Proceedings of Building Simulation 2011:
12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.

MULTIFUNCTIONAL WHOLE BUILDING SIMULATION AS A METHOD IN ASSESSING RETROFITTING STRATEGIES IN HISTORICAL BUILDINGS

Torun Widström[1] and Magnus Mattsson[2]
[1]Department of Civil and Architectural Engineering, KTH The Royal Institute of Technology, Stockholm, Sweden
[2]Centre for Built Environment, University of Gävle, Gävle, Sweden

ABSTRACT

The design of retrofitting strategies for historical buildings involves various challenges. The aim is often not only to save energy while providing acceptable indoor conditions for its users, but also to preserve the building and potential cultural artifacts, making it a multi-criteria issue, with multiple demands on the simulation tools and methods. This paper describes one way to fulfill on these demands through a serial, stepwise simulation process and a special tool, designed for that process. A case study, performed with the use of the method and tool, is presented. The results show that the method is workable and provides good agreement between simulated results and measured data.

INTRODUCTION

Background

The often sensitive nature of the cultural heritage objects makes it crucial to be able to evaluate the merits of different retrofitting strategies. This makes multi-functional simulations a valuable tool in the designing process.

The study presented in this paper is part of a multi-disciplinary project, Energy Efficiency and Preventive Climate Control, involving several Swedish universities, financed by the Swedish Energy Agency as part of a larger national research program. The aim of that project is to produce guidelines and recommenddations for owners and/or custodians of historical buildings and their advisers, and this means that knowledge must be gathered and that tools and methods must be investigated. The part described here is focused on simulation tools and methods, and how to deal with the demands the historic substance pose on these.

When performing building simulation in the context of the cultural heritage, the tools and methods utilized need to be able to embrace several interdependent aspects, such as energy, comfort and moisture. In addition, multi-zonal whole-building simulation is useful to assess general performance, but assessment of conditions at specific risk prone points is also of importance, and getting both requires at least 2D-studies to be added to the 1D-calculations of the whole-building simulation process. And, finally, it would be preferable to have the simulations provide estimated damage risk levels, for the comparison between different strategies. The study presented here is investigating ways to meet these demands and include the required multi-functionality in a single work process, in order to facilitate decision-making by the owners/ custodians.

Simulation tools of different kinds

One characteristic of historical buildings, dating from different times and different traditions, is that they differ not only from modern buildings but also from each other. Thus, what may be true of one building is not necessarily true of another, and while some cases can be assessed using fairly simple studies, others require more thorough investigations.

Available tools and methods for simulation processes that include several aspects are mainly of two different kinds. Grunewalds et al. (2003), discussing HAM-simulation tools, classifies these two kinds as simplified models and research models. They also conclude that, while easier to use and thus more readily available to practitioners, the simplified models are limited in validity, whereas the research models are limited in practical applicability due to their complexity. In cases that comply with the range of complexity that the software-designer has chosen as reasonable, the simplified models may perform quite satisfactory, but many historical buildings deviate too much from that range. Thus, practitioners simulating historical buildings often face a lack of suitable tools, since there is a gap between the two kinds of tools defined by Grunewalds et al. (2003).

The method and the tool presented in this article are created as steps in a process to bridge that gap, and deliver the desired functionality while maintaining usability as well as satisfactory accuracy.

METHOD

Demands and simulation tools

In order to identify requirements on the tools and methods that would suit the task, it is necessary to consider what aspects it is essential to examine in historical building cases.

General performance, as well as specific indoor conditions and comfort levels are of importance, and in many cases also the conditions of local micro-climatic points where damage already has occurred or may be likely to occur.

Long-term simulations are necessary, preferably running over several years. In addition, we have to deal with irregular geometries, unknown component structures and/or materials, unknown states of deterioration, difficulties in gaining access due to fragile or culturally valuable surfaces, and the general need for flexibility and inventiveness in modeling different strategies.

Therefore, we require multi-functional long-term whole-building simulations that comply with the conditions of the practitioners in the field.

