UNCERTAINTY APPROACHES FOR HYGROTHERMAL BUILDING SIMULATIONS - DRYING OF AN AAC FLAT ROOF IN DIFFERENT CLIMATES.

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ABSTRACT

In civil engineering there is an increasing demand for calculation methods to assess the moisture behaviour of building components. Current tasks, such as preserving historical buildings or restoring and insulating existing buildings are closely related to the moisture conditions in a building structure. In this context, questions regarding moisture behaviour and the related transport processes occurring under natural climatic conditions as well as the risks thus involved always occur. These questions can either be answered with the help of experiments or by numerical simulations. In view of the fact that experiments are often time-consuming and, in some cases, meteorologically both problematic and expensive, intensive work has been done over the past few years on the development of mathematical approaches and procedures to evaluate real thermal and moisture transfer processes. Until now the uncertainty of input data was explicitly left out of hygrothermal modeling. This was done because the understanding of the individual physical processes and their impact on the component assembly was the first priority. But the hygrothermal conditions within a construction and the building depends on a large number of factors such as outdoor and indoor climate and material properties. This may introduce significant uncertainities in the results. Today, an increasing demand exists to define more realistically processes which also include kind and dimension of the element of uncertainty. These influence on the results considered in this paper. The necessary input data for hygrothermal calculations are described with a specific uncertainty. This work is focused on uncertainty approaches for hygrothermal building simulations; With the help of the sensitivity analysis, one can study how sensitive the solution of a problem based on the data confidence input and its reaction to a single parameter of uncertainty.

INTRODUCTION

To protect a flat roof from interstitial condensation, a vapour retarder is required in cold climates. However, in the case of an autoclaved aerated concrete (AAC) roof a vapour retarder would also prevent the construction moisture from drying, and thereby, severely impair the thermal insulation quality of the AAC. In order to find out whether an unvented flat roof of AAC works without a vapour retarder field test or computational simulations can be made. Experimental investigations are expensive and of limited transferability. An alternative is the use of validated models to assess the hygrothermal behaviour of proposed constructions. Until now the uncertainty of input data was explicitly left out of hygrothermal modelling. This was done because the understanding of the individual physical processes and their impact on the component assembly was the first priority. In the following work the necessary input data for hygrothermal calculations are described with a specific uncertainty. Today, an increasing demand exists to define more realistically processes, which also include characteristic and dimension of the element of uncertainty [i, ii, iii, iv, v].

In order to study the influence of the different uncertain input paramteres a base case simulation is needed, in which the input parameters are set to the best estimates of the parameters under consideration. In this paper drying potential of an 200 mm thick AAC flat roof with trapped moisture (20 Vol.-%) under natural climate conditions was studied. The top of the roof is sealed from outside with a vapour tight bituminous membrane. On the interior surface a gypsum plaster is applied. Hourly weather data measured for a typical year in Holzkirchen (1991) represent the climatic conditions. The room climate varies as a sine curve between 20 °C, 40 % relative humidity in the winter and 22 °C and 60 % relative humidity in the summer. These values correspond to normal conditions in residential buildings of central Europe [vi]. For the wet and humid climate typical weather conditions for Miami (USA) with constant indoor conditions (25°C and 65 %RH) are assumed. The heat transfer coefficient at the external surface is 17 W/m^{2}K, and 8 W/m^{2}K on the inside. The short-wave absorption coefficient of the bituminous felt is 0.9 (for Miami 0.6). Rainwater absorption is neglected. The starting point is the beginning of January with an initial moisture content of 20 vol.% in the roof. The hygrothermal behaviour is simulated over a period of five years. As criteria for the influence of the different input parameters the amount of dried out moisture after one year is chosen.

