VTT mold model – Equations, parameters, performance criteria

Buildings XIII Workshop
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- Background and motivation
- Visual findings and mold index
- Model equations
- Mold growth conditions
- Classification of materials – Sensitivity to mold growth
- Decline of mold index
- Effect of parameter selection on simulated mold growth
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Background and motivation for mold model

- Mold growth is one of the first signs of too high moisture content in (building) materials
  - It may affect the indoor air quality and the appearance of surfaces
  - Increasing moisture may lead to structural damages

- natural ageing
  - grey wood
    - mould
      - indoor air
      - structures
        - VOCs
        - aesthetics
  - load exceeds tolerance
    - decay
      - damage
Mold Index

- Mold growth potential can be predicted by solving a numerical value, MOLD INDEX
- Values between [0, 6] depending on the growth coverage
- The model was originally based on mold growth studies on wooden material surface
- Same model can be used for other building materials – scaling coefficients for equations
Critical factors

- Humidity
- Temperature
- Time
- Substrate

![Graph showing critical factors for mold growth](image-url)
Mold Model principles – Visual findings interpreted as mold index values

- Index levels between 0 and 6

<table>
<thead>
<tr>
<th>Index</th>
<th>Description of the growth rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No growth</td>
</tr>
<tr>
<td>1</td>
<td>Small amounts of mould on surface (microscope), initial stages of local growth</td>
</tr>
<tr>
<td>2</td>
<td>Several local mould growth colonies on surface (microscope)</td>
</tr>
<tr>
<td>3</td>
<td>Visual findings of mould on surface, &lt; 10% coverage, or, &lt; 50% coverage of mould (microscope)</td>
</tr>
<tr>
<td>4</td>
<td>Visual findings of mould on surface, 10 - 50% coverage, or, &gt;50% coverage of mould (microscope)</td>
</tr>
<tr>
<td>5</td>
<td>Plenty of growth on surface, &gt; 50% coverage (visual)</td>
</tr>
<tr>
<td>6</td>
<td>Heavy and tight growth, coverage about 100%</td>
</tr>
</tbody>
</table>
Mold growth parameters used in the model

- **Substrate**
  - Typical building materials

- **Growth conditions**
  - Limit levels of RH and temperature

- **Growth intensity**
  - Depends on material, conditions and growth level

- **Maximum growth (Mold index) level**
  - Depends on material and conditions

- **Decline of visible growth level during unfavorable conditions**
  - Seasonal long-period conditions outside the growth area
  - Level of growth and growth intensity after decline periods
General mold growth equations – Reference material pine

\[
\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68 \ln T - 13.9 \ln RH + 0.14 W - 0.33 SQ + 66.02)} \cdot k_1 k_2
\]

\[
k_1 = \begin{cases} 
\frac{t_{M=1, pine}}{t_{M=1}}, & \text{when } M < 1 \\
\frac{t_{M=3, pine} - t_{M=1, pine}}{2 \cdot (t_{M=3} - t_{M=1})}, & \text{when } M \geq 1
\end{cases}
\]

\[
k_2 = \max[1 - \exp[2.3 \cdot (M - M_{max})], 0]
\]

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

- **Scaling factors** $k_1$ and $k_2$ for different materials
- **Coefficient** $k_1$ is used to scale the growth intensity
- **Coefficient** $k_2$ to limit the growth to maximum possible index level
Parameters for northern timber - W

\[ \frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68 \ln T - 13.91 \ln RH + 0.14W - 3.33SQ + 66.02)} k_1 k_2 \]

W for timber:
Pine  \( W = 0 \),
spruce \( W = 1 \)

Faster growth for pine

Timber and surface quality parameters only with spruce and pine, when known

+20°C, 93% RH
Parameters for northern timber – Surface quality

\[
\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.681 \ln T - 13.91 \ln RH + 0.14 W - 0.38 SQ + 66.02)} k_1 k_2
\]

SQ for surface quality:
- Planed, sawn SQ = 0
- Kiln dried SQ = 1

Faster growth when dried under high temp.