Focusing on the most essential demands, it is evident that a simulation method suitable for the purpose needs to be:

- Able to include multiple aspects: energy, comfort, moisture performance, damage risks and reliability, including CO_2 emission, exergy and other aspects of resource usage
- Dynamic, preferably able to simulate several years
- Multi-zonal, able to embrace the whole building
- Able to forecast average performance as well as local microclimate conditions at critical points
- Fast, accessible, reliable, flexible and easy to calibrate

Methods to meet the demands

Multi-functional simulations can be achieved in several ways (cf. Citherlet et al. (2001). One way is to examine independently in parallel the various features to be simulated and then gather the results and manually evaluate conflicting interests and prognoses, based on the experience of the expert performing the evaluation. This corresponds to the model a in figure 1. The main problems here are that the interdependence of the various aspects is not taken into account and that the result relies on experiences from the past and personal skill in the evaluation. Although the skill and judgment of the expert are indispensable assets, an evaluation of interdependent aspects relying solely on these forces them to replace much of what simulations might contribute. In addition, the quality of the outcome of such a process is difficult to assess.

Another way of solving multi-functionality is to use an advanced, either fully integrated or closely coupled tool, as represented by model b in the Figure. This procedure is likely to reduce error risk by dealing with a single model and performing more detailed calculations with all the simulated aspects simultaneously, but the risk of instability, user errors due to complexity and limited use increases.

In the present work, the approach adopted is to find a third path by dividing the simulation process into several steps, as indicated by model c in the Figure, adding aspects one or two at a time in series. This leads to a more stable and less complicated simulation process, although recalculation is necessary in order to simulate interdependent aspects. Of course, simplifications have to be made and these will be discussed in this article.

This serial simulation process can be seen as a hybrid coupling/integrating simulation model, (cf. Citherlet et al. 2001). Although a parallel approach may seem more natural given the interrelated nature of the as-

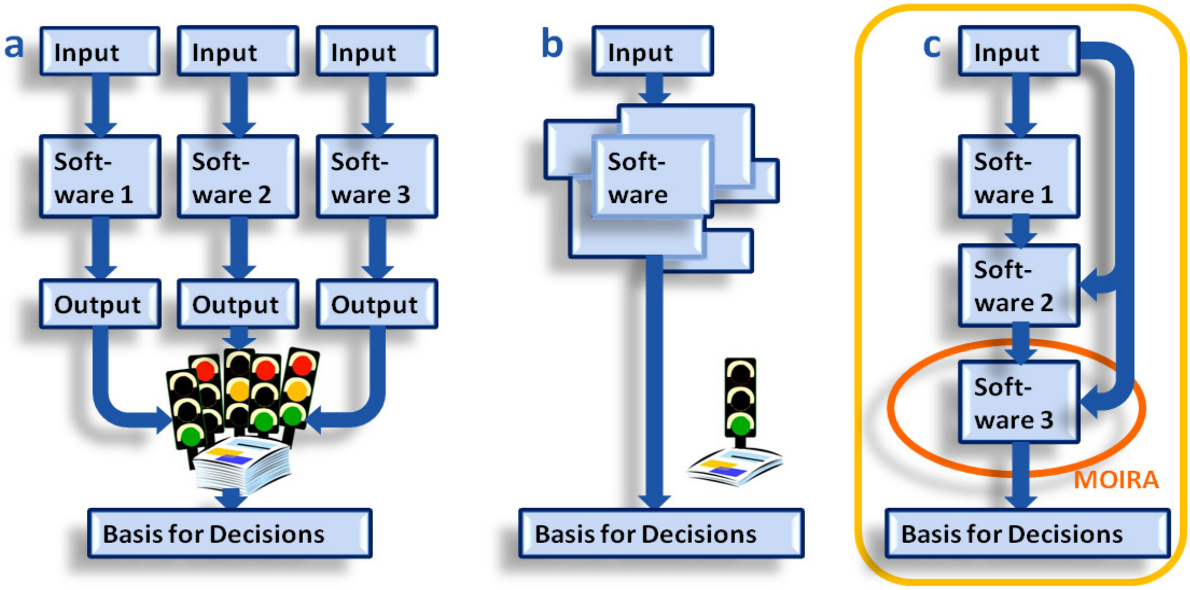

Fig. 1: Different models for simulation of multiple aspects: a. Parallel simplified – a multitude of results that need to be balanced against each other, b. Advanced fully integrated or closely coupled and c. Serial, with the new tool MOIRA encircled.

