Whole building simulation and damage risk assessment in historical buildings

Torun Widström*
Department of Civil and Architectural Engineering, division of Building Technology
KTH, The Royal Institute of Technology, Stockholm, Sweden
e–mail: torun.widstrom@byv.kth.se

Magnus Mattsson
Centre for Built Environment
University of Gävle, Sweden
e–mail: magnus.mattsson@hig.se

ABSTRACT

When simulating historical buildings, available tools tend to be intended for simulations of either of two kinds: whole building simulations of energy-/moisture performance, from which we can determine general conditions that may give an indication of potential damage risks, though unspecific, or detailed simulations that look into what takes place at specific points/materials, which provides us with knowledge about the specifics but without much context. Both are efficient scientific methods, but when dealing with reality we need both perspectives simultaneously. This paper describes multi-criteria simulations that take this into account, using a new tool integrating display of specific moisture-connected risk-factors into whole building simulations, providing a coherent basis for decision-making when retro-fitting, and compares the results to case-study measurements.

KEY WORDS: Multifunctional whole building simulations, historical buildings, damage risk assessment

INTRODUCTION

Maintaining our built cultural heritage poses a greater and greater challenge, as the need to reduce energy usage becomes increasingly urgent and climate changes start to alter the conditions of existence for artefacts created during other times. There are several implications of this, of which this study deals with the need for new tools to assess the possible consequences of potential strategies for how to deal with this task. The necessity to decrease energy usage makes previous energy demanding strategies less feasible and it becomes even more important than before to get a good knowledge about how the buildings function today, how they were intended to function – possibly revealing passive strategies that can be reused or at least taken into account when retrofitting – and how they would function in the future, if retrofitted according to different strategies.

However, tools available to the practitioners on the field are generally either intended for single-domain simulations of whole buildings – the whole building function being

* Corresponding author

desirable as the interaction between different components and zones is valuable for the overview of the general performance of the building – and more specific software that allow us to examine the conditions of specific spaces/points/materials/ components, provided that we know the boundary conditions and the investigations are steady state studies or at least limited in time as well as in space. The whole building simulations then provide us with general knowledge and average values that inform us of potential problems, and this over longer periods of time which is desirable, but they do not reveal what is actually taking place at the points where those problems are most likely to occur. So we get an indication, but that is all. The specific software reveals the information missing in the results of the whole building simulation, but not over time, and when we start to look at the multitude of criteria the simulation process of a historical building would have to cover to give us the full picture of the consequences of different alternative retrofitting strategies, this combination of a number of programs, computer models to build and boundary conditions to connect to, as well as a multitude of sometimes contradictory results and interaction effects not taken into account, it becomes clear that this process would gain on being simplified.

Also, we have the practical issue of how to make such a simplified process available to as many practitioners on the field as possible, for the sake of providing decision-maker deciding on retrofitting strategies the most adequate background for their decisions. This is adding the complication that the process must comply with the conditions of consultants on a market. So we need easily available, fast, reliable, multifunctional, easily overviewed and managed simulation tools that provide us with results that take all aspects into account that we need in the decision-making process. This means finding simple methods to deal with a multifaceted task, which in turn requires a balance between complexity and simplification.

This is the background for the study of this paper, which is part of the Swedish national research program Spara & Bevara (Energy Efficiency in Historical Buildings), financed by the Swedish Energy Agency. Its aim is to find and recommend tools and methods that correspond to the aforementioned requirements, and as part of that work this study displays a method to perform multifunctional semi-integrated simulations partly using existing tools, partly a new one, developed as part of the sub-project. The study in this paper deals mainly with damage assessment aspect of the different functionalities taken into account, as this is both of utmost importance and an area that can do with more elaborate description of consequences, but the simulation as such includes several aspects, as displayed in table 1.

THE INTEGRATION OF SEVERAL ASPECTS IN ONE SIMULATION PROCESS

The demand for multifunctional simulation tools is not new, there has been a development of programs integrating two or more domains during quite some time, where the HAM-programs might be the ones where most work has been done, focused on in for example IEA Annex 24 [1] and IEA Annex 41 [2]. There are also simulations integrating more aspects, like energy, lighting, acoustics, comfort and environmental aspects, such as displayed in an article by Citherlet and Hand [3]. The theoretical background for the development of integrated multifunctional rather than coupled programs has been well described in the work of Citherlet, Clarke and Hand [4]. Taking the investigation more specifically to the area of implementing the scientific knowhow of HAM-simulations on the level of a more general application Grunewald, Häupl and Bomberg [5] has presented an approach to how this can be done, and van Schijndel [6] amongst others has elaborated HAM integration in greater detail.

