MOULD GROWTH DAMAGES DUE TO MOISTURE: COMPARING 1D AND 2D HEAT AND MOISTURE MODELS?

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ABSTRACT

An excessive level of moisture in building damages their quality. Key factors associated to the development of this damages mainly depend on the hygrothermal fields inside building envelope. These key factors can be associated with HAM models to predict the development of moisture damages. Different granularities of HAM modelling exist in literature and can be used. In this paper, main advantages and drawback of most common approaches are presented and discussed. A test case is chosen to illustrate the different issues.

INTRODUCTION

Excessive level of moisture in buildings damages construction quality. Moisture also has an effect on indoor air quality and thermal comfort. Thus moisture can be a source of pathology in buildings. Many works have been published focusing on one specific damage like mould growth, corrosion, indoor air quality...etc. For instance Vereecken identifies and evaluates existing models predicting the development of mould in buildings (Vereecken and Roels, 2012). Coupled hygro-thermo-mechanical models can be found in literature ((Davie et al., 2010), (Khoshbakht and Lin, 2010)) to study the swelling and shrinking in material due to temperature and moisture content. However a comprehensive approach aiming at modelling all potential cases of moisture damage is still lacking in the literature. The work proposed in the present paper focuses on one of the important steps toward this ambitious issue.

Previous works aimed at defining an exhaustive list of damages due to moisture in buildings (Berger et al., 2012). These damages strongly depend on the hygrothermal fields in materials and ambient air. Each type of damage are associated with one key factor governing its development. A comprehensive set of key factors influencing the development of moisture related damages was proposed in this previous paper. These key factors can be associated with HAM (heat-air-moisture) models in order to predict the development of moisture damages. Furthermore, different granularities of HAM modelling exist in literature and can be used for the prediction of moisture damages. Granularity is related to the size of the volume or the finite elements modelled for heat and mass transfers. It goes from simplest transfer functions, through 1D, over 2D to 2D modelling.

The choice of the granularities is a relevant matter. In this paper, two modelling approaches are compared and discussed to expose their main advantages and drawback. These approaches are illustrated on a test case. It is a student apartment in a residential building, having some moisture related damages.

METHODOLOGY

To compare both modelling approaches, two models are chosen: a 1D-HAM model and a 2D-HAM model, presented in the following subsections. Each model is associated to the key factor predicting mould growth on material. A test case is used to compare the efficiency of prediction of mould in both approaches. The computational time is also studied. Figure 1 illustrates this methodology. In following sections, the different models chosen will be presented.

1D HAM model

The first kind of modelling chosen is one-dimensional (1D). It takes into account heat, liquid and vapour moisture transfers. The coupled differential equation can be expressed as (2) and (1) ((Piot, 2009), (Tariku et al., 2010)):

$$\rho_0 * c(w) * \frac{\partial T}{\partial t} = \nabla(\lambda(w) * \nabla T) + L_v * \nabla(\delta_v(w) * \nabla P_v) \quad (1)$$

$$\xi * \frac{\partial P_v}{\partial t} = \nabla(\delta_v(w) * \nabla(P_v)) + \nabla(K_l(w) * \nabla P_c) \quad (2)$$

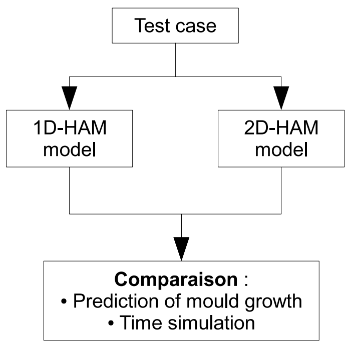

Figure 1: Methodology of the study

With $c(w) = c_0 + \frac{w}{\rho_0}$ the effective capacity, $\lambda(w)$ the thermal conductivity, $K_l(w)$ the liquid conductivity and $\delta(w)$ the vapour permeability of the material. P_c is the capillary pressure given by the equation (3):

$$P_c = -\frac{R_g * T * \rho_l}{M_l} * ln(\frac{P_v}{P_{sat}}) \quad (3)$$

ξ the moisture storage capacity is given by (4) :