Timber and surface quality parameters only with spruce and pine, when known

+20 C, 93 % RH
Use of different materials

- Scaling of mold growth intensity using scaling factor $k_1$
- Scaling of maximum mold growth level using scaling factor $k_2$
- Lowest critical relative humidity level allowing mold growth $\text{RH}_{\text{crit}}$
Effect of $k_1$ coefficient

- Growth intensity changes after the first signs of mold (MI = 1)
- Change depends on material
- Example: Sensitive and very sensitive materials under +20 °C and 95 % RH

\[
\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68 \ln T - 13.9 \ln RH + 0.14 W - 0.33 SQ + 66.02)} k_1 k_2
\]

+20°C, 93 % RH

Mould Index $[0, 6]$

Days

Dec. 4, 2016, Buildings XIII, Workshop on Mold Risk Evaluation
Mold growth intensities on material surfaces

![Graph showing mold growth intensities on various materials at RH 97% and 23°C. The graph plots Mould index against Time (week). Different materials including particle board, fibre board, plywood, gypsum, concrete, cement screed, and pine are represented with different line types and markers. The graph highlights the varying growth rates and intensities over time.]
Mold growth intensity classes

RH 97 %, 23 °C

- particle board
- fibre board
- plywood
- gypsum
- concrete
- cement screed
- pine

Mould index vs. Time (week)
Mold growth intensity classes for different materials – use of $k_1$ coefficient

![Graph showing mold growth intensity classes for different materials and the use of $k_1$ coefficient.]

- Very sensitive = pine sapwood (reference material)
- Experimental findings for growth intensity of different materials
- Scaling coefficients $k_1$ for material sensitivity classes

<table>
<thead>
<tr>
<th>Sensitivity class</th>
<th>M &lt; 1</th>
<th>M ≥ 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>very sensitive, vs</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>sensitive, s</td>
<td>0.578</td>
<td>0.386</td>
</tr>
<tr>
<td>medium resistant, mr</td>
<td>0.072</td>
<td>0.097</td>
</tr>
<tr>
<td>resistant, r</td>
<td>0.033</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Mold growth sensitivity classes

Pine sapwood, 
Surface with nutrients

Glued wooden boards, 
PUR with paper surface, 
Wood based products

Concrete, aerated and 
cellular concrete, EPS, 
glass wool, polyester wool

PUR polished surface, 
glass, metal,

Peuhkuri, R; Viitanen, H; Ojanen, T. Modelling of mould growth in building envelopes.
Proceedings of the IEA ECBCS Annex 41.
Closing seminar, Copenhagen, June 19, 2008

Dec. 4, 2016, Buildings XIII, Workshop on Mold Risk Evaluation
Maximum Mold Index level - coefficient $k_2$

\[
\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68 \ln T - 13.9 \ln RH + 0.14 W - 0.33 SQ + 66.02)} \cdot k_2
\]

\[
k_2 = \max [1 - \exp(2.3 \cdot (M - M_{\text{max}})), 0]
\]
Maximum long period mold index level under stationary conditions
Maximum long period mold index level under stationary conditions

Maximum levels of growth

Classification according material types

RH 97 %, 23 °C
Effect of $k_2$ on growth close to maximum

- The growth is damped close to maximum growth index
- $M_{\text{max}} = f(T, RH\%)$
Maximum Mold Index level - coefficient $k_2$

'Scaling' coefficients $k_2$ are derived from experimental findings

Maximum Mold Index level - coefficient $k_2$

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

\[ M_{\text{max}} = A + B \cdot \frac{\text{RH}_{\text{crit}} - \text{RH}}{\text{RH}_{\text{crit}} - 100} - C \cdot \left( \frac{\text{RH}_{\text{crit}} - \text{RH}}{\text{RH}_{\text{crit}} - 100} \right)^2 \]

<table>
<thead>
<tr>
<th>Sensitivity class</th>
<th>$k_2$</th>
<th>$\text{RH}_{\text{min}}$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>very sensitive, vs</td>
<td>A=1</td>
<td>B=7</td>
<td>C=2</td>
</tr>
<tr>
<td>sensitive, s</td>
<td>0.3</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>medium resistant, mr</td>
<td>0</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>resistant, r</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Pine, reference

Values for new sensitivity classes
Maximum Mold Index levels at different RH % conditions

![Graph showing maximum mold index levels at different RH % conditions.

- Red line: very sensitive
- Orange line: sensitive
- Blue line: medium resistant
- Gray line: resistant

The graph indicates the maximum mold index levels under different RH % conditions at +20 °C. The y-axis represents the maximum mold index, and the x-axis shows the RH %.

