Drying of an AAC flat roof in different climates. Computational sensitivity analysis versus material property measurements

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1. The Problem

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 kind and dimension of the element of uncertainty [1, 2, 3].

2. Numerical Approach

This work is focused on two uncertainty approaches for hygrothermal building simulations; the sensitivity analysis and the probability (stochastically) based analysis. With the help of the sensitivity analysis, one can study the sensitivity of a problem solution based on the data confidence input and its reaction to a single parameter of uncertainty. If information about the stochastically deviation of the influencing factors is known, this can be included in a probability based analysis. Both types of analysis of the input data are included in the computer program WUFI, which allows the calculation of the transient heat and moisture, transport in building assemblies [4, 5] and was developed at the Fraunhofer Institute for Building Physics in Holzkirchen. WUFI has repeatedly been validated by comparison with experimental data. The drying behaviour of an AAC roof under different exterior and interior climate conditions is object of this study.

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 with a vapour tight bituminous membrane. On the interior surface a gypsum plaster is applied. Hourly weather data measured in 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 [6]. By changing the magnitude, different other humidity loads can be simulated. The heat transfer coefficient at the external surface is 17 W/m²K, and 8 W/m²K on the inside. The short-wave absorption coefficient of the bituminous felt is 0.9. 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, two, three and five year is chosen.

Table 1: List of hygrothermal material properties

Hygrothermal Material Properties for the AAC		Default Values	Standard deviation P
Bulk density	[kg/m³]	600	5 %
Heat capacity	[kJ/kgK]	0.85	5 %
Heat conductivity	[W/mK]	0.8	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 %
A-Value	[kg/m²/√s]	0.094	20 %
$D_{w,\ Surface\ Diffusion}$ at RH of 71.5 % (±10 %)	[m²/s]	2.0e-10	10 %
$D_{w,\ Suction}$ at free Saturation	[m²/s]	1.6e-7	10 %
$D_{w,\ Suction}/D_{w,\ Drying}$	[-]	3	30 %

3. 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:

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

The two free parameters φ_0 and p_φ can be determined from the moisture content at 80 % und

95 % RH [7]. 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 measured material parameters as shown in Table 1.

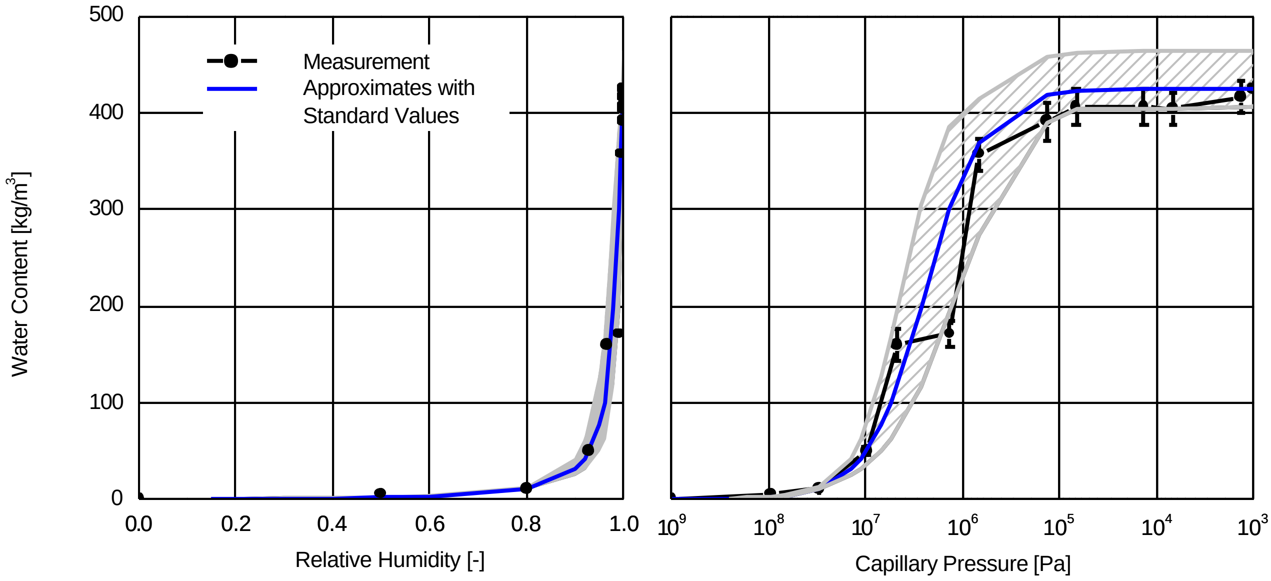

Figure 1: **Measured and approximated moisture storage function for the AAC (Density 600 kg/m³) as function of the relative humidity (left) and the capillary pressure (right). The measured values including the observed derivation determined by vapour absorption experiments and pressure plate measurements 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.**