The aspects included in this study are heat transfer, energy and exergy usage, temperatures and moisture performance in general and for critical points, mould growth risk and fluctuation patterns, and to a limited extent comfort and IAQ. Not yet included are environmental impact, frost risk, pollution, salt activity, financial impact and value of cultural heritage affected by the scenarios.

This focus on practical application in this study has made several compromises necessary. Where [4] defines different strategies for multifunctional simulation ranging from parallel stand-alone applications through different interoperable applications, coupled programs and finally reaching the level of fully integrated software, this study presents a hybrid, performing several simulation processes serially, making the best use of existing resources while yet achieving the multifunctionality desired. This has two reasons: one that there are already programs whose reliability and workability can be made use of instead of and secondly the flexibility, as this method allows for different tools to be used and also flexibility as far as integrated aspects goes, since we are no longer looking at the integration of two or three domain, but rather at a much broader range.

This is of course not without its complications and without specific demands on the existing software made use of. For one thing, the parallelism of the coupled and integrated models of course fills the function of taking the interacting of the different aspects into account, and to assure that this is not lost in the serial version does cause some process to have to be repeated. Also, there is a certain untangling of variables to do in order to perform that repetition and/or continue in a secondary software where the first one ends, which means requires the results, also at a rather detailed level, to be exportable. It is of course also valuable if the existing programs are already partly integrated, covering several domains already.

Another aspect to take into account is the flexibility in the building of the computer model. Many simulation programs aimed at modern buildings are not necessarily particularly flexible, as it is assumed that buildings are designed according to about the same principles everywhere and that the implications of the simplifications that might be necessary to fit a somewhat more irregular building into that mould are more of less well known. Historical buildings, however, are by their nature often “irregular” today, built as they are in other times with other standards. And the implications of simplifications in these cases can be a lot more unpredictable and come with a price-tag of loss of cultural heritage. The specific requirements of the buildings also often poses different demands on the creativity of the retrofitting strategies suggested, which also makes it of utmost importance that we can simulate the actual strategy, including where appliances are located, how they are controlled etc.

We also have the issue of the one-dimensionality of the whole building simulation processes to take into account, since where a lot of the damages are going to take place at the points where the heat- and moisture transfer is not one-dimensional. So we need to supplement the whole-building simulation software used as a base with another, able to deal with two- and three-dimensional flows.

THE PROCESS

The result is a process that is not yet quite as fast and simple as could be desired, but that integrates both the desired domains and flexibility, displays the desired aspects using limited computer resources and time. It starts out with the analysis of the object, and here Comsol Multiphysics is used to study thermal bridges and other potentially critical points. The ones found to be worth taking into account are then translated into a modified construction to be inserted in the whole building simulation model. Since one-dimensional programs are not suited to deal with rounded and/or irregular geometries there are often simplifications to be done, and here too a three-dimensional tool such as Comsol is of value to make sure that the model corresponds to reality.

The result of this preparatory phase is then made into a whole building computer model, in this case in IDA-ICE 4.0. IDA-ICE has the advantage of being modular, flexible, already integrating energy performance, basic comfort aspects and IAQ, it is multizonal and able to log any variable and to export the results in ASCII-format, which was some of the requirements in this study. More aspects, such as exergy performance, can be included in the form of macros or components created by the user, but the flexibility of the equation-based software comes at the cost of a limit as to the amount of added complexity it can take, as the stability gets challenged. So, the important moisture aspect is more or less missing and is not feasible to be added as a new component, and thus this then, together with the damage risk assessment, becomes the main task of the last step in the simulation process.

This is thus done in a separate program, MOIRA, that takes the resulting ASCII-files of IDA, complemented with files describing the node system, connections and node data, and runs it again, supplementing it with moisture calculations. In the terms of [5] these can be said to be simplified since the driving potential chosen for the calculations is water content rather than pressure, due to practical reasons. However, it does include both capillary and diffusive transport plus potential suction of ground moisture according to

$$g = \delta_v \nabla v + D_w \nabla w + S_w \tag{1}$$

where δ and D_w are moisture dependent. As previously concluded, we are often dealing with materials whose qualities, including curves for these values, are often fairly unknown, thus it is essential to the entire process, disregarding if this method or any other is used, that the model is calibrated according to measurements, made over sufficiently long periods of time and detailed enough.