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23
Evaluation of the model with mold sensitivity classes: Experiment vs. numerical predictions 1

Pine and spruce under 97 % RH and +5 °C
Evaluation of the model with mold sensitivity classes: Experiment vs. numerical predictions 2

C) Concrete, RH 97%, +22°C (1)

Mould index (0-6)

Weeks

Dec. 4, 2016, Buildings XIII, Workshop on Mold Risk Evaluation
Effect of dynamic conditions on mold growth

- Dynamically changing conditions delay the growth
- Decline of visible growth level after (long) periods with unfavorable conditions
Growth delay due to dynamic conditions

- Hourly / daily cycles can slow down the growth
- Both material capacity and mold growth dynamics have effect on this
- Predicted mold growth on pine sapwood under dynamic cyclic conditions RH 97 % / 75 % and +20 C
Decline of Mold Index

- Detected: Decrease of mold index after unfavorable growth conditions
  - Too cold, too low humidity
  - Does it really affect the level of restarting growth
  - What is the growth intensity after decline periods
- Model for wood gives high decrease
Decline of Mold Index – Seasonal effects on growth level

- Experiments under laboratory conditions
- Winter period with freezing temperatures at critical surface

Relative mold decline coefficients

<table>
<thead>
<tr>
<th>$C_{mat}$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Significant decline, pine, short periods</td>
</tr>
<tr>
<td>0.5</td>
<td>Relevant decline</td>
</tr>
<tr>
<td>0.25</td>
<td>Relatively low decline</td>
</tr>
<tr>
<td>0.10</td>
<td>Almost no decline</td>
</tr>
</tbody>
</table>

\[
\frac{dM}{dt}_{mat} = C_{mat} \cdot \frac{dM}{dt}_{Pine}
\]
Example – Four year simulation period data – 1

- WUFI 6 – Solved temperature and RH data for critical boundary
- Test the mold model and effect of parameters on Mold index
Example – Four year simulation period data - 2

- Solved mold index levels using different sensitivity classes for growth
- Decline coefficient 0.25 – includes safety

<table>
<thead>
<tr>
<th>Date</th>
<th>10/16</th>
<th>10/17</th>
<th>10/18</th>
<th>10/19</th>
<th>9/20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mould Index</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mo = 3
Critical level for exterior structure parts

Mo = 1
First microscopic findings of mold
= Critical level for indoor structure parts
Example – Effect of decline index

- Medium resistant material – variation of decline index
- All (except C = 1) have risk at indoor surfaces
- None has risk at exterior surfaces
- Risk level about the same when decline index has some safety

<table>
<thead>
<tr>
<th>Date</th>
<th>Mould Index [0, 6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/16</td>
<td>C=1</td>
</tr>
<tr>
<td>10/17</td>
<td>C=0.5</td>
</tr>
<tr>
<td>10/18</td>
<td>C=0.25</td>
</tr>
<tr>
<td>10/19</td>
<td>C=0.1</td>
</tr>
<tr>
<td>9/20</td>
<td>MR</td>
</tr>
</tbody>
</table>

- Mo = 3
  Critical level for exterior structure parts
- Mo = 1
  First microscopic findings of mold
  = Critical level for indoor structure parts
Modeling mold growth on different materials

- Model equations for wood
- Coefficients for different material groups
- Classification according to mold sensitivity classes
- Critical RH-levels for starting growth
- Maximum mold levels
- Decline coefficients for materials
Model evaluation with laboratory experiments

- The (RH/T) conditions and the mold index levels were monitored at the critical interface of two materials

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>Summer/autumn</td>
<td>Winter</td>
<td>Spring</td>
<td>High exposure</td>
</tr>
<tr>
<td>Time, months</td>
<td>7</td>
<td>4</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>RH %</td>
<td>80 ... 100</td>
<td>92 ... 100</td>
<td>60 ... 95</td>
<td>94 ... 100</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>27 ... 18</td>
<td>-5 ... +3</td>
<td>2 ... 10</td>
<td>20 ... 24</td>
</tr>
</tbody>
</table>

Case 1
Boundary: Solution using the properties of the more sensitive material
Parameters set according to material classification – Case 2

![Graph showing mould index over time for different materials and calculations.]

- LW concrete (experim)
- EPS (experim)
- Calc. s/r_0.25r
- Calc. s/r_0.10r
- Calc. mr/mr_0.10r

Date range: 30.4.07 to 22.8.08

Mould index [-]
Parameters set according to material classification – Case 3
Parameters set according to material classification – Case 4
Analysis principles

- Critical parts of the structure, critical boundaries
- Typically use the more sensitive material of the boundary as critical
  - Except when there are inhibitors limiting the growth (fresh concrete, some fire resistance materials, etc.)
- Different criteria for different parts of structure
  - Inside surfaces and material layers that can be in contact with indoor air – typical criteria MI = 1 (max)
  - Exterior or closed internal parts of the structure – criteria MI = 3
Summary

- Classification of materials according to mold growth sensitivity
- Coefficients scale the VTT Mold model for different materials
- Path from experiments to mold index parameters
- **Mold Risk prediction** for different materials
- Sensitivity analysis possible
Thank you for your attention!