Table 1: Material properties and their uncertainty

Hygrothermal Material Properties for the AAC		Default Values	Standard deviation
Bulk density	[kg/m^3]	600	5 %
Heat capacity	[kJ/kgK]	0.85	5 %
Heat conductivity	[W/mK]	0.08	5 %
Moist. Related Supplement	[%/M.-%]	3.7	5 %
Water content at RH of 80% (± 2 %)	[vol. %]	1.07	10 %
Water content at RH of 93% (± 2 %)	[vol. %]	5.0	10 %
Free saturation	[vol. %]	42.5	10 %
Porosity	[vol. %]	72.0	5 %
Vapour Diffusion Resistance	[-]	8.3	15 %
A-Value	[kg/m^2/√s]	0.094	20 %
$D_{w,\ Surface\ Diffusion}$ at RH of 71.5 % (± 10 %)	[m^2/s]	2.0e-10	10 %
$D_{w,\ Suction}$ at free Saturation	[m^2/s]	1.6e-7	10 %
$D_{w,\ Suction}/D_{w,\ Drying}$	[-]	3	30 %

MATERIAL PROPERTIES AND THEIR UNCERTAINTY

WUFI-StOp [ii] and it's family of predecessor WUFI [i] and WUFI-ORNL/IBP is a menu-driven PC program which calculates the transient hygro-thermal behavior of multi-layer building components exposed to a set of climatic conditions. The model includes vapor diffusion and liquid transport in building materials. The model only requires standard material properties and moisture storage and liquid transport functions. During the last years WUFI was validated by several comparisons between measurements and calculations, which showed a good agreement. Other simplifications or limitations include: hysteresis of the moisture retention curve is not taken into account; air flow by total pressure differences is not included; the influence of ice formation on enthalpy and liquid transport is accounted for but not its effect on thermal conductivity.

MATERIAL PROPERTIES AND THEIR UNCERTAINTY

The hygrothermal material parameters required for AAC including their observed standard derivation are listed in Table 1. For the calculations both measured and approximated moisture storage functions respectively moisture transport coefficients were used. For the approximation of the moisture storage function a new method was used. A detailed analysis of more then 30 capillary active materials used in civil engineering showed that from the gradient of the moisture storage function between 80 % and 95 % RH its total progress can be predicted. Based on this, the following function can be derived:

The two free parameters φ_0 and p_φ can be determined from the moisture content at 80 % und 95 % RH [vii].

Figure 1 shows both, the measured and the approximated moisture storage function for the AAC as functions of the relative humidity (left) and the capillary pressure (right). The measured values including the observed derivation determined by vapour absorption experiments and pressure plate measurements are shown as dots. The hatched area in both graphs represents the possible range of the approximated moisture storage function given by the uncertainty of the material parameters as shown in Table 1.

$$u(\varphi)=\frac{u_f}{1+\left(\frac{\ln(\varphi)}{\ln(\varphi_0)}\right)^{p_\varphi}} \qquad \text{(Eq. 1)}$$

In cases of elevated water content the liquid transport has a particular influence on the moisture behaviour of envelopes, especially if build in moisture has to dry out. The drying process is a superposition of liquid transport and vapour diffusion. The correct determination of the transport coefficients for liquid transport is thus of decisive importance. As discussed in [viii], a distinction must be made between wetting and drying, i.e. these two boundary conditions produce different liquid transport coefficients. The determination of these transport coefficients, which are highly dependent on water content, is made possible by the measurement of water-content profiles in the building material using a special scanning apparatus. Accurate but time-consuming and cost-intensive determination is, however, often not always available for a practitioner. For this reason the corresponding moisture transport coefficients are approximated according to [ix, x, xi]. They are obtained from basic hygric parameters already known for most building materials or from simple additional experiments.