$$\xi = \frac{\partial w}{\partial P_v} \quad (4)$$

A finite difference model is used to represent equations (1) and (2). The physical layers of the wall are divided into several numerical layers of thickness e. In the center of each numerical layer, a numerical node i is inserted. The temperature and the vapour pressure are computed for each time step with the following explicit scheme :

$$\begin{aligned} e * \rho_0 * c(w) * \frac{\partial T}{\partial t} &= \frac{T_{i-1} - T_i}{R_{i+1} + R_i} - \frac{T_i - T_{i+1}}{R_i + R_{i+1}} \\ &+ L_v(\frac{P_{v,i-1} - P_{v,i}}{R_{v,i-1} + R_{v,i}} - \frac{P_{v,i} - P_{v,i+1}}{R_{v,i+1} + R_{v,i}}) \end{aligned} \quad (5)$$

$$\begin{aligned} e * \frac{\partial w}{\partial t} &= (\frac{P_{v,i-1} - P_{v,i}}{R_{v,i+1} + R_{v,i}} - \frac{P_{v,i} - P_{v,i+1}}{R_{v,i+1} + R_{v,i}}) \\ &-(\frac{P_{i-1} - P_{s,i}}{R_{s,i+1} + R_{s,i}} - \frac{P_{s,i} - P_{s,i+1}}{R_{s,i+1} + R_{s,i}}) \end{aligned} \quad (6)$$

The thermal, vapour and liquid resistances are defined as :

$$R_i = \frac{e}{2\lambda(w_i)}, R_{v,i} = \frac{e}{2\delta_v(w_i)}, R_{s,i} = \frac{e}{2K_l(w,i)}$$

The thickness e of each node calculated and the time step is chosen by the user. This 1D-HAM model was validated following benchmarks 2 of HAMSTAD project (Hagentoft, 2004). It was developed in an object oriented environment *Dymola*. This tool uses the open modelling language *Modelica* and enables multi-domain physical modelling. It is possible to create your own libraries of models and build larger model by assembling different ones.

2D HAM model

The second modelling approach uses existing HAM model *Delphin* (Bauklimatik Dresden, port). This model takes into account same equations of heat and mass (liquid & vapour) transfers in 2 dimensions (3 dimensions simulations are also possible). Benchmark validation and equation details are given in (Grunewald and Nicolai, 2006).

Mould growth model

Several models for predicting mould growth exist (Vereecken and Roels, 2012). Two types of models exist : some indicates the start of mould growth and others estimates the growth and decline of mould. So, the VTT model has been chosen (Berger et al., 2012) to predict the mould growth for this study. It is a mathematical model based on experiments. It was first proposed for wood materials and recently extended for other materials. It takes into account the dynamic conditions of temperature and relative humidity, the material sensitivity to mould growth and models the dynamic growth of mould. For our study, this model was implemented in *Dymola*. Inputs of this model are temperature field, relative humidity field and sensitivity class of materials.

Both 1D and 2D modelling approaches enable to predict temperature and vapour pressure inside the materials of the walls. This results are used as inputs for the VTT model. Direct coupling was done in *Dymola* between the 1D HAM model and the VTT model. For 2D modelling, the results of *Delphin* are extract and used as inputs for the VTT model in *Dymola*.

SIMULATION

Presentation of the test case

The case study is a residential building, in Rennes (France). Its area is 4800 m^2. It includes 344 single student room of 9.3 m^2 (figure 2). The building, built in 1971, was constructed using bricks and insulated with extruded polystyrene. In 2000, retrofitting was done. The single glazed windows were replaced by double glazed windows. Each student room contains a single bed, a wash-hand basin and a desk. One radiator, linked to a central gas boiler, supplies the heating of the room. No ventilation system was installed.