In the present version of MOIRA we do not calculate the temperatures; they are kept from the IDA-simulation. Thus the effect of moisture in the building components and its potential influence on the energy performance can not be determined, nor is the effect of evaporation or condensation evaluated, but the program is prepared for such calculations. Instead it now takes the temperatures determined by IDA and uses as boundary conditions for the building components in which the moisture transfer is calculated. For each time step MOIRA delivers a moisture contribution that is then added up and delivered to the air node of the zone in question, just as the different zones also delivers their contributions to each other through the air exchange between them according to

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

where G is an addition from internal moisture sources or a reduction accomplished by a dehumidifier, n is the number of components in contact with the zone, g_k the moisture flow from the component surface in question, A_k the area of that component, m is the number of adjacent zones, L_i the air flow from a specific neighbouring zone and vi its humidity by volume.

THE VERY SMALL WALL PART METHOD

Another issue to deal with is the aforementioned fact that it is not in the average values found in the zonal nodes that the status of the critical point is to be found, it is in the conditions of those specific points, thus these need to be determined. For short time slices, which of course could be chosen as the most critical conditions we can get the state of these points from the initial Comsol simulations, but for their performance over time we need to integrate them into the whole building simulation. This is also essential for the damage risk assessment as we do not only need the data on temperature and humidity for these points but also on fluctuations and duration of conditions suitable for microbiological growth. If we'd integrate the thermal bridges or other critical points as real size elements, these would have to be constructed in the computer model to correspond to their average values, since they otherwise would affect the calculations of the building performance. This makes it impossible to get the actual temperatures and RH at these points, thus this work chooses another method, and that is to separate the effect on the building performance and the studies of the actual conditions at the most critical points. The effect of the thermal bridges is included as ψ-values just added numerically in the section in IDA intended for this, though IDA's preprepared categories to some extent has to be ignored, which is quite possible to do. The second goal is reached by the use of very small wall parts included in the IDA-model, so small that they will not affect the performance but they will deliver correct temperatures at these points. The values for these are then included in the data entered into MOIRA which reveals the actual humidity at these points. We now have temperature and RH curves not only for the average values of the node but also for the points that are most likely to be affected by damage, and from these we then get calculations of the duration of conditions suitable for mould growth and fluctuation patterns.

DAMAGE RISK CURVES

As one base for this work of Sedlbauer [7] has been used, from which mould growth risk curves has been constructed based on the isopleths systems of [7]. In doing so we have made some simplifications based on the following grounds:

- Health risk is important to the use of the building, but problems for the building itself or items kept in it may occur before such levels are reached, thus we've chosen to disregard the higher curves for the more hazardous mould types for now.
- Germination and mycelial growth could be displayed in two different sets of results, however, as we consider that these buildings have endured many kinds of conditions and possible onsets of mould growth before, the threshold of germination may often already be passed and might thus not be as interesting as the actual mycelial growth. So the curves selected have been the latter ones, not the germination curves.
- A possibility to choose substrate category before simulation could be of use but would be less suitable for a building containing a mix of potential substrates. For that reason, we chosen the most extreme substrate category, which might be rendering slightly too high results, but given the conditions and values at stake we find it motivated.

Information from the curves is compiled in two different way, as a Mould Growth Risk Index, displaying the most extreme of the RH and temperature conditions related to the mould risk curves and as the most extreme duration of conditions above the growth rate curves, indicating potential growth rate. These methods serve as indicators, yet, as we will see of the results, they might need to be complemented with averages as well instead of just the extremes, as single events can disrupt the picture of the performance of the different scenarios.

The other kind of damage risk result included in the simulation process at this time is the fluctuation patterns, where the background considerations up until now are mainly based on the Bratasz article on the effect of moisture fluctuations on wood in the COST publication [8]. However, this section of the damage risk assessment of the simulation process has to be developed further as well as further validated.