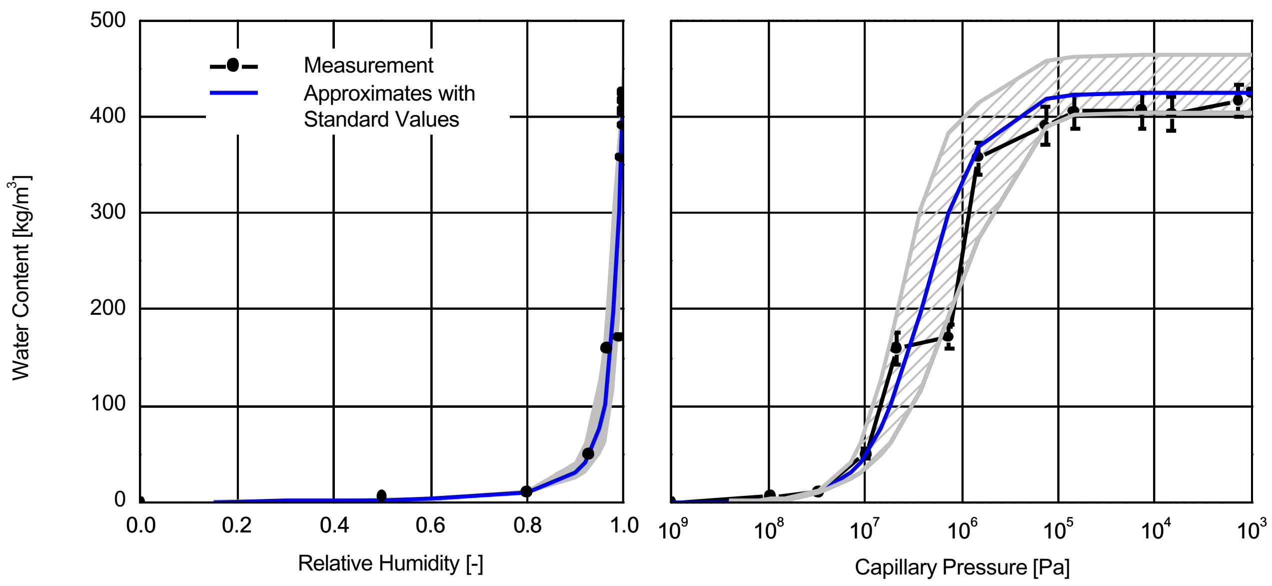

Figure 1: **Measured and approximated moisture storage function for the AAC (Density 600 kg/m³) as function of the relative humidity (left) and the capillary pressure (right). The measured values including the observed derivation determined by vapour absorption experiments and pressure plate measurements are shown as dots. The hatched area in both graphs represents the possible range of the approximated moisture storage function given by the uncertainty of the material parameters as shown in table 1.**

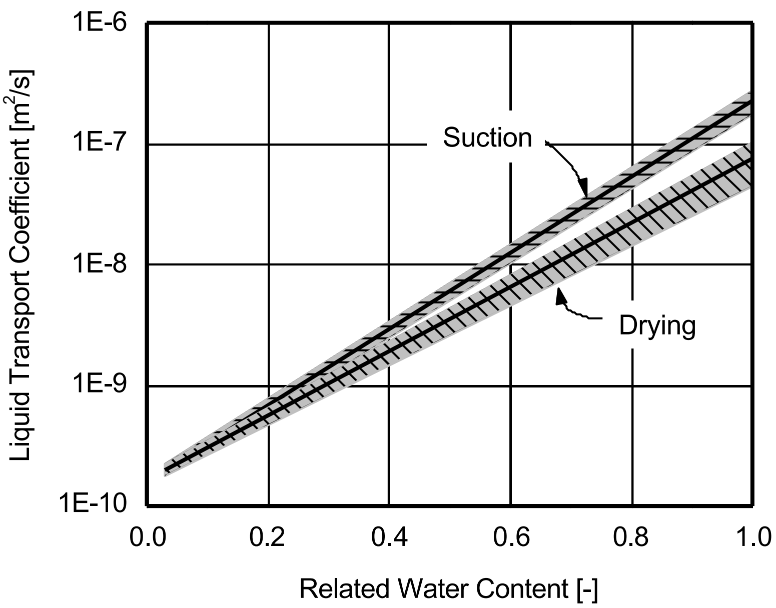

Figure 2: **With uncertainty of the material parameters as shown in table 1 the hatched area represents the possible range of the approximated liquid transport coefficients for suction and drying.**

