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Hygrothermal Assessment of Two Solid-brick Walls Under Varying Internal and External Parameter Settings

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Abstract

Hygrothermal simulation incorporates transient heat and moisture transport in 1D and 2D wall assemblies. There is a need to understand how hygrothermal analysis can play a role in buildings designed to be moisture resilient. This paper investigates the hygrothermal effects on two different wall structures using different distributions of input parameters and two different weather scenarios. Results show that the differences in weather and distribution of the parameters have a limited effect on the sensitivity of parameters, but have a large impact on the uncertainty of the outcomes. A normal distribution of parameter means and an accurate weather scenario will improve the accuracy of the simulation, but might not be necessary if only the sensitivity of the parameters is of concern.

Introduction

Models are inherently a simplification of a real-world situation. That means different types of uncertainties are introduced, such as physical (to do with uncertainties related to materials), scenario (based on different weather conditions) and design (due to designer's choices) (Hopfe and Hensen, 2011; Hens, 2015). Uncertainties are caused by variations due to differences that are not captured in a model. For example, in the case of physical uncertainties, these can be variations in construction materials, ageing of materials and in the case of scenarios changing weather conditions (Tian, 2013). These variations will have an influence on the outcomes of the model and thus lead to outcomes of the model that deviate from the actual situation.

When specifically looking at hygrothermal simulation (HTS), there are a number of factors that can vary, such as hygrothermal material properties, dimension of materials and boundary conditions (McLeod and Hopfe, 2013). This complexity can lead to faulty predictions of energy usage and moisture levels in a building as a consequence. In reality, this may lead to discomfort in homes, damage to structures and last but not least, impaired health of inhabitants (e.g. asthma) (Hens, 2011).

A large number of studies analysed the different sources of uncertainty in HTS, either for whole buildings or components (for example Macdonald and Strachan, 2001; Prada et al., 2014; Nielsen et al., 2012). Macdonald and Strachan (2001) performed an uncertainty analysis (UA) for a complete building with both the properties of a building and the occupancy as input variables. It was concluded that the UA has made it possible to improve the reliability of the results from the simulation by giving the distribution of possible outcomes for changes in input variables. Prada et al. (2014) analysed the heat flow through different building structures under dynamic boundary conditions and with different modelling procedures. The sensitivity analysis (SA) identified parameters, such as specific heat and specific mass, that showed the largest effect on the outcomes. Nielsen et al. (2012) examined the hygrothermal behaviour of a single wall structure, analysing the insulated case in one dimension. It was shown that in particular the boundary conditions, specifically wind driven rain, had the largest impact on the hygrothermal behaviour of a wall.

The combination of UA and SA is thus a method to increase the robustness of a simulation and consequently, drawing conclusions by allowing for multiple results (opposed to single solution). Furthermore, performing an UA/SA for HTS could have further benefits by simplifying models through omitting variations in insignificant parameters and by identifying unexpected parameters with a large influence on outputs (Hopfe and Hensen, 2011).

Both the boundary conditions and the material properties can have a significant impact on the simulation outcomes. This is why the UA/SA in this paper will build on previous research such as the studies mentioned above, but will look specifically at:

- two dimensional flow through a wall structure under two sets of static weather conditions;
- the effect of different distributions of the input parameter means, and;
- two different wall structures, resembling an original solid-brick wall and the wall after insulating.

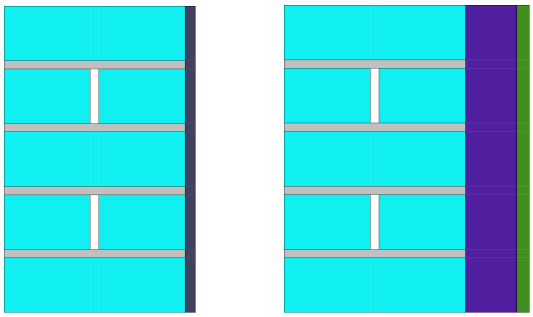
Methodology

In this paper an UA/SA for the hygrothermal behaviour of two wall structures, under two climates and with two different distributions of material parameters is presented. The UA looks at the reliability of a model, based on the uncertainty in the input parameters. The SA analyses the variations in the output and how this can be proportionally attributed to variations in the input variables. The process was divided into pre-processing, simulation and post-