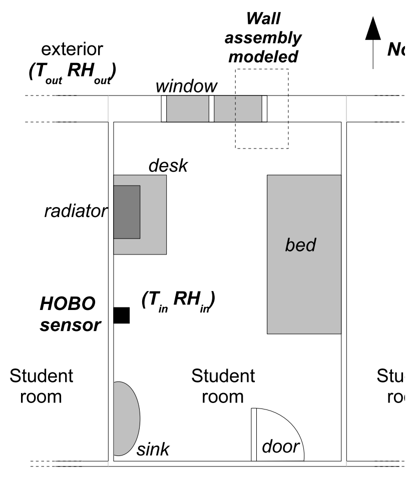

Figure 2: Schematic view of a student room with the wall assembly modelled

In 2008, a second important retrofitting was decided to reduce the energy consumption of the building and the enhance the comfort inside rooms. Therefore preliminary studies, diagnosis and infra-red inspection were done. In addition, temperature and relative humidity measurements were settled inside several students rooms during one year. Sensors were also settled for monitoring outside temperature and relative humidity.

Prosensor HOBO H21-002 were used and installed at a central wall of the room, protected from direct solar radiation and moisture sources.
Following this diagnosis, mould growth and thermal comfort problems were highlighted in some rooms. Occupants complained about too high temperature during winter.
Mould growth were observed under the windows ledge, on both concrete and brick parts of the wall. Therefore modelling will be focus on this part of the room (figure 2).
Figure 3 gives the detail of this part of wall assembly.

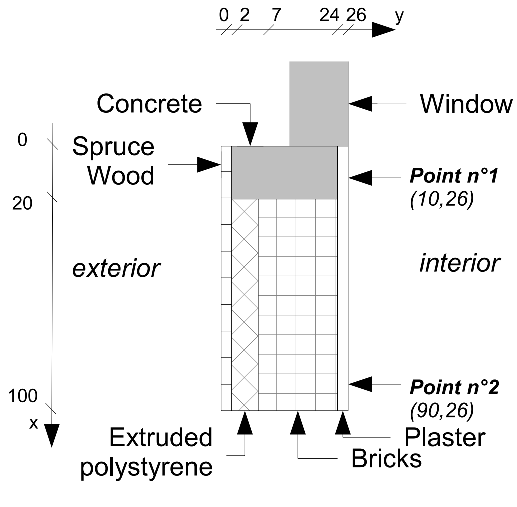

Figure 3: Wall assembly for modelling

1D and 2D HAM modelling approaches

With the 1D HAM model, it is possible to model the main part of the exterior wall, composed of different layers: spruce wood, thermal insulation, bricks and plaster (Figure 3).
On the other hand, the 2D HAM modelling approach enables to model complex assemblies. It is possible to model the thermal bridge under the window ledge (Figure 3).
The material properties are the one available in *Delphin* library. Experimental data are available for the different hygro-thermal coefficients : thermal conductivity λ, retention curve, vapour permeability δ_v and liquid permeability K_l.
In the 2D HAM model, linear extrapolation are done between experimental data to determine the coefficients.
For the 1D HAM model, the variation of these coefficients with water content were translated by functions fitting with the *Delphin* library experimental data experimental data (7) and (8):

$$w = \frac{a}{(1 - \frac{ln(\frac{P_v}{P_sat})}{b})^{\frac{1}{c}}} \quad (7)$$

$$\lambda = \lambda_0 + b \cdot w \quad (8)$$

Tables 1 and 2 and give the different values of coefficients (a, b, c) and values of other parameters.

Table 1: Coefficients of sorption curve and thermal conductivity functions

material	λ	$w = f(P_v)$
brick	$b = 6,0 \cdot 10^{-3}$ $\lambda_0 = 0.996$W/m/K	$a = 1000$ $b = 146 \cdot 10^{-6}$ $c = 1.59$
PS	$b = 6,22 \cdot 10^{-3}$ $\lambda_0 = 0.04$W/m/K	$a = 950$ $b = 135 \cdot 10^{-6}$ $c = 1.78$
plaster	$b = 5.71 \cdot 10^{-3}$ $\lambda_0 = 0.75$W/m/K	$a = 850$ $b = 0.014$ $c = 1.15$
spruce	$b = 6 \cdot 10^{-3}$ $\lambda_0 = 0.23$W/m/K	$a = 700$ $b = 250 \cdot 10^{-6}$ $c = 2.9$