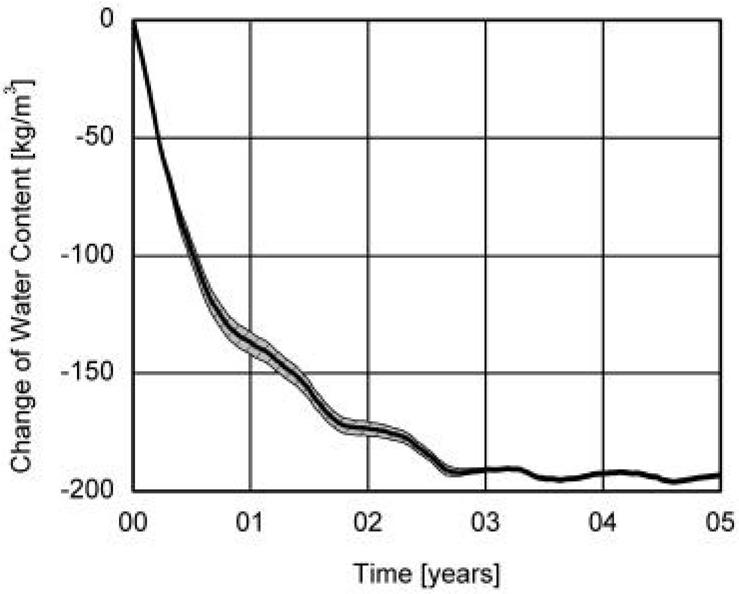

Figure 3: Material sensitivity analysis for the transient drying behaviour of the AAC flat roof under typical climate conditions for Holzkirchen. Each material parameter was changed from P to P + ΔP respectively from P to P - ΔP, giving a total of 25 simulations.