In cases of elevated water content the liquid transport has a particular influence on the moisture behaviour of envelopes, especially if build in moisture wants to dry out. The drying process is a supperpostion of liquid. The correct determination of the transport coefficients for liquid transport is thus of decisive importance. As discussed in [8], 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 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 [9, 10, 11]. They are obtained from basic hygric parameters already known for most building materials or from simple additional experiments. In order to validate the chosen approximation method two simple experiments on AAC-samples were performed. For two AAC samples the liquid absorption according to the German standard and the drying behaviour through one open surface were measured. From the A-value and the resulting free saturation the corresponding liquid transport coefficient as a function of the related water content are approximated and compared in Figure 2 (top) with those determined by the NMR. The approximation method is based on a exponential function. The Dw,s from the NMR were measured at different samples. This leads to the different absorption behaviour shown at the bottom of Figure 2.

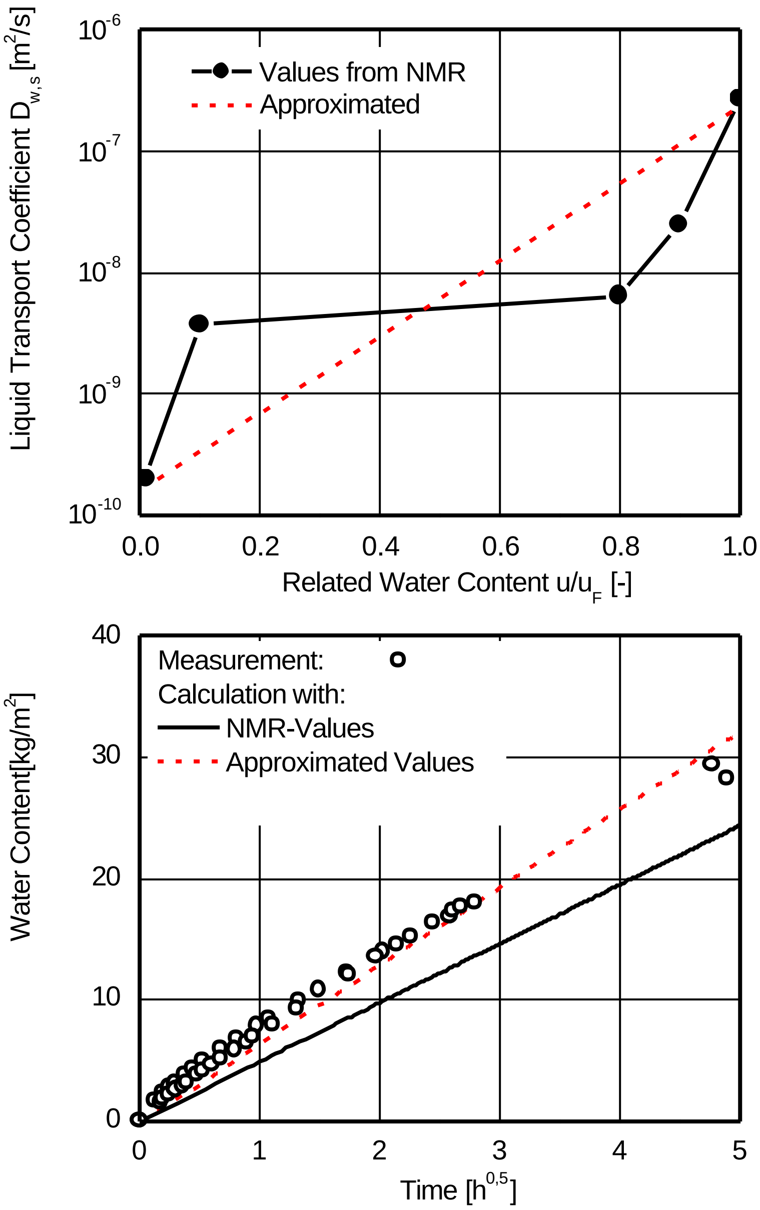

Figure 2: **Top:** **Liquid transport coefficient for suction as a function of the related water content for the suction process determined by the NMR-apparatus and approximated from simple hygric material parameters like the A-value. The approximation method is based on a exponential function.**

Bottom: **Comparison of a liquid uptake experiment with calculations using the $D_{w,s}$ obtained by the NMR respectively by approximation.**