Table 2: Vapour permeability and liquid conductivity for the different materials

material	δ_v	K_l
brick	$1.13 \cdot 10^{-11}$	$3.26 \cdot 10^{-18}$
PS	$1 \cdot 10^{-50}$	$1 \cdot 10^{-50}$
plaster	$2.17 \cdot 10^{-11}$	$2 \cdot 10^{-23} \cdot e^{0.0734 \cdot w}$
spruce	$1.10 \cdot 10^{-7}$ $-1.57 \cdot 10^{-10} \cdot w$	$8 \cdot 10^{-17}$

Problems of mould growth were highlighted under the window in this room, on both concrete and brick parts of the wall. The issue is to evaluate prediction of mould growth by both modelling approaches on the plaster surface.
The 2D HAM modelling approach enables to take into account the singularity of the wall and the presence of a thermal bridge. Therefore, surface temperature and water content were used to predict mould growth for two different points (figure 3):

1. 2D modelling : point 1 $(x = 10; y = 26)$: plaster with concrete behind it, representing the thermal bridge
2. 2D modelling : point 2 $(x = 90; y = 26)$ plaster with bricks behind it, representing the main part of the wall
3. 1D modelling : point 2' $(x = 90; y = 26)$ plaster with bricks behind it, representing the main part of the wall

For the 1D Ham modelling approach, this distinction for wall assembly is not possible. Only main part of the wall is modelled and mould growth is only evaluated for point 2. For differencing both approaches modelling, point 2 is noted point 2' for the 1D HAM model.

Boundary and initial conditions

The boundary conditions of both simulations correspond to the relative humidity and temperature measured with the sensors. Data are available from 14^{th}

of January 2009 until 11^{th} of January 2010. Figures 4 and 5 show the measurements.

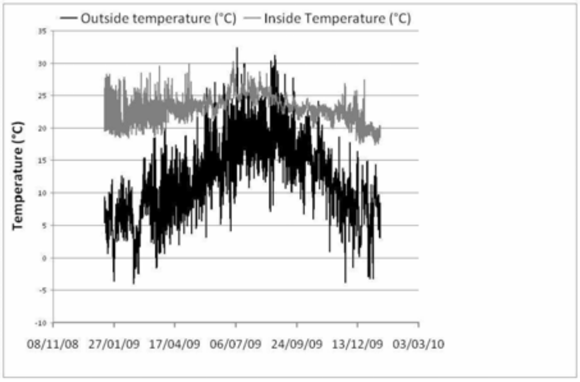

Figure 4: Variation of inside and outside temperature

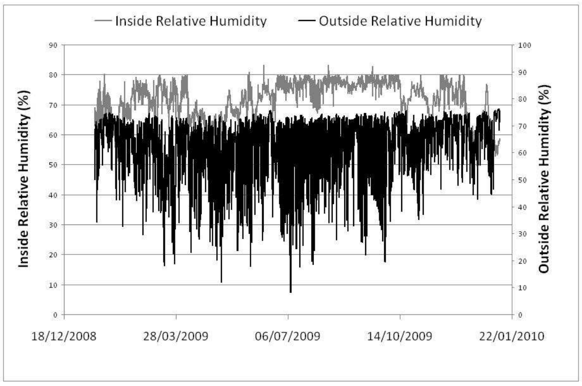

Figure 5: Variation of inside and outside relative humidity

The surface exchange coefficients transfer taken into account for modelling, are given in the table 3.

Table 3: Surface exchange coefficients

	Interior	Exterior
Heat surface transfer coefficient $[W/m^2K]$	8	30
Vapour surface transfer coefficient $[s/m]$	$3 * 10^{-8}$	$3 * 10^{-8}$

The choice of initial conditions is not easy for this building of 40 years old. (Moon, 2005) gives some value of initial moisture content for material in recently and existing constructed materials. He highlights the lack of precise data on this topic. However, he suggests that all layers of existing constructional element should begin with a relative water content of 40% for calculation. For our case study, this relative water content was taken as initial conditions.