pects included, the stepwise addition of complexity can not only increase stability but also provide better opportunities for calibration and error checking.

The new model

In order to build this serial process, existing software was investigated, and it was found that since flexibility is difficult to add at a later stage, this should be given priority in the choice of the primary tool. Thus, a modular tool, IDA-ICE 4.0, was chosen to provide the basic model, to simulate heat and air flows and to provide a rough estimate of indoor RH-behavior, based solely on the moisture transferred by the air flow. This model also discloses indoor air quality with respect to CO_2 content and basic thermal comfort, and it has the advantage of being easy to log the results in, in any preferred order and compilation, which is necessary in order to be able to transfer them to the next step. The output from the first simulation is taken as input to the next step that recalculates the heat and moisture behavior. The tool for this latter step, including damage risk assessment, curves for the prediction of mould growth and temperature and moisture fluctuation patterns, did not exist and thus had to be created. We are therefore now developing a serial method, as well as a specific simulation tool, MOIRA (MOIsture Recalculation Application) to be used within the method.

With regard to risk assessment, the derivation of predictable conditions is of course an important step, but the risks that actually arise under these conditions are another matter, and this makes the task somewhat more difficult. Risk assessment in this model is based on several sources, but primarily on the suggestions made by Camuffo, Fassina and Havermans (2010) and by Sedlbauer (2001).

Thermal comfort is a factor included in IDA-ICE 4.0, but comfort standards in historical edifices may deviate significantly from those of modern buildings, and this requires deeper consideration so that it can be properly included in this process.

There is however another crucial issue that must be addressed: the conditions at critical points – and these may require at least a 2D-simulation within a 1D whole-building simulation. This means that a step must be added ahead of the primary whole-building simulation tool, in this case an investigation using Comsol Multiphysics providing results to be used in the subsequent steps.

More aspects are included in the study, but this paper discusses only results relating to energy, temperature, humidity and the risk of mould growth.

Calculations

Methods and simplifications

Several simplifications made in this study may affect the result and may therefore be altered in a later development of the tool. Convective moisture transport through the building components is calculated only as a mass flow. No influence on the temperature of condensation or evaporation is yet included; rain loads on component surfaces are in this study, mainly due to lack of local data, and so also is thermo-diffusion, which is assumed to have a negligible influence in this context (Künzel 1995, Baker et al. 2009).

The moisture transport method in the presented study is simplified, according to the classification suggested by Grunewald et al. (2003), especially in its choice of moisture transfer potential, which is humidity per volume instead of for instance vapor pressure. Pressure is doubtlessly a technically more correct potential, and in later versions it is implemented as driving force of the moisture transport instead of the moisture content.

To compensate for the most obvious disadvantage of the choice of potential, a temperature-dependent volume shift factor is used in the calculations. Liquid and vapor transport through the building components are taken into account, but convective transfer is added to mass flow for the transport due to ventilation. This leads to the following formulas for the moisture transport, with modifications of the functions used according to the degree of saturation of the material, and the moisture level in the zone:

$$g = \delta_v \frac{\partial v}{\partial x} + D_w \frac{\partial w}{\partial x} + S_w \qquad (1)$$

and

$$v_t = \frac{\left(v_{t-1} + \frac{G dt + \sum_{k=1}^{n} g_k A_k dt}{V} \right) \left(V - \sum_{i=1}^{m} L_i dt \right) + \sum_{i=1}^{m} L_i v_i dt}{V} \qquad (2)$$