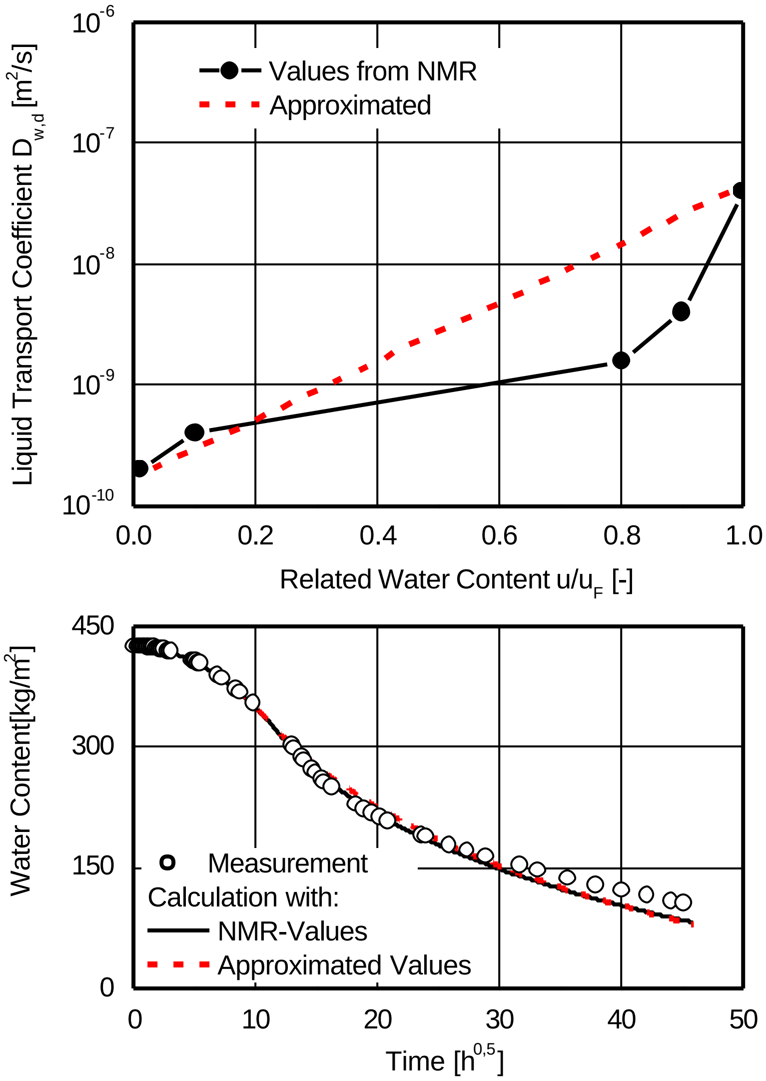

Figure 3:	**Top:**	**Liquid transport coefficient for drying as a function of the related water content for the suction process determined by the NMR-apparatus and approximated with the values from Figure 2 and from the drying experiment shown in the bottom.**
	Bottom:	**Comparison of the experiment with calculations using the Dw,d obtained by the NMR respectively by approximation.**

After the water absorption test the free saturation water content was measured. Beginning from that water content, the drying process for a period of more then 3 months was observed. Figure 3 (bottom) shows the measured values as a function of the square root of time. From the absorption and the drying experiment the liquid transport coefficient for drying as shown were calculated and compared with those determined by the NMR-apparatus, as shown at the top of Figure 3. For both the calculations agree very well with the measurements.

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 4. The hatched range represents the envelope of all possible approximated coefficients. For the following sensitivity analysis, the described approximated material properties with observed uncertainty were used.

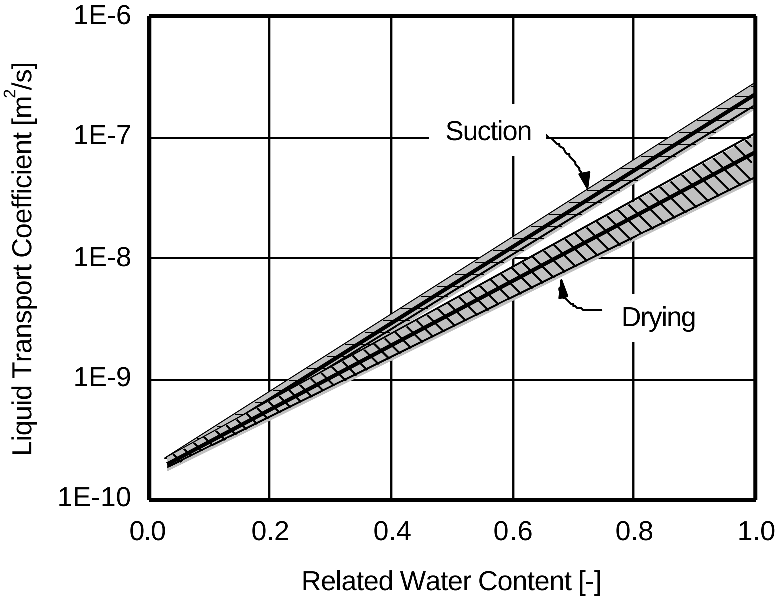

Figure 4: With uncertainty of the material parameters as shown in Table 1 the hatched area represents the possible range of the approximated liquid transport coefficients for suction and drying.