RESULTS

Prediction of mould growth

The figure 6 shows the mould growth index M for:

- points 1 and 2 with the 2D approach modelling,
- point 2' with the 1D approach modelling.

For point 2 and 2', the index M is lower than the point 1. The 2D model enables more detailed description on wall assembly geometry and predicts wall mould growth in point 1. For this point, the index M reaches the value of 3, which corresponds to a visual findings of mould on the surface. In summer period, the index decreases but always stays higher than 1. The 2D approach modelling is more efficient than the 1D one, which predicts no mould growth.

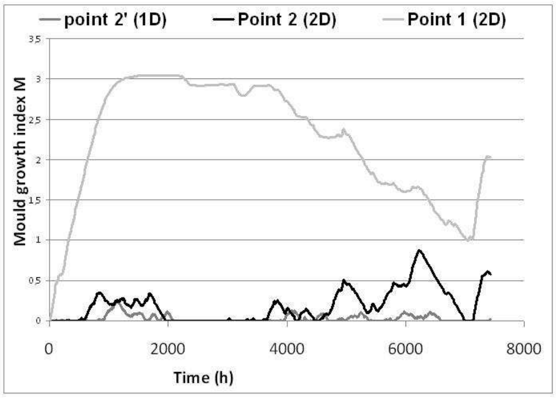

Figure 6: Mould growth index M for both HAM modelling approaches

With the presence of concrete under the ledge window, thermal resistance of main part of the wall is reduced. This assembly is considered as a thermal bridge. This specific constructional element modifies the hygrothermal fields inside the walls. It can be highlighted with figures 7 and 8. They give the relative difference ε (9) of temperature and relative humidity at the surface of the material for points 1 and 2.

$$\varepsilon(T) = \frac{T(point2) - T(point1)}{T(point2)} \quad (9)$$

Temperature for point 2 is higher than the one for point 1. On the contrary, the vapour pressure for point 2 is lower than the one for point 1.

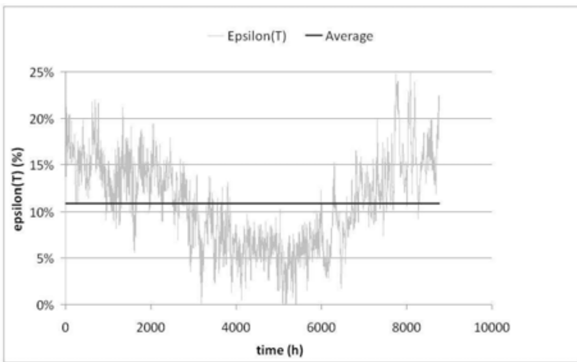

Figure 7: Relative difference for temperature between points 1 and 2

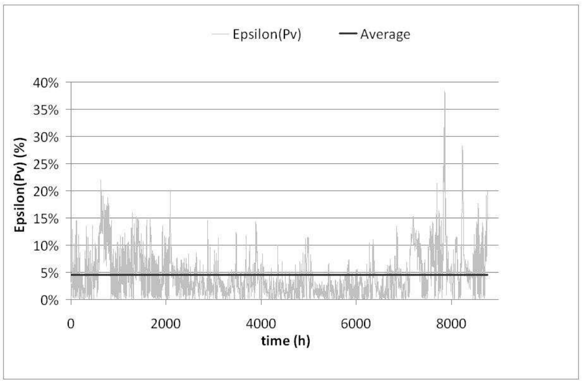

Figure 8: Relative difference for vapour pressure between points 1 and 2

For all the points between point 1 and point 2, the couples (average temperature, average relative humidity) are plotted on the experimental data of mould growth from (Clarke et al., 1999) (see figure 9). These experimental data give the mould limiting growth curves (or isopleths) for a common mould in building, *Aspergillus versicolor*. Again, this picture enhances the change of the hygrothermal fields inside the walls. The presence of concrete beam modifies the hygrothermal fields inside the wall until the limit of mould growth is reach. The limit is reached for the point at a distance of 0.15 m from the concrete.