processing. In the pre-processing phase the different simulation runs were created. These were formed for a combination of two different wall structures and the uniform or normal distribution of the physical uncertainties. Each simulation was performed in Delphin, with the outputs further analysed in Python. To account for scenario uncertainties, the different wall structures were tested for two different weather scenarios. This allows for eight combinations in total for which the UA/SA was executed. Each of the steps is discussed in the following in more detail.

Model of the wall structure

The model is a two dimensional representation of a solid-brick wall with two different types of wall finish. Five courses of brickwork in English bond (alternating headers and stretchers), with four layers of mortar and air voids (micro-cavities) were modelled, see figure 1. The two different wall structures that were examined are (a) a typical Victorian wall (solid-brick wall with a lime mortar plaster, LM wall) and (b) an internally insulated wall (solid-brick wall with mineral wool insulation, a vapour barrier and gypsum board finish, MW wall). In table 1 the dimensions and characteristics of the materials are summarized.



(a) Lime mortar *(b) Mineral wool*

Figure 1: Model of the brick wall (cyan and light grey) with air voids (white) and either (a) using lime mortar plaster (dark grey) (LM), or (b) with mineral wool (purple), vapour barrier (black) and gypsum board (green) (MW).

Boundary conditions

The boundary conditions of the wall were defined for seven parameters: the temperature, relative humidity (RH) and air speed over the wall for both the inside and the outside and the horizontal rain flux on the exterior side of the wall. Two sets of steady-state boundary conditions were defined.

Exterior conditions: weather scenarios

Four parameters related to the hygrothermal nature of weather were used to create two different weather scenarios. In table 2 the values of the scenarios are given, based on synoptic weather data (UK Meterological Office, 2017) from two UK weather stations (3 on one of the northernmost islands of the British isles and 554 in the Midlands of England), see figure 2. For each of these weather stations the mean value of 30 years of data of the measured temperature, calculated RH and measured wind speed and precipitation amount were used. These were collated to a weather scenario for each of the two locations. Other weather parameters (such as cloud coverage, atmospheric pressure etc.) were not considered in the present model for two reasons: either the influence on the temperature and moisture condition of the façade is negligible or the effect of the parameter under steady-state conditions is very limited.

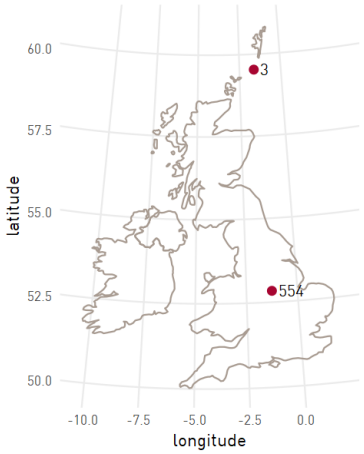


Figure 2: Locations of two selected weather stations in the UK with parameters. The names and other data of the stations are given in table 2.

Interior conditions

The interior boundary conditions of the wall were kept steady-state as well and modelled as a 'warm' interior:

- Air temperature: 23 °C
- Relative humidity: 50 %
- Internal air speed: 0.5 m/s

(Hamilton et al., 2017; Oreszczyn et al., 2006; Van der Linden et al., 2008). These boundary conditions were used for both wall structures, weather scenarios and parameter distributions.