4. 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. In the latter category Monte Carlo Analysis has been used, too [12]. 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 5 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 thick 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 change of water content since the beginning is plotted in Figure 6. After the first year the average moisture content was reduced from initial 200 kg/m^3 to 65 kg/m^3 with a variation of ± 5 kg/m^3. 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/m^3 (± 1.5 kg/m^3). 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.

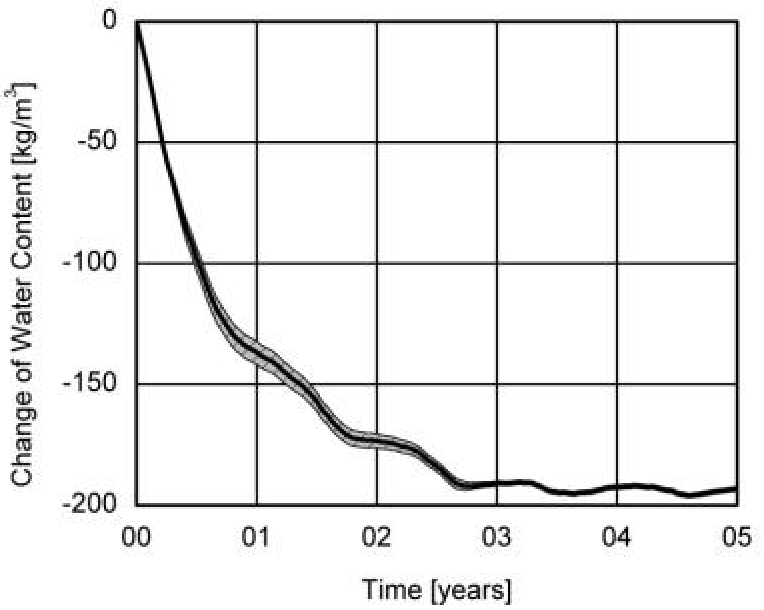

Figure 5: **Material sensitivity analysis for the transient drying behaviour of the AAC flat roof under typical climate conditions for Holzkirchen. Each material parameter was changed from R to $R + \Delta R$ respectively from R to $R - \Delta R$, giving a total of 25 simulations.**