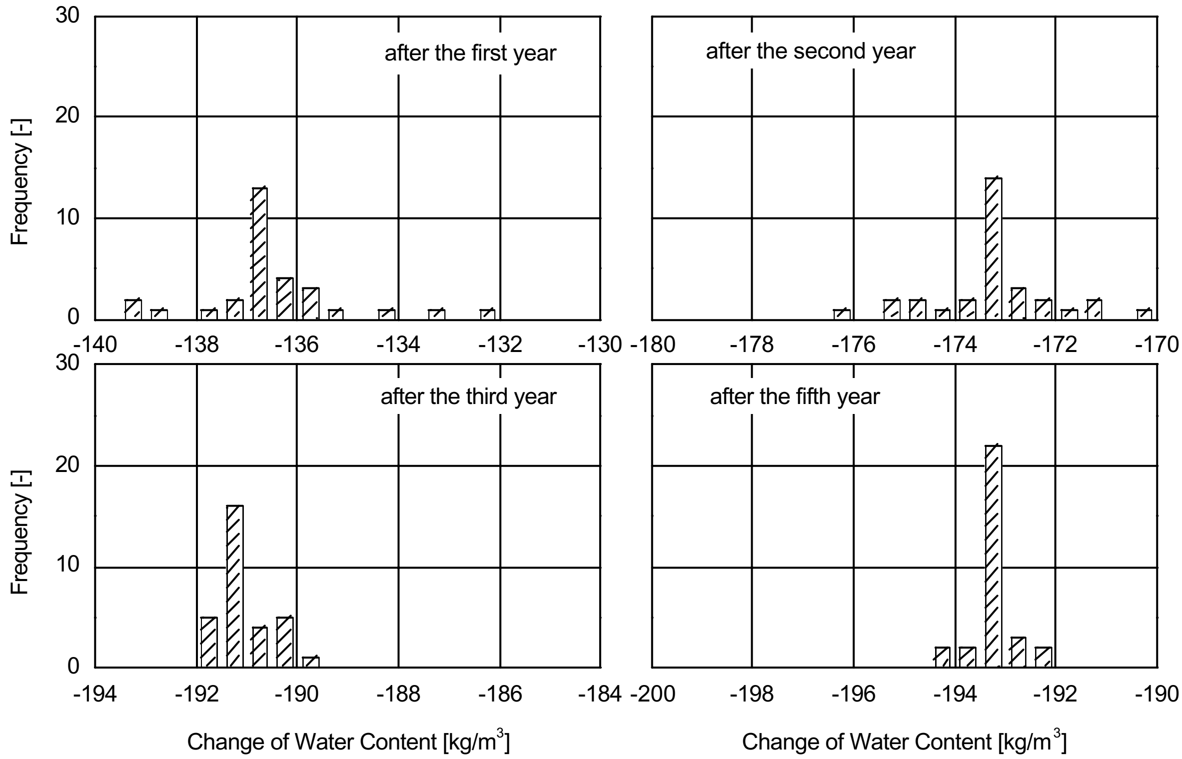

Figure 4: Frequency distribution of the change of water content since beginning after the first, second, third and fifth year. (Interval width: 0.1 kg/m³)

With uncertainty of the material parameters as shown in table 1 the liquid transport coefficients for both, suction and drying approximated from these values have also a certain confidence range which is shown in figure 2. The hatched range represents the envelope of all possible approximated coefficients. For the following sensitivity analysis, the described approximated material properties with observed uncertainty are used.

SENSITIVITY ANALYSIS: MATERIAL PROPERTIES

There are many sources of uncertainty when using modelling to assess the hygrothermal behaviour of a given construction. Therefore it is important to evaluate the influences on the hygrothermal behviour from these uncertainties. An important technique for determining these influences is the sensitivty analysis. Answers, like how important are material properties compared to other input data can be found. With these results conclusions on the importance of physical correct data like moisture storage functions determined by pressure plate apparatus or liquid transport coefficients determinded by NMR can be made. The technique applied in this case is the Differential Sensitivity Analysis. [xii]. Therefore a standard case simulation is needed, in which the input parameters are set to the best estimates of the parameters under consideration. Then the simulation is repeated with one input parameter changed from P to P + ΔP respectively from P to P - ΔP and the effect on the amount of dried out moisture after one year noted. This is done for each material parameter of table 1 in turn, which gives a total of 25 simulations. With this method it can be found out, which of the analysed parameters have the greatest influence on the output results, but does not identify any interaction between the parameters.

Figure 3 shows the course in time of the water content for the examined variants of the AAC flat roof under typical climate conditions for Holzkirchen. The hatched area represents the envelope of the 25 resulting variations. The solid line is the corresponding average course in time of the sensitivity analysis. It can be concluded, that within 2 ½ years the AAC has lost most of its construction moisture and is reaching its hygroscopic equilibrium. After that, in summer the solar radiation leads to high temperatures and consequently elevated vapour pressures under the impermeable bituminous felt. Moisture is moving, mainly through vapour diffusion, to the colder parts of the roof and condenses somewhere in the middle or dries to the interior. In winter the temperature gradient is reversed and the moisture accumulates beneath the roofing membrane.

In order to emphasis the influence of the different material properties, the frequency distribution of the