THE CASE STUDY

The simulation method was used in a case study of Hamrånge church in a locality in central Sweden, on the Baltic coast. The church is from the 1850's but harbours some medieval items from the previous church on the site. It is a stone building with fairly thick walls, 1,55 m, large windows, a barrel vaulted wooden ceiling and a church hall with a volume of about 8750 m^3. The floor is wooden too, with a layer of gravel between the beams, covering a crawl space underneath. The church hall doesn't have any noticeable moisture issues but the crawl space does, which causes some concern since much of the air flowing into the church hall reaches it through the crawl space.

The heating is done by electrical radiators placed under the pews and under the windows, with a control strategy regulating the indoor temperature to a minimum of 20 degrees during the weekends and a minimum of 12 degrees during the week. Due to the high costs of electrical heating and the moisture problems in the crawl space there is now one method of dealing with these issues being tested, and that is to close the crawl space vents, diminishing the cold air being sucked in there cooling the crawl space as well as indirectly the church hall. The measurements from that test have however not been available yet for use in this study, so the calibration of the model has been done according to measuring performed before the closing of the vents. Thus validation of the closed vents scenario still remains to be performed.

Several scenarios have been run, of which 3 are being accounted for here: 1. Status quo, 2. Vents closed and 3. A dehumidifier installed in the crawl space.

RESULTS

The first part of the study includes validating the output of MOIRA. First against the results of IDA by sealing off all moisture flows through building components and comparing only the transfer through the ventilation, which IDA also calculates. This revealed a perfect match. The next step was to add the moisture flow through and buffering in the building components and compare to measured values. This showed a reasonable compliance, with some deviation, about 2 percent, in the crawl space at times, which could be due to rain water reaching the crawl space either through the crawlspace walls or though the ground due to poor drainage. Precipitation is not yet included in MOIRA, mainly due to difficulties to access data on measured values.

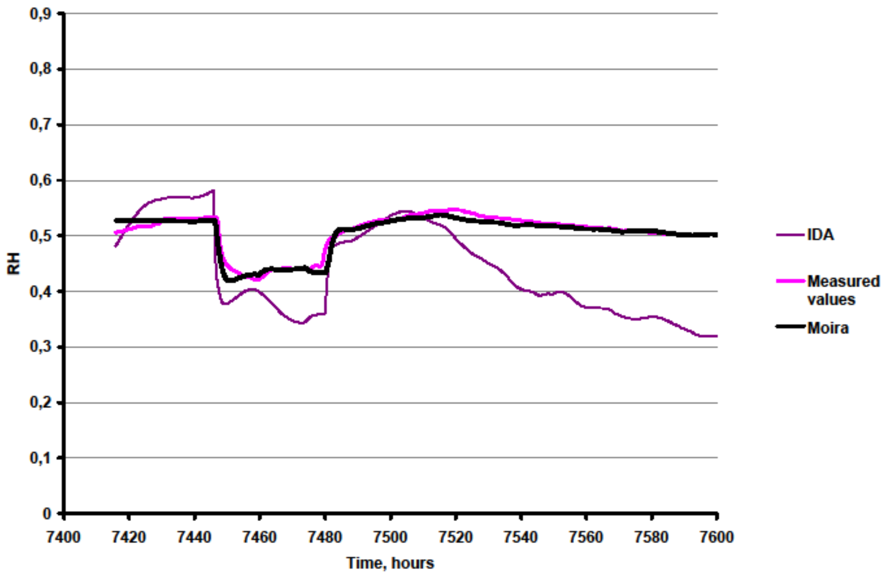

Figure 1. Comparison RH levels of the air in the church hall for IDA, MOIRA and measured values.

In addition, one might expect to find greater deviations in the crawl space, given that MOIRA as other whole building simulation tools assume well mixed air for the values of zonal nodes. The air in the crawl space is less likely to be well mixed and thus discrepancies should occur. The comparisons are seen in figure 1 and 2.