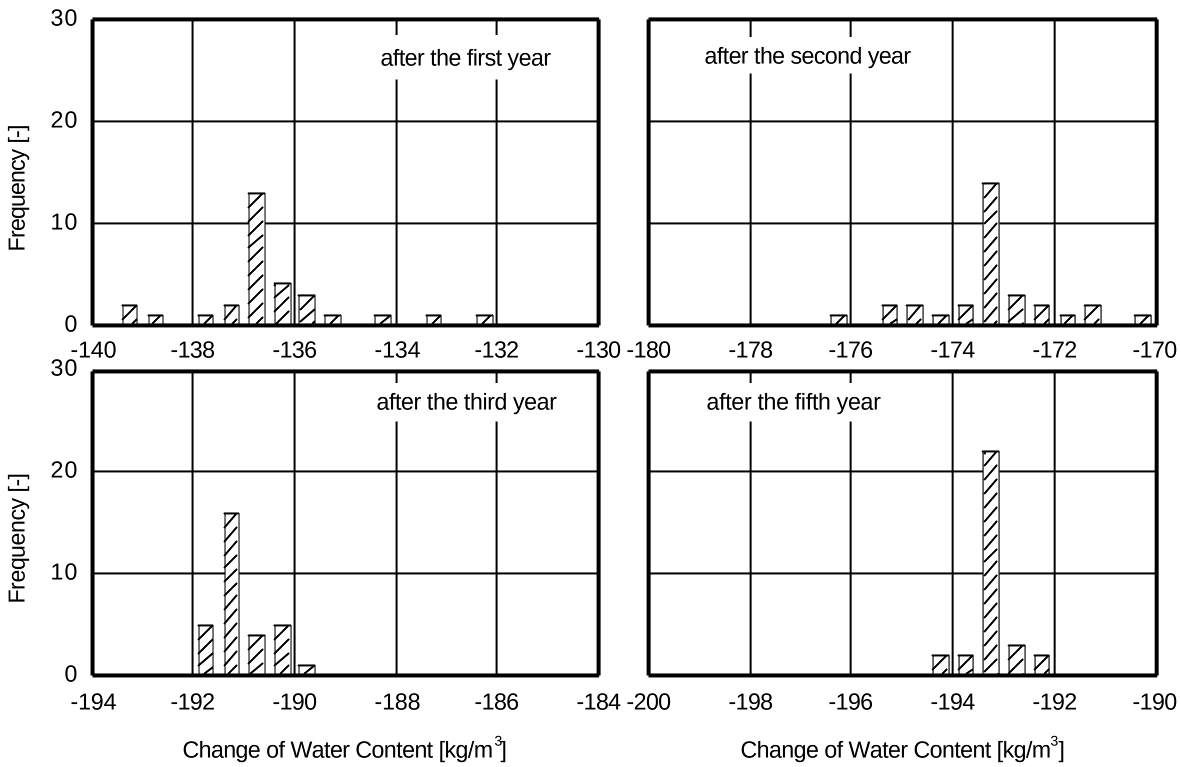

Figure 6: **Frequency distribution of the change of water content since beginning after the first, second, third and fifth year. (Interval width: 0.1 kg/m^3)**