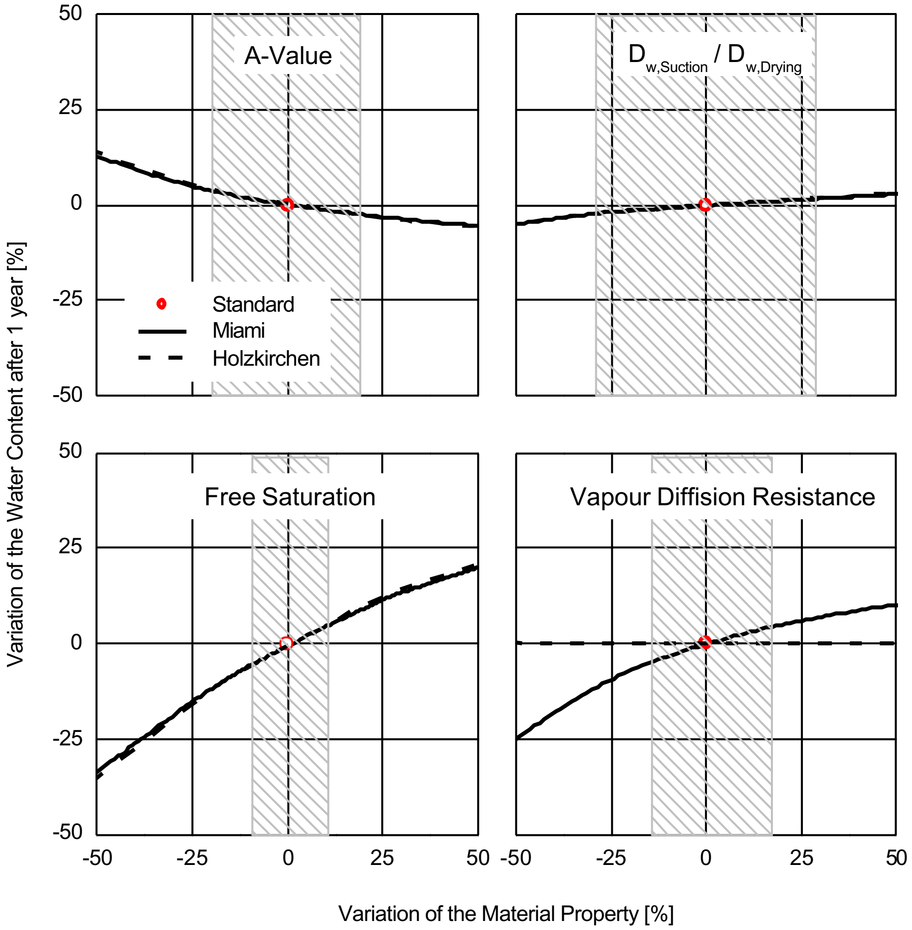

Figure 5: Sensitivity Analysis for the transient drying behaviour of the AAC flat roof under typical climate conditions for Holzkirchen for the first year.

change of water content since the beginning is plotted in figure 4. After the first year the average moisture content was reduced from initial 200 kg/m³ to 65 kg/m³ with a variation of ± 5 kg/m³. The main influence is given by the A-value and the free saturation. The vapour diffusion resistance and the liquid transport coefficient for surface diffusion give a moderate influence. All other parameters like density, porosity and heat conductivity have a minor effect on the result. After the second year the average moisture content is about 28 kg/m³ (± 1.5 kg/m³). The distributions after the third and the fifth year are nearly identical, because the AAC flat roof is in a hygroscopic equilibrium. Here the parameters influencing the moisture storage function (water content at RH of 80% and 93%) are mainly responsible for the small variation observed.

SENSITIVITY ANALYSIS: CLIMATIC SITUATION

The sensitivity analysis for the material properties showed, that based on the uncertainty of table 1, the maximum deviation of the moisture content after one year is about 5-6 %. But not only the material properties are subject to fluctuation. Since the external and internal climate conditions are also of random character, it is necessary to study their influence, too. The way of using a room is mostly influencing the indoor climate. For the different occupant's behaviour the internal moisture load is a significant parameter. Here this parameter was varied between high, normal and low. Figure 6 shows the drying behaviour of the AAC flat roof during the first year under typical climate conditions for Holzkirchen (1991) and the different interior moisture loads. For very humid rooms (high moisture load) the moisture content after one year is about 140 kg/m³, for dry rooms (low moisture content) 130 kg/m³. This is equal to a change of nearly 4% against the original case.