where S_w represents the flow of liquid moisture into the walls from the ground, added into the 1D-calculations as an additional moisture source, v_t represents the moisture per volume of the air in a zone at a given time step, v_{t-1} the moisture per volume for the previous time step, G represents added internal moisture, including any temperature- and humidity-dependent reductions accomplished by a dehumidifier, n the number of components in contact with the zone, g_k the moisture flow from the surface of component k, A_k the area of that component, m the number of adjacent zones, L_i the air flow from a specific neighboring zone and v_i its humidity. The heat flow is then calculated according to Fourier's law, with λ-values, δ and D_w-values adjusted according to the moisture content.

Integrating 2D/3D into a 1D-model: the Very Small Wall-part Method

Whole-building simulations are generally performed as 1D-calculations, and thus they do not normally give answers about local conditions affected by 2D or

3D heat and moisture flows. In this simulation process, however, we seek both the overall performance with its average values and the specific conditions at the points at which problems are most likely to occur. Thus we begin with a 3D-program, in this case Comsol Multiphysics, in which all the critical points are simulated and λ-, δ- and D_w-equivalents are calculated, to mimic the behavior of these points in the whole building simulation.

The calculation of the performance of these points is then split into two different paths. One deals with the effect that thermal bridges have on the general performance of the building, using ψ-values that are entered into the whole-building software. The other makes the behavior at the chosen points visible by using very small wall parts in the whole-building model, small enough not to affect the calculation of the overall performance. These wall parts are assigned the equivalent properties derived in the first step of the procedure, and the results for these specific points can then be logged parallel to those showing the average performance of the building components. The differences can be seen, and damage risk curves for these points and average data values can be obtained in a single simulation.

The case study

The simulation procedure was tested with respect to Hamrånge church, situated on the Swedish Baltic coast. The church, with an indoor volume of about 8750 m^3, is from the 1850's, but it contains items from an earlier medieval church and has fairly thick stone walls. The ceiling is a wooden barrel-vaulted construction. The floor is also wooden, permitting an air and moisture exchange with the crawl space underneath. There are no discernible moisture problems in the church today, but there are problems in the crawl space, and this has led to some concern and to investigations.

The church is heated by electrical radiators, placed below the windows and under the pews, and the control strategy in 2010 has been intermittent heating with a minimum temperature of 11°C during the week and 19°C during the weekends. In 2009, the minimum temperatures were respectively 12°C and 20°C.

To deal with the crawl space problem, as well as the high costs for heating, the strategy currently being tested is to close the crawl space vents. New measurements are now being made to study the effect of that measure. The model of this study is being calibrated against data from the time before the vents were closed, and it is being validated against data from after the closing. Four strategies have been simulated: 1 – Crawl space vents open (Sc 1), 2 – Crawl space vents closed (Sc 2), 3 – Crawl space vents closed during the first half of the year and open during the second half (Sc 3), and 4 – Dehumidifier (3,0 kW) installed in the crawl space and the crawl space vents closed (Sc 4).

Issues

Material properties

Apart from the problem of simplification, it is difficult to acquire useful input values for the material properties. The only practical, although arduous, way to deal with this problem has been to calibrate the model according to measured data.

Measurements

To calibrate and to validate the model it is imperative to have reliable measurement data over a sufficiently long time. It is also important to have a sufficient number of measurement points. This can be a troublesome feature of a whole-building simulation of an historical building, since measurements can be both a disturbance in the use of the building, depending on the equipment and where it is placed, an added cost and a delay in the investigation.

Geometrical issues

The often complex and irregular geometries generally fit the whole-building simulation software badly, making considerable simplifications necessary. Equivalents have been calculated in this study, and Comsol Multiphysics was used where necessary, but a study of structured forms for this kind of pre-calculation could benefit the process.

RESULTS

The results consist of a comparison of the results for the different strategies, and a first validation of the method and tool, comparing the calculated values to measured ones.