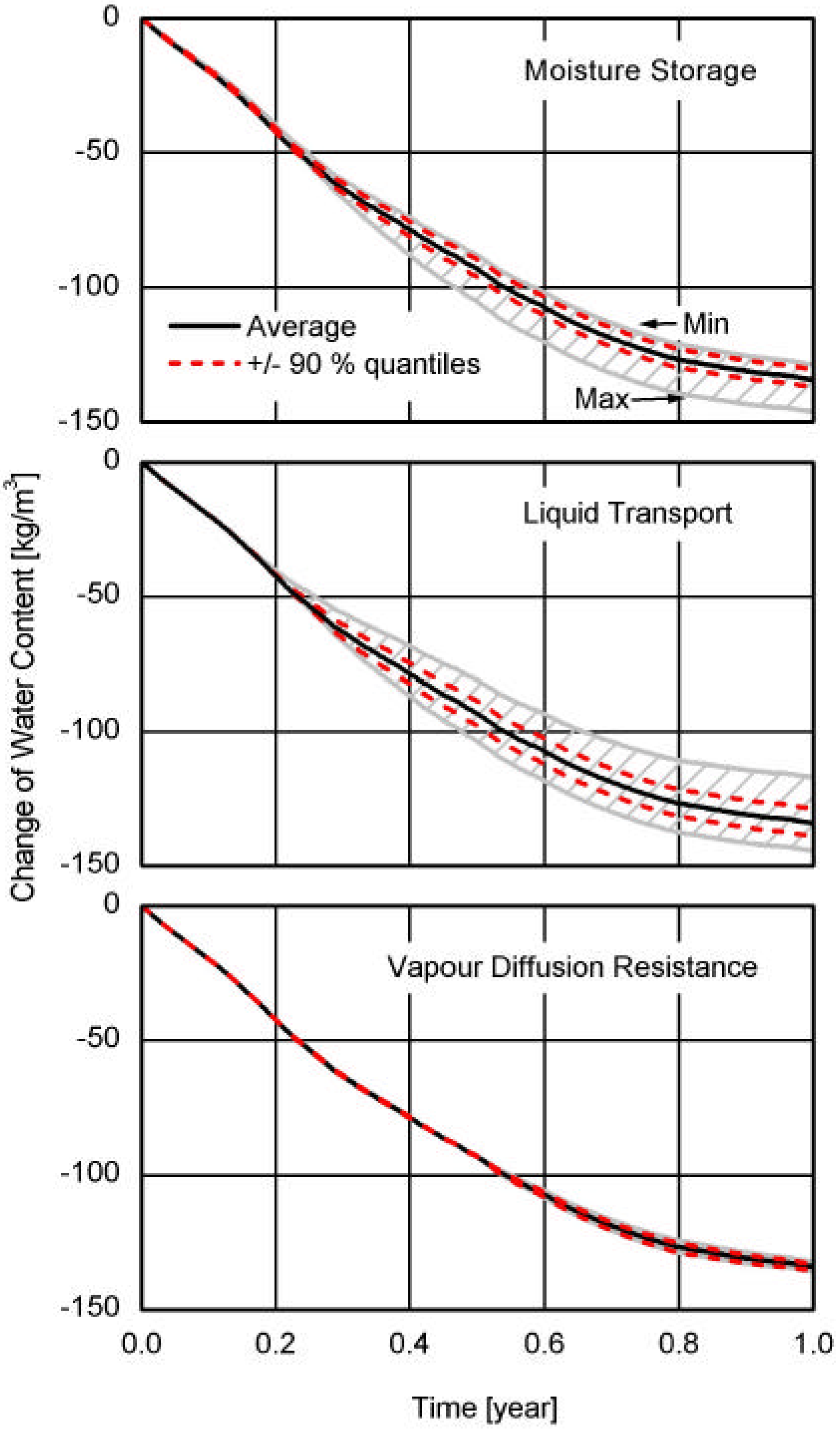

Figure 7: **Monte Carlo Sensitivity Analysis for the transient drying behaviour of the AAC flat roof under typical climate conditions for Holzkirchen for the first year (mean and standard deviation). At top, the influence of the moisture storage function, in the middle at the bottom the influence of the liquid transport properties and at the bottom the influence of the vapour diffusion resistance is shown.**

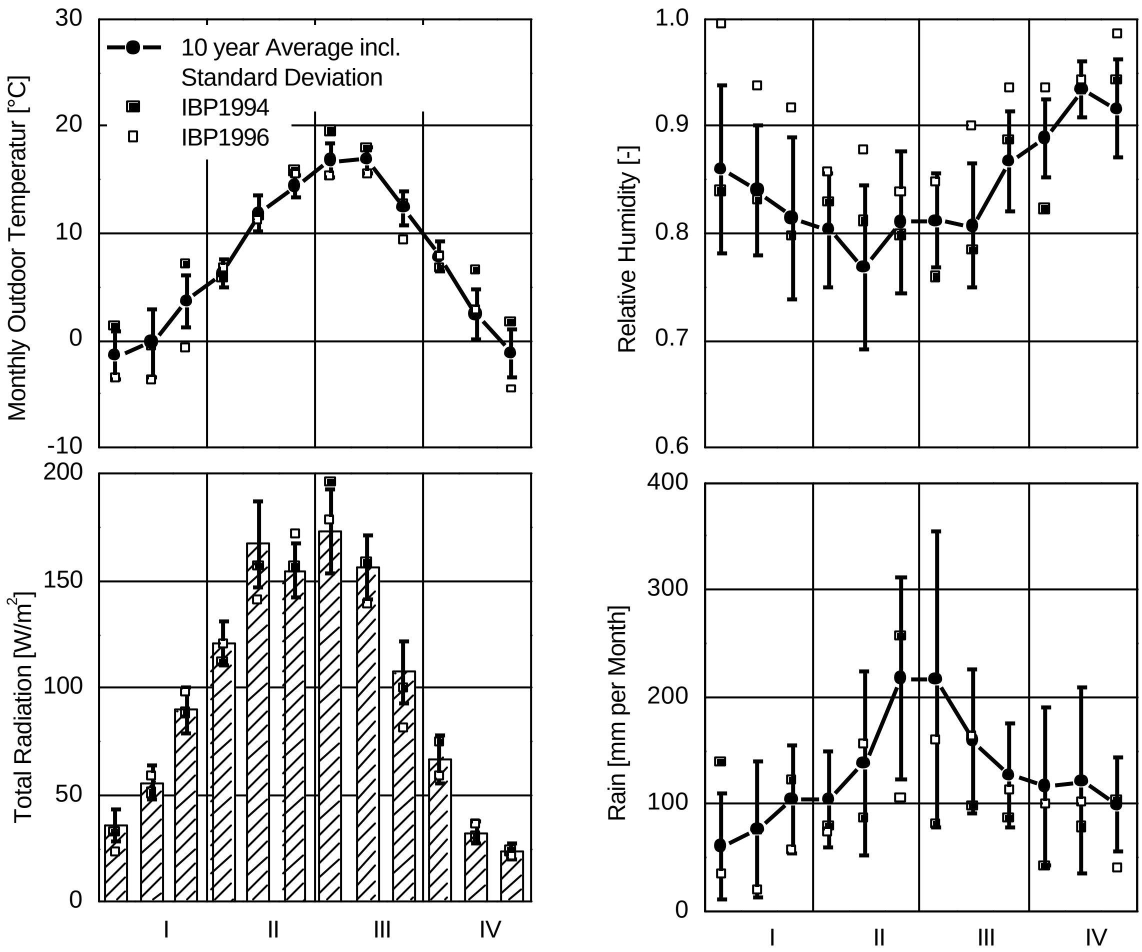

Figure 8: **Monthly values for the outdoor temperature, RH, total radiation and precipitation observed in Holzkirchen during the years 1990 and 1999. The years 1994 and 1996 is the hottest respectively the coldest year during this period. In all graphs the measured standard deviation is also shown.**

With the knowledge of the results of the Differential Sensitivity Analysis, the Monte Carlo Analysis has been used, too. Therefore a probality distribution of the material parameters influencing the moisture storage function, the liquid transport properties and vapour diffusion is assumed. For every material property 50 random values were generated and a simulation was carried out. Figure 7 shows the results for the 3 Monte Carlo Analyse as course in time of the water content per unit of area. In each graph the resulting average of all simulations including the 10 % and 90 % quantiles is shown. The hatched area represents the envelop between minimum and maximum observed values.