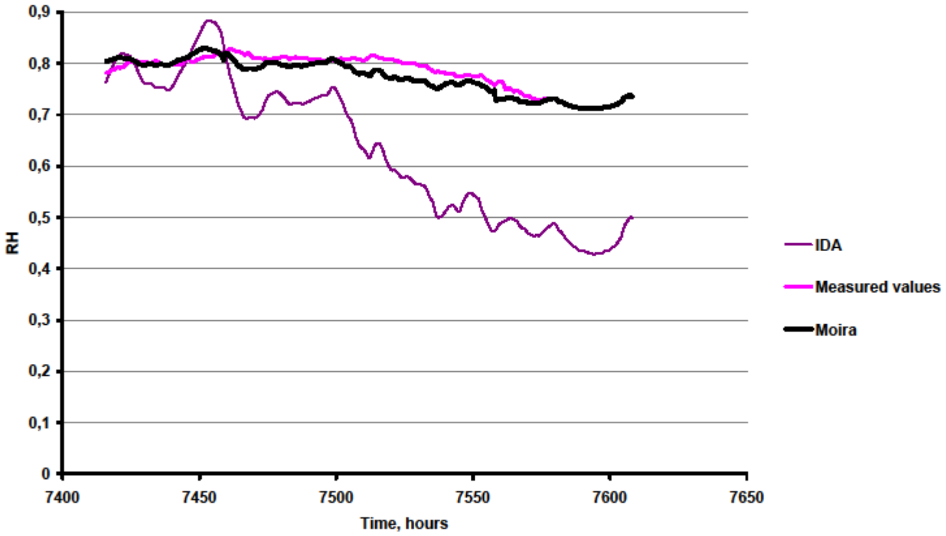

Figure 2. Comparison RH levels of the air in the crawl space for IDA, MOIRA and measured values.

A display of the deviation of conditions between the mean air values and the conditions at a thermal bridge is to be found in the RH curves for the month of June, as seen in figure 3. At this point the RH levels in the status quo scenario and of the closed vents scenario are approximately at the same level, the period during latet summer and fall where the closed vents alternative displays much higher moisture levels than status quo has not yet occurred, and still we can see the conditions at the thermal bridge studied in this work is revealing much more precarious levels. We can also see the curve of the dehumidifier option below the others.

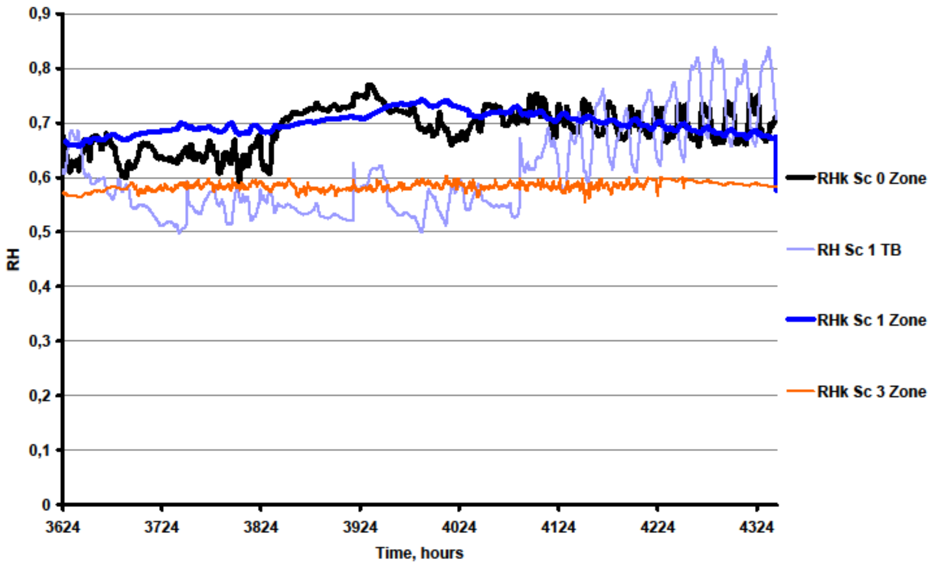

Figure 3. Air RH levels in the crawl space and of the thermal bridge in scenario 2.
Another aspect to take into account when looking at figure 3 is, that even if the humidity levels are fairly similar in the scenario 1 and 2, the RH of scenario 2 has to be related to a higher temperature, increasing the mould growth risk significantly. This is however not reflected in the Mould Growth Risk Index, as one single event where the outdoor temperature raises rapidly and brings in air of much higher moisture content into the crawl space causes one peak in scenario 1, which

otherwise displays considerably more moderate values, which makes the scenario 2, according to the simulation actually displaying much more dangerous humidity levels during longer period of time, appear slightly better. Only the value of scenario 4 stays below 1, meaning that there conditions never reach the risk curve levels.

