffusion)
Examples of the models	1-D HAM, WUFI-ORNL/IBP, MOIST	ESP-r, BSIM2002, EnergyPlus

Table 2. Overview of existing mold growth analysis methods

	ESP-r (Clarke 1999)	**LATENITE** (Hukka 1999)	**Biohygrothermal Model** (Krus 2001)
Method	Mold growth limitation curve	Critical relative humidity based on Mold Index	Lowest Isopleth for Mold (LIM)
Features	• Superimposition of the calculated surface conditions on the mold growth limitation curves.	• The largest possible mold index.	• Calculation for spore moisture content • Spores as biological wall in WUFI
Limitations	No quantified results.	Applicable only to pure pine and spruce sapwood	Hard to acquire the required moisture properties for spore

Table5. Causes of mold growth and related situation factors

Causes	**Real building examples from literature review**	**PI elements**	**Buildings***
HVAC Defect	Direct infiltration of humid air	PI*	1,2,3
	Negative pressure across the envelope	PI*	1,2
	Inadequate moisture removal (return duct)	N/A	1
	Inadequate ventilation	PI*	1,2,3
Design Defect	Low permeance of the exterior weather barrier	PI*	1
	Vapor retarder in the wrong location	PI*	1,2
	Leakage of precipitation	PI*	3
	Defective drainage	N/A	1,2,3
	Impermeable surfaces (vinyl flooring, vinyl wall paper)	PI*	1,2
	Inadequate insulation, thermal bridges	d	1,2
Building Usage	High occupant density	PI*	1
	Pattern of use, cooking habits	PI*	1,2
	Low air conditioner thermostat setting	PI*	1
	Stock of wood, papers, books	a	1
Maintenance/ Operation	Inadequate maintenance and operation of equipment	c	1
	Cleaning	c	2
	Aging of construction materials	c	3
Construction Defect	Poor site drainage	N/A	1
	Location and orientation	N/A	1,2
	Water leakage from piping, roof, basement.	N/A	1,3

(Buildings* 1: residential 2: commercial 3: schools and daycare centers)