The 2D approach is more interesting to appreciate the modification of the hygrothermal fields in the wall by specific point like thermal bridge. Associating the whole key factors with a 1D HAM model leads to a lack of information to predict moisture damages in buildings.

Computational time

The computational time of both 1D and 2D approaches is significantly different as referenced in table 4 with *AMD Phenom II, Processor 2.99GHZ, 3.49 Go RAM*. It is due to the number of nodes in the different approaches. The model developed on *Dymola* was not numerically optimized. It can be noticed that the computational time for this 1D model could be reduced.

Table 4: Computational time for both models

	2D model	1D model
Computational time (min)	40	7
Number of nodes	1700	135

DISCUSSION

Prediction of mould growth

Some differences can be noticed between point 2 and point 2' for the index of mould growth. Figures 10 and 11 give the differences for temperature and vapour pressure for both points.

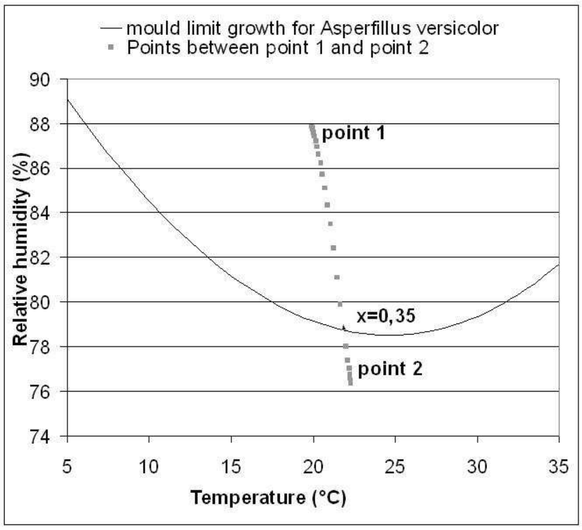

Figure 9: Mould growth limits for Aspergillus versicolor for all the points (T,RH) at the surface obtained with 2D HAM modelling approaches

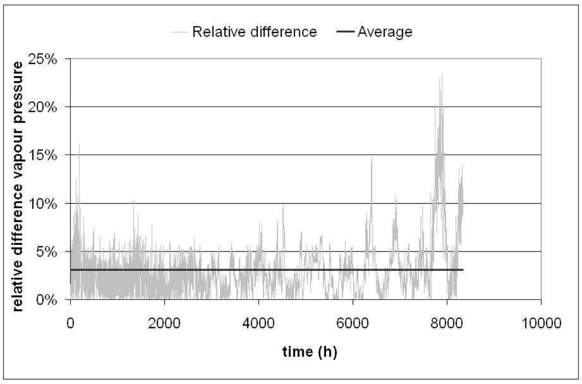

Figure 10: Relative difference for vapour pressure between point 2 and point 2'

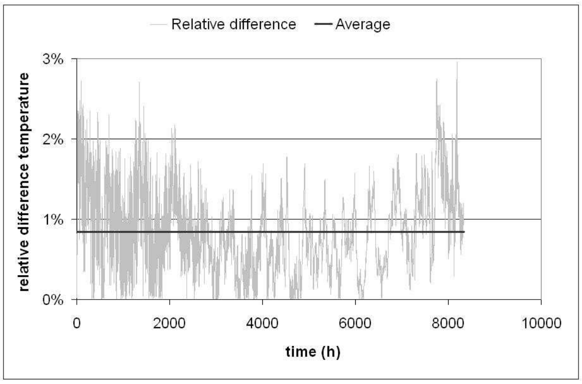

Figure 11: Relative difference for temperature between point 2 and point 2'

The relative difference does not exceed 23% for vapour pressure with an average of 3% and 3% for temperature with an average of 0.8%. To go further this analysis, the heat flux and vapour flux going through the wall were calculated on period of 1 day. As Relative humidity is the important parameter for predicting mould growth, the period of higher difference of vapour pressure between inside and outside has been chosen for study. The resulted flux are plotted on figures 13 and 12.