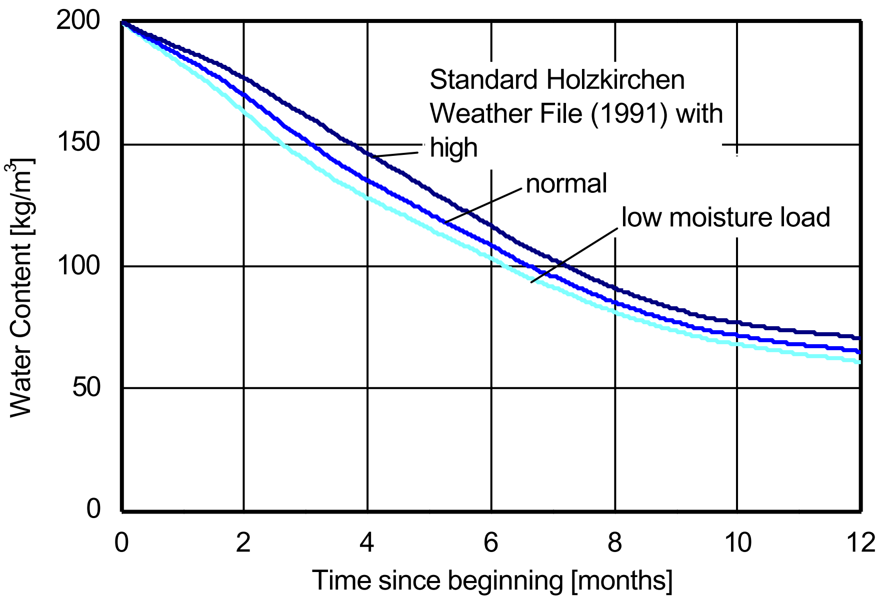

Figure 6: Drying behaviour of the AAC flat roof during the first year under typical climate conditions for Holzkirchen and different interior moisture loads.

For the A-value, capillary saturation, factor between the two liquid transport coeffcients and the vapour diffusion resistance a singe sensistivity anaylsis for both climate was performend. For each calculation only the studied material parameter was changed step by step in a possible range of ± 50 % of its original value. The hatched area in figure 5 represents the envelop between minimum and maximum observed values according to table 1. The results show, that in the range of typical expected measurement uncertainty the maximum resulting error in the simulation is about 5-10 %. Also due to the different temperature conditions in Miami and Holzkirchen, the influence of the vapour diffusion resistance is different. For central moderate climate situation the influence of the vapour diffusion resistance variations can be neglected, on the other hand, for hot and humid climate it has to be considered.

The total change of the water content in the AAC flat roof after one year under different climates in Germany and United States is shown in Figure 7. It can be concluded, that the driving out potential is a linear function of the annual mean temperature and the internal climate conditions. From the statistical analysis of the results for Holzkirchen the mean water content after one year of 137 kg/m³ results. For the hottest year this value is 5 kg/m³ lower, for the coldest about 5 kg/m³ higher. The same observations can be made for the North American weather files.