Energy usage

The calculated energy usage for the different scenarios is shown in table 1:

Table 1: yearly energy usage in the different scenarios, MWh

SCENARIOS	ENERGY USAGE, MWH
Sc 1, crawl space vents open	132
Sc 2, crawl space vents closed	129
Sc 3, crawl space vents timed	130
Sc 4, dehumidification	141

Humidity

The three alternative strategies all lead to a reduction of about 5% in the RH inside the church, but this reduction is not really necessary since the moisture levels do not approach the risk levels. In the crawl space, however, the situation is different. Scenario 2 with the vents closed does not really reduce the RH and at times it increases considerably, especially during the fall. Even when the RH is similar to that of the status quo strategy, scenario 1, with the vents open, the conditions at the thermal bridges are worsened by this strategy, as shown in figure 2.

During the fall, the level of scenario 2 is generally higher, seen more in detail in the comparison of the curves for a week in November, in figure 3.

The performance of MOIRA has been assessed by comparing the simulated results against the measured values for the late fall of 2009 (figure 4), and for about the same period in 2010, after the vents had been closed (figure 5).

Although the data for 2009 show a good fit some of the time, there are deviations. This may be due in part to the fact that the climate data used were taken from the nearest weather station and not from the site itself, because the measurements made on the site did not cover a sufficiently long period. Also, the outdoor measure equipment at the site was placed close to a wall, which affected the data for the outdoor conditions at the site and made them less reliable. The climate data used will probably give a reasonable result, but there will be deviations from actual local conditions. More important, MOIRA was at the time of this study not yet able to handle the wetting of outdoor surfaces due to rain. Local data were lacking, and the amount of precipitation in Gävle, some 25 km away, did not seem useful. However, the results from 2009 clearly show that this functionality is not negligible and, after this study, it has therefore been added to the calculations. During the second test period, in 2010, there was no precipitation, and the results are accordingly in closer agreement.

Damage risk factors

Mould growth

The risk curves included here will not be described in full detail, as it would require another article to do, yet the ability to provide damage risk assessment is an important feature to include in the simulation process, and therefore they are still presented here. The risk of mould growth is known to be related to temperature, humidity and the availability of nutrients, but the duration of the conditions is also important. Temperature and moisture graphs may show whether the conditions for mould growth are present at any given moment, but to evaluate the actual risk the dimension of time must be added. This means that boundaries for what are to be considered risk zones had to be established, at first only three. We have based them on the work of Sedlbauer (2001), who displays a wide range of isopleth systems for different kinds of growth, health classes and substrates. To make this workable in the present con-text, only one particular set of curves was selected. The health risk for humans, although important, was ignored since the chosen curves representing risk of mould infestation in the building were lower and thus also safer from a health point of view. The germination isopleths have also been disregarded in this con-text, since it has been assumed that the risk of new infestation is probably less than the risk of continued growth of existing mycelia. To create a safety margin, the most extreme substrate category was been chosen. This may raise an alarm too early, and can thus be subject to change later, but the choice was done to be on the safe side. A mould growth risk index, MGI, has been created, where the RH at each time step is compared to the value found on the isopleth temperature curve for that time step. A value less than 1 indicates that the curve for potential mycelial growth was never crossed, a value between 1 and 2 indicates that the RH/temperature combination led to a risk for mould growth risk but did not reach the level of 1 mm per day, and a value greater than 2 indicates a level greater than 1 mm/day. The thus derived risk curve indicates not only whether the