The lack of clarity of the Mould Growth Risk Index in this case, that in other cases may reveal valuable information on how close to the curves different options come, is compensated by the other mould growth indicator, the maximum duration values, seen in table 1.

Table 1 Mould Risk Duration for the crawl space of the scenarios, hours

	Scenario 1	*Scenario 2*	*Scenario 3*	*Scenario 4*
Mean air	171	1566	24	0
Critical point	182	1098	158	0

The alternative of the closed crawl space vents thus seem less favourable, whereas the scenario 3 seem a better option. However, the differences are small in actual humidity levels, and again only the dehumidifier shows clearly lower values. Comparing the energy usage reveals that in this case the studied options does not provide an optimization fulfilling all criteria, as the dehumidifier does add to use of energy instead of reducing it, using 6,6% more energy than the status quo, whereas scenario 2 brings a reduction of 2,9% and scenario 3 2,0%.

CONCLUSIONS

Using these tools and this method of simulation we get a gathered assessment of the potential consequences of different retrofitting strategies as well as of the pre-retrofitting situation, including many of the aspects we need to make decisions that will grant us maintainable and preserveable historical buildings. The tools are in themselves fairly fast and simple to use, still there is however somewhat time-consuming preparations of the models, including possible error sources due to multiple model building processes, mentioned as an issue by [4], and the basic requirement – though applicable to any simulation method dealing with historical buildings – is the even more time consuming measuring of the object before the simulation in order to have reliable data to calibrate against. This may very well be the most troublesome part in making the use of whole building simulations more widely spread in the investigations of historical buildings: making the owners of such structures aware of the value of potentially disturbing, costly and time-consuming long term measuring to acquire reliable simulation results.

The last part of the process, still remaining to integrate and thus not yet included, might also be one of the most important: the evaluation of the different values and curves delivered by the simulation and putting them in relation to the cost of retrofitting, the cost maintenance, environmental impact and impact on the cultural heritage values, both by the retrofitting as such but also, as focused on in this article, due to long term consequences of the choice of strategy. Thus a multi-criteria decision analysis would be a desirable addition, and is being prepared for.

The advantages of the serial approach, though it adds issues to deal with and may seem to contest the very idea of integration of interacting aspects, include that the results can be evaluated and calibrated at different stages in the simulation process, before adding the next level of complexity. Though potentially time-consuming too it compensates for the added error risk in the building of multiple models. And of course the transition between the primary whole building simulation program and MOIRA does include checks of correspondence, since the files delivered by the primary whole building simulation program needs to fit the structure built in MOIRA.

ACKNOWLEDGEMENTS

We thank professor Tor Broström, Gotland University, coordinator of the research program Spara & Bevara, which this study is a part of, 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 Ove Söderström, all at KTH, for their valuable contributions as sounding board for this work. We are also very indebted to programmers Carl-Johan Wägner and Thorbjörn Lindh, for their generous assistance.

REFERENCES

1. IEA, International Energy Agency, Energy Conservation in Buildings and Community Systems Programme, Annex 24, Heat, Air and Moisture Transport. http://www.ecbcs.org/annexes/annex24.htm, 1996.
2. IEA, International Energy Agency, Energy Conservation in Buildings and Community Systems Programme, Annex 41, Whole Building Heat, Air and Moisture Response. http://www.ecbcs.org/annexes/annex41.htm, 2008.
3. Citherlet, S. & Hand, J., Assessing Energy, Lighting, Room Acoustics, Occupant Comfort and Environmental Impacts Performance of Building with a Single Simulation Program, *Building and Environment*, Vol 37, pp 845-856, 2002.
4. Citherlet, S., Clarke, J.A. & Hand, J., Integration in Building Physics Simulation, *Energy and Buildings*, Vol. 33 No. 5, p. 451-461, 2001.
5. Grunewald, J., Häupl, P. & Bomberg, M., 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, 2003.
6. Schijndel, A.W.M. van, Integrated Heat Air and Moisture Modeling and Simulation, *PhD Thesis*, Eindhoven University Press, Eindhoven, (ISBN-10 90-6814-604-1, ISBN-13 978-90-6814-604-2). 200 p, 2007.
7. Sedlbauer, K., Prediction of mould fungus formation on the surface of and inside building components, *PhD Thesis*, Stuttgart University, 2001.
8. Camuffo, D., Fassina, V. & Havermans, J. (Editors). 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, 2010.