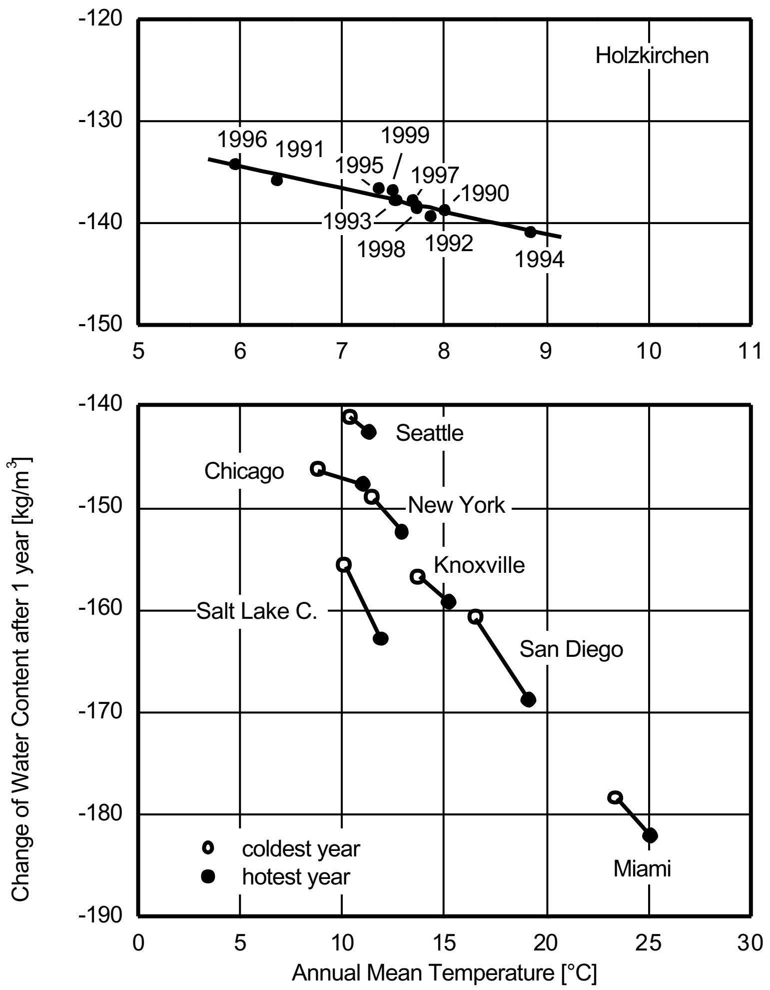

Figure 7: Change of water content in the AAC flat roof after one year under different climates in Germany and United States.

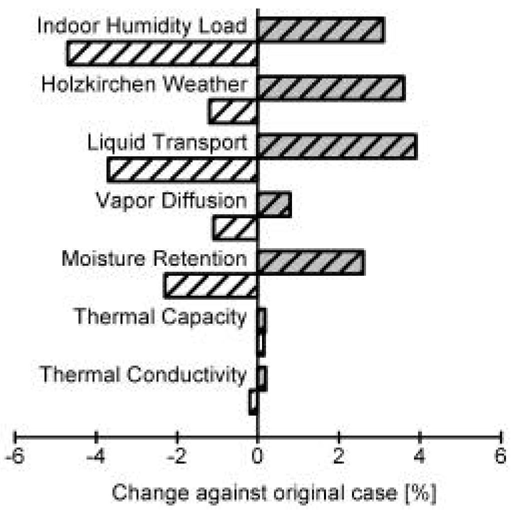

Figure 8: Summary of the Sensitivity Analyse.

Discussion of the results and conclusions.

Computer calculations are of increasing importance for the assessing the balance in building components, since modern calculation methods achieve good agreement with measurements. A broader application of these methods is hampered, however, by the laborious measurements needed to determine the moisture retention curve and the capillary transport coefficients essential for the calculations. The approximation techniques presented which allows to estimate these material parameters from basic and often well-known parameters (free capillary saturation, practical moisture content and water absorption coefficient) shows only moderate and acceptable deviations from reality. By using these methods, the hygrothermal behaviour of building components can not only be determined in a deterministic way. The very important stochastically approach is almost impossible without these approximation methods. An important technique to evaluate these influences from the input uncertainties is a combination of Single and Multiple Differential Sensitivity Analysis. This was shown here with the example of the drying behaviour of an AAC flat roof. Its behaviour is mainly influenced by sources of uncertainty, like material properties due to an inhomogeneous pore structure and production processes and weather data. In figure 8 the influence of the uncertainities for Holzkirchen are compared. The evaluation of the results shows, that the influence of the exterior and interior climatic conditions is comparable (sometimes even higher) to the influence of the material property variation. The main influencing material properties are the moisture retention curve and the liquid transport coefficients in Holzkirchen, respectively vapour permeability in Miami . Other parameters like density, porosity and heat conductivity can be neglected.

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