5. Sensitivity analysis: climatic situations

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 indoor climate is mostly influence by the way, the room is used. For the different user habits the internal moisture load is a significant parameter. Here this parameter was varied between high, normal and low. Figure 9 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/m^3, for dry rooms (low moisture content) 130 kg/m^3. This is equal to a change of nearly 4 % against the original case.

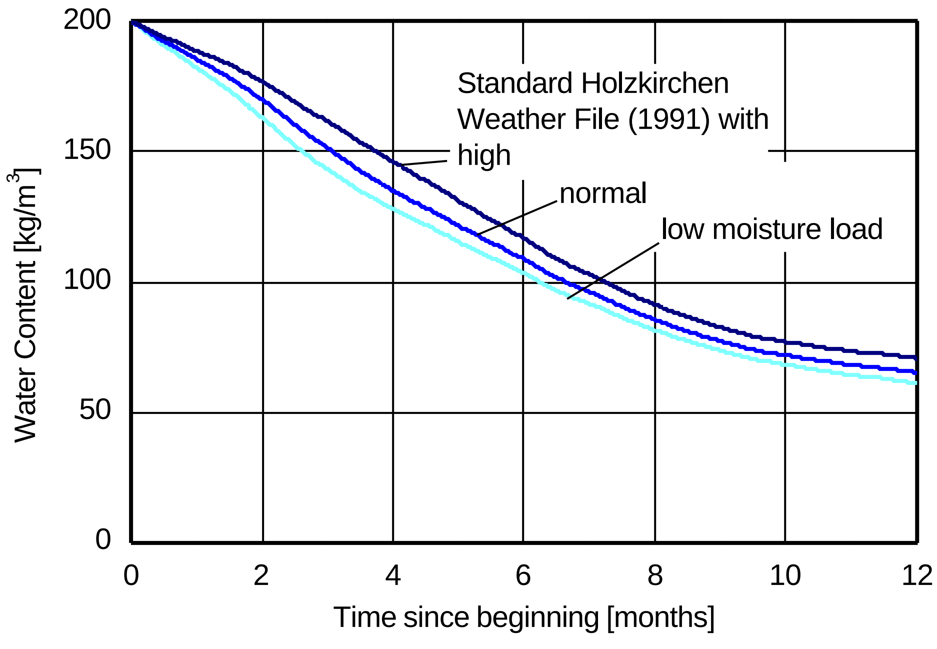

Figure 9: **Drying behaviour of the AAC flat roof during the first year under typical climate conditions for Holzkirchen and different interior moisture loads.**