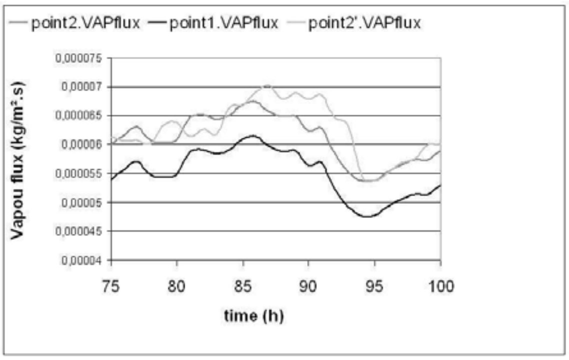

Figure 12: Vapour flux for period of 1 day for the different points

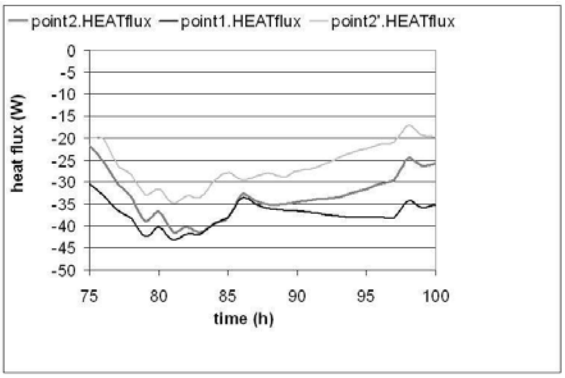

Figure 13: Heat flux for period of 1 day for the different points

Both flux predicted by 1D-HAM modelling at point 2' are relatively the same with the ones predicted by 2D-HAM modelling at point 2. The average relative difference is 3% for vapour flux and 9% for heat flux. Again, the influence of the thermal bridge can be noticed. The heat flux at point 1 is more important than at point 2. Therefore temperature at point 1 is lower than the one at point 2. And respectively, the vapour flux at point 2 is less important than at point 2. The vapour pressure is higher at point 2. It is the same analysis than for 9: high temperature and low relative humidity for point 2 and respectively low temperature and high relative humidity for point 2. It clearly shows how the presence of thermal bridge modifies the hygrothermal fields. The 2D-HAM modelling is more convenient for mould growth prediction.

Differences might be explained by the spread between two numerical solutions of models and by the materials properties used. In the 2D approach modelling, with *Delphin*, material properties are taken into account by linear interpolation of experimental data. In the 1D model, functions are approximated with the experimental data from *Delphin* library. An example of this difference is given for the sorption curve of plaster in figure 14.

This analysis highlights the importance of the characterization of building material properties. For predicting mould growth in buildings and more broadly moisture damages, modelling the properties of materials must be precise. In our case, linear interpolation from numbers of experimental data seems to be more accurate. Another important point is the hysteresis of sorption curve. No hysteresis was introduced in the model. Improving models by taking into account this feature should improve accuracy for moisture damages prediction.

The HAM model used in our study takes into account the boundary temperature and relative humidity (inside and outside). The boundary conditions as wind, wind driven rain, short and long wave radiations are not taken into account. As precised in (Cornick et al.) these element has an important impact on the prevision of hygrothermal fields in layers and therefore for the prediction of moisture damages.