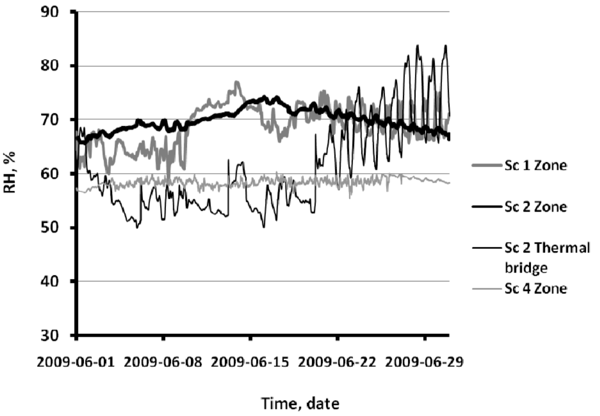

Fig. 2: Simulated mean RH of the air in the crawl space for scenarios 1, 2 and 4 in June 2009, with the addition of the RH for the point by the thermal bridge in scenario 2. (Air RH for scenario 3 is equal to that of scenario 2, since both display closed crawl space vents at this point in time)

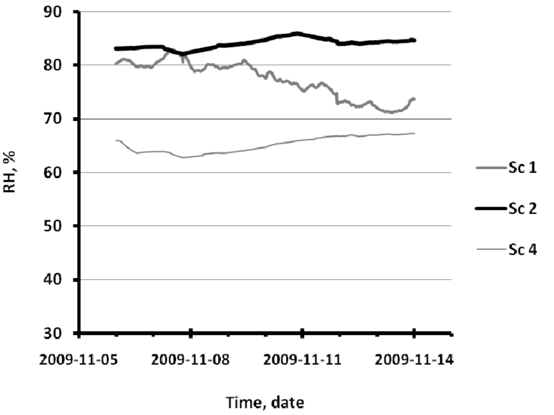

Fig. 3: Simulated mean RH of the air in the crawl space for a week in November 2009, for scenarios 1, 2 and 4. (Scenario 3 similar to scenario 1, as they both have the crawl space vents open at this time and the effect of higher humidity accumulated during spring/summer in Sc 1 is levelled out at this point.)

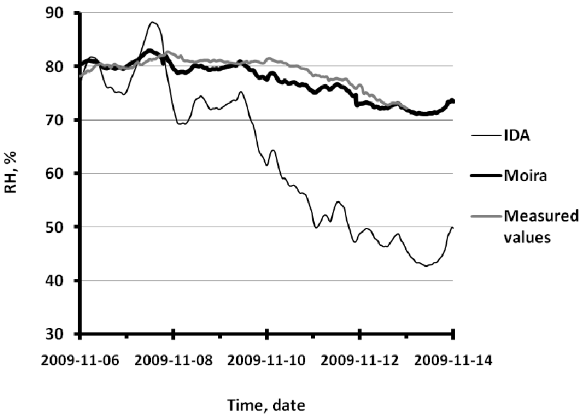

Fig. 4: Measured RH of the air in the crawl space together with the results of the initial IDA-simulation and of the MOIRA-simulation (Sc 1, corresponding to the open crawl space vents at the time of measuring), for a week in November 2009, before the crawl space vents were closed.

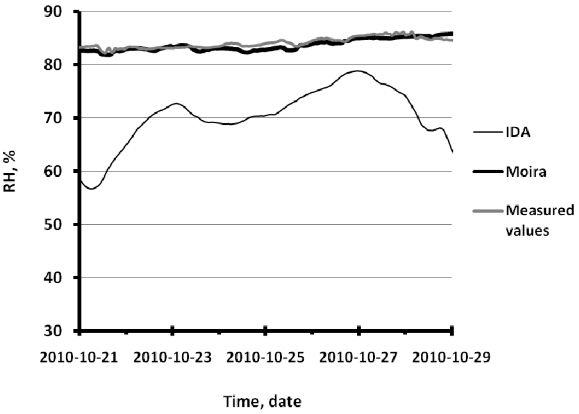

Fig. 5: Measured RH of the air in the crawl space together with the results of the IDA- and the MOIRA-simulations (now the Sc 2, crawl space vents closed), for a week in October 2010, after the crawl space vents had been closed.

RH has exceeded the limits for mycelial growth but also how close it is to doing so, as seen in figure 6.