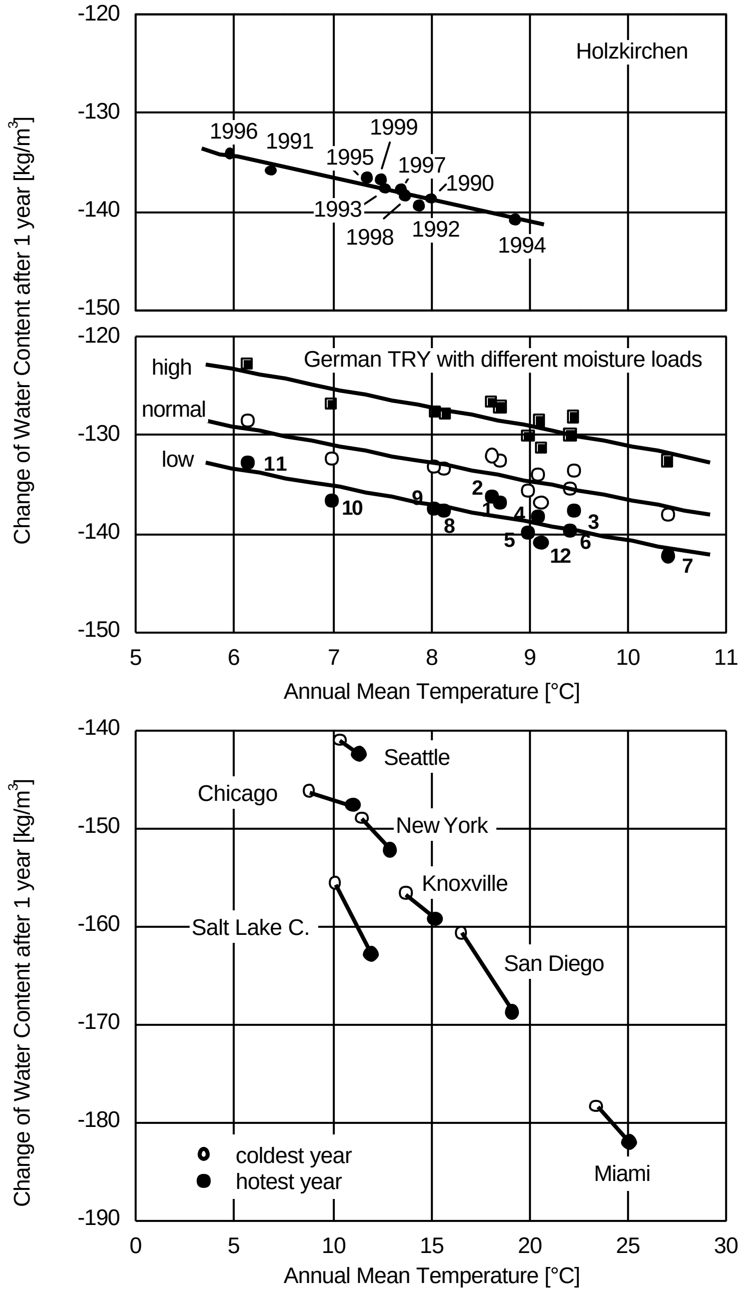

Figure 10: Change of water content in the AAC flat roof after one year under different climates in Germany and United States. The driving out potential is a linear function of the annual mean temperature and the internal climate conditions. The numbers for the German TRY correspond to the following cities: 1 = Bremerhaven, 2 = Hannover, 3 = Essen, 4 = Trier, 5 = Würzburg, 6 = Frankfurt/Main, 7 = Freiburg, 8 = Augsburg, 9 = Munich, 10 = Stötten, 11 = Hof, 12 = Friedrichshafen

6. Discussion of the results and conclusions.

Computer calculations are of increasing importance for the assessment of moisture 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 Differential Sensitivity Analysis and the Monte Carlo Analysis. This was shown here with the example of the drying behaviour of an AAC flat roof. Its behaviour is mainly influenced by many sources of uncertainty, like material properties due to an inhomogeneous pore structure and production processes and weather data. In Figure 11 the influence of the uncertainities are compared together. 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. It can be concluded, 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. Other parameters like density, porosity and heat conductivity can be neglected. It can be concluded, that in this studied case it is not enough to determine the moisture retention curve or the liquid diffusivities of the AAC with a very high accuracy. Also the given uncertainties of the material due to an in homogenous pore structure and production processes should be registered because their effect is comparable to influence of the total random character of the climate data.

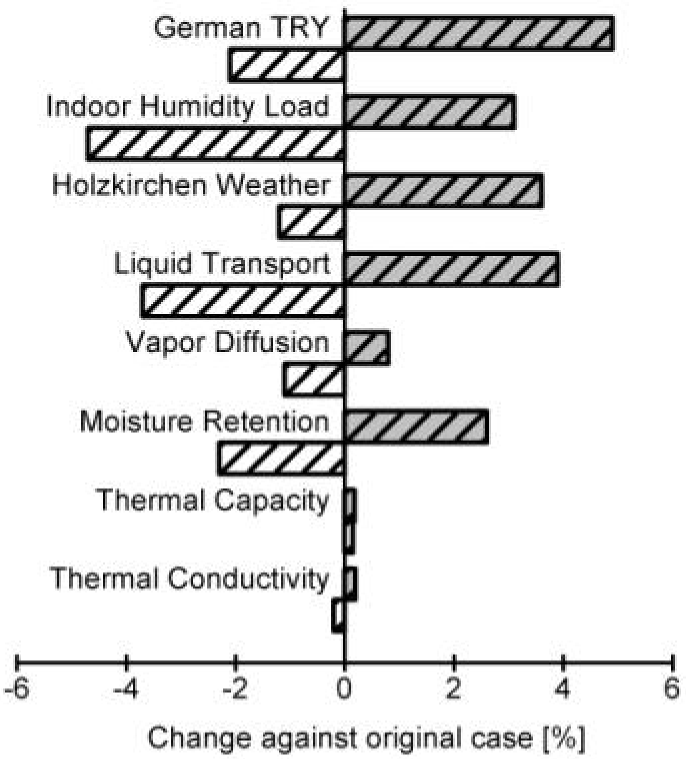

Figure 11: **Summary of the Sensitivity Analyse.**

7. References

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