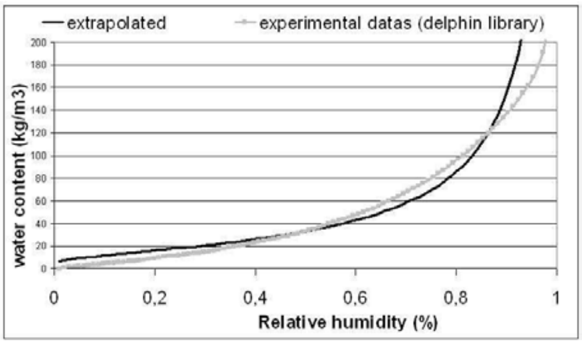

Figure 14: Difference between experimental data linearly interpolated (2D model) and equation extrapolated for sorption curve of plaster

Computational time

Results shows that the 2D model is able to take into account the variations of the hygrothermal fields inside the walls due to singular points like thermal bridges. The 1D model was not able to predict mould growth. On the other side, even with a 1D model not numerically optimized, the 2D model takes almost 6 time as much as 1D model for simulating. The choose of the granularity of the HAM model associated to the key factors for predicting moisture damages is a compromise between computational time and lack of information on the hygrothermal fields.

The development of moisture damages in building is a long process, specially for frost and mechanical damages. To appreciate the conditions of apparition of moisture damages in building, the time study of such model should be higher than 1 year. A reasonable proposal could be 10 years. For the test case, the simulation time would be about 7 hours for 2D model and less than 2 hours for the 1D one.

The prevision of mould growth was done only for one room of the whole building. In the 2D HAM modelling, just a singular point was interested in. Several other thermal bridges could be studied as the corner of two outside walls, the intersection between floors and walls…etc. The study of moisture damages in buildings should concerns all the singular points (thermal bridge) where there are more risks for moisture damages.

Furthermore, it is important to notice that effects of moisture on indoor air quality and hygrothermal comfort could be studied only if the HAM model is associated with a whole building energy simulation (BES). The computational time of such model should increase.

In this subsection, the main interest was computational time. In the case of existing building, it is difficult to know details of whole construction assembly. Therefore, 2D HAM modelling becomes time consuming because of the time needed for determining construction assembly.

Synthesis

With the results of this study, table 5 gives the main advantages and disadvantages of both modelling approaches.

Table 5: Synthesis of advantages (Adv.) and disadvantages (Dis.) of both approaches

Modelling approach	**1D**	**2D**
Adv.	computational time opportunities for whole BES	accurate prediction of hygrothermal fields
Dis.	less information on hygrothermal fields	computational time know of detailed construction assembly

CONCLUSION

With the issue of associating HAM model with key factors to explore moisture damages in building, the main advantages and drawback of the granularity of two modelling approaches were discussed on a test case. It appears that the choose of the granularity of the HAM model associated to the key factors for predicting moisture damages is a compromise between computational time and lack of information on the hygrothermal fields. 2D HAM modelling enables to predict impact of singular points as thermal bridges on the whole wall assembly. It anticipates moisture disorders on singular points and also on the main part of the wall whereas the 1D HAM modelling does not succeed to this prediction. On the other side, 1D HAM approach reduce computational time and gives opportunities to whole building energy simulations.

Future works will concerns model reduction applied to heat and moisture models. The issue is to simulate with reduced order models to obtain less but sufficient informations for the prediction of moisture damages. By the time, the computational time would be reduced and able to take into account the whole sensitive areas like thermal bridges in a building.

NOMENCLATURE

c	specific heat (J/kg K)
e	thickness (m)
K_l	liquid permeability (s)
L_v	enthalpy of evaporation/condensation (J/kg)
M_l	molar mass for water (g/mol)
M	Mould index ()
P_v	vapour pressure (Pa)
P_c	capillary pressure (Pa)
P_{sat}	saturation pressure (Pa)
R	thermal resistance (m^2.K/W)
R_v	vapour resistance (m^2 s Pa /kg)
R_s	liquid resistance (m/s)
R_g	gaz constant (J/kg K)
R_v	gaz constant for vapour (J/kg K)
RH	relative humidity (%)
t	time (s)
T	Temperature (K)
w	water content (g/m^3)
δ_v	vapour permeability (kg/m s Pa)
ϵ	relative difference (%)
λ	thermal conductivity (W/m K)
ξ	moisture storage capacity
ρ_l	densitiy of water (kg/m^3)
ρ_0	densitiy of material (kg/m^3)

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