Examples of the mould growth risk index curves are shown in figure 5, and the maximum mould growth risk duration levels reached are given in table 2.

DISCUSSION

The results of the different simulations show that, although the crawl space vents were closed in order to lower the relative humidity in the crawl space, the problem is not the moisture brought in from the ambient air but is to a much greater extent the moisture rising from the ground. Thus the strategy of scenario 2, in which the crawl space vents were closed, had little effect in the spring when providing protection against moist warm air entering the still cold crawl space but actually led to a considerable increase in the RH there during the fall, since the moisture rising from the ground was not ventilated away. Nevertheless, the RH within the body of the church was lowered by this strategy, since the air flow from the crawl space was greatly reduced and was replaced by an of the RH was not however necessary, as the RH was not at a risk level in the first place. This strategy is thus not a solution to the problem. The strategy of scenario 3, which kept the vents closed during the first half of the year, to prevent moist air from entering into the cold crawl space in early summer, and opened the vents in the second half of the year, showed little difference from the situation with the vents open. This strategy led to a 2% reduction in the energy consumption and, although it may not be considered an efficient solution to the crawl space moisture problem, it is very cost efficient. The only strategy that delivered the desired result of keeping the crawl space free from the risk of mould risk was to install a dehumidifier – but that in turn resulted in an increase of 6.6% in the energy consumption. The desires to improve the energy performance and to keep the crawl space free from the risk of mould growth were thus not reconcilable using any of the studied strategies, but the periodic opening and closing of the vents, the historical method, did lead to a slight improvement in the situation.

It should be noted that the calculations are based on the assumption that the air in the respective zones is well mixed and that the average humidity per volume can be used to estimate the RH in the zone as well as at the investigated critical points. The validity of this assumption might however be questioned, especially regarding the crawl space, and even more so after the closing of the vents. With a height of some 0.70 – 0.80 m, a floor area of about 740 m^2 and numerous walls and pillars separating the air into several volumes, the mixing of the air is likely to be limited.

Table 2: Prediction of maximum continuous duration at risk levels, in days, for the scenarios, during 2009.

	AIR IN ZONE			MOST EXTREME POINT		
	Mould growth risk	*Growth risk 1-2 mm/day*	*Growth risk > 2 mm/day*	*Mould growth risk*	*Growth risk 1-2 mm/day*	*Growth risk > 2 mm/day*
Scenario 1, Sc1	7.14	0.53	0	7.59	3.84	1.55
Scenario 2, Sc 2	62.24	4.14	0	45.76	25.22	2.90
Scenario 3, Sc 3	0.99	0	0	6.59	0	0
Scenario 4, Sc 4	0	0	0	0	0	0

CONCLUSIONS

A simulation tool has been presented and it has been validated against measured data from a case study in a Swedish church with good agreement. The simulation takes only a very short run time, with about 100 000 time steps in 24 seconds, it is flexible and, provided that the time steps are kept within limits, it shows good stability. The tool is still at an experimental level. More tests and validation with better climate data as well as an improved user interface and version handling are highly desirable, as is increased functionality and in particular the inclusion of the impact of precipitation wetting on component surfaces.

ACKNOWLEDGEMENTS

We thank professor Tor Broström, Gotland University, coordinator of the research program Spara & Bevara, of which this study is a part, and it's financers the Swedish Energy Agency and The Church of Sweden. We also thank professor Folke Björk, assistant professor Kjartan Gudmundsson, PhD-student Marco Molinari, senior researcher Per O Isaksson and professor emeritus Ove Söderström, all at KTH, for their valuable contributions as sounding board for this work. We are also very indebted to programmer Carl-Johan Wägner for his generous assistance.

REFERENCES

Baker P.H., Galbraith G.H. & McLean R.C. 2009. Temperature Gradient Effects on Moisture Transport in Porous Building Materials. Building Services Engineering Research & Technology, vol. 30 No. 1, p. 37-48

Camuffo D., Fassina V. & Havermans J. (Editors) 2010. Basic Environmental Mechanisms Affecting Cultural Heritage. Understanding Deterioration Mechanisms for Conservation Purposes. COST Action D 42: Chemical Interactions Between Cultural Artefacts and Indoor Environment (ENVIART). Nardini Editore, Firenze. (ISBN 978-88-404-4334-8) 176 p.

Citherlet S., Clarke J.A. & Hand J. 2001. Integration in Building Physics Simulation. Energy and Buildings, Vol. 33 No. 5, p. 451-461.

Grunewald J., Häupl P. & Bomberg M. 2003. Towards an Engineering Model of Material Characteristics for Input to Ham Transport Simulations – Part 1: An Approach. Journal of Thermal Envelope and Building Science, Vol. 26 No. 4, p. 343-366

Künzel H.M. 1995. Simultaneous Heat and Moisture Transport in Building Components. Fraunhofer IRB Verlag, Stuttgart (ISBN 3-8167-4103-7)

Sedlbauer K. 2001. Prediction of mould fungus formation on the surface of and inside building components. Dissertation, Stuttgart University.

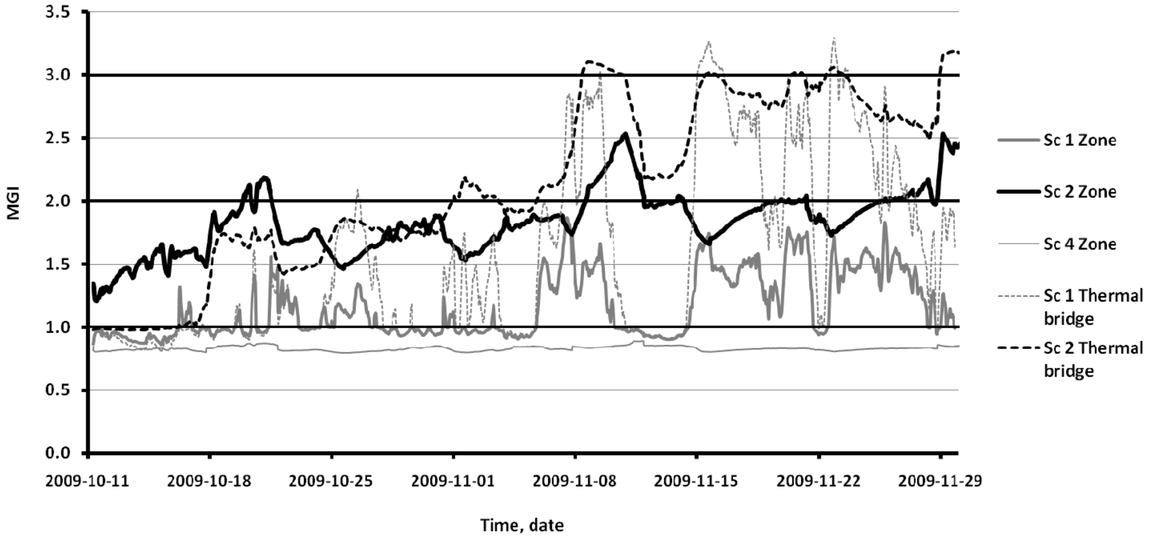

Fig. 6: Mould Growth Risk Index Curves for zones and thermal bridges, in the fall of 2009. The growth risk levels are based on curves for a. the limit for any potential growth, representing an MGI-value of 1 in this graph, b. a potential growth rate 1mm per day, equivalent of an MGI-value of 2, and c. a potential growth rate 2mm or more, represented by an MGI-value of 3. Thus the condition of the air in scenario 2, consistently remaining above the value of 1, is indicating some mould growth risk throughout the period. The thermal bridge point in scenario 2 shows a continuous risk for a growth rate of 1mm/day or more all the time from the first week in November and thereafter. MGI is dimensionless, as it represents a certain risk level, not a specific growth rate. A revealed risk for growth should not be taken as a prediction that growth will occur.