Distribution of wall parameters

For the UA/SA, the wall parameters were assigned two different distributions: a uniform distribution and a (truncated) normal distribution. These two were evaluated side-by-side to determine any anomalies and as an indication for the robustness in the outcomes between the two distributions. A normal distribution will be similar to the actual distribution of the means of the material parameter, but is also more difficult to implement and requires data about the mean and the standard deviation. To avoid particularly extreme values it was further necessary to truncate the distribution at a minimum and maximum value. A uniform distribution on the other

Table 1: Material properties of the two brick walls including all sampling values for the UA/SA for the normal distribution (mean, standard deviation (SD), min and max) and the uniform distribution (min and max). For each material the parameters are divided into four categories: thermal, porosity, hygric and dimensional. For more information on the parameters, see nomenclature. The values of the material properties are taken from Delphin (Fechner et al., 2017) and are further referenced in the program's database.
† The bricks have been chosen to primarily determine the dimensions of the wall and the length, height and width of each individual brick is varied, where for the other materials only the thickness of the layer is varied.

Parameter	**Mean**	**SD**	**Min**	**Max**
Brick (B)				
ρ [kg/m³]	1835.620	30.594	1743.839	1927.401
c [J/kgK]	814.592	13.577	773.862	855.322
λ [W/mK]	0.528	8.80e-03	0.501	0.554
θ_{por} [m³/m³]	0.307	5.12e-03	0.292	0.323
θ_{eff} [m³/m³]	0.283	4.71e-03	0.269	0.297
θ_{cap} [m³/m³]	0.170	2.83e-03	0.162	0.179
$\theta_{80\%}$ [m³/m³]	5.21e-03	9.01e-05	4.94e-03	5.48e-03
AW [kg/m²$\sqrt{s}$]	0.178	1.52e-03	0.173	0.182
μ [-]	15.662	0.261	14.878	16.445
$K_{l,eff}$ [s]	2.91e-11	4.84e-13	2.76e-11	3.05e-11
L [mm] †	215	0.716	212.855	217.15
H [mm] †	65	0.217	64.350	65.650
D [mm] †	102.500	0.342	101.475	103.525
Mortar (M)				
ρ [kg/m³]	1498.420	24.974	1423.499	1573.341
c [J/kgK]	802.373	13.373	762.254	842.492
λ [W/mK]	0.412	6.87e-03	0.392	0.433
θ_{por} [m³/m³]	0.435	7.24e-03	0.413	0.456
θ_{eff} [m³/m³]	0.430	7.17e-03	0.409	0.452
θ_{cap} [m³/m³]	0.250	4.17e-03	0.238	0.263
$\theta_{80\%}$ [m³/m³]	0.034	5.70e-04	0.033	0.036
AW [kg/m²$\sqrt{s}$]	0.019	3.16e-04	0.018	0.020
μ [-]	9.257	0.154	8.795	9.720
$K_{l,eff}$ [s]	1.84e-10	3.06e-12	1.74e-10	1.93e-10
D [mm]	10	0.167	9.500	10.500
Lime mortar (LM)				
ρ [kg/m³]	1520	25.333	1444	1596
c [J/kgK]	850	14.167	807.500	892.500
λ [W/mK]	0.800	0.013	0.760	0.840
θ_{por} [m³/m³]	0.430	7.17e-03	0.409	0.452
θ_{eff} [m³/m³]	0.380	6.33e-03	0.361	0.399
θ_{cap} [m³/m³]	0.350	5.83e-03	0.333	0.368
$\theta_{80\%}$ [m³/m³]	0.058	8.63e-04	0.056	0.061
AW [kg/m²$\sqrt{s}$]	0.071	1.17e-03	0.068	0.075
μ [-]	51	0.850	48.450	53.550
$K_{l,eff}$ [s]	4.57e-11	7.62e-13	4.34e-11	4.80e-11
D [mm]	15	0.250	14.250	15.750

Parameter	**Mean**	**SD**	**Min**	**Max**
Mineral wool (MW)				
ρ [kg/m³]	168	2.800	159.6	176.4
c [J/kgK]	840	14	798	882
λ [W/mK]	0.04	1.57e-03	0.038	0.042
θ_{por} [m³/m³]	0.920	0.015	0.874	0.966
θ_{eff} [m³/m³]	0.900	0.015	0.855	0.945
θ_{cap} [-]	0.900	0.015	0.855	0.945
$\theta_{80\%}$ [-]	1.60e-04	2.67e-06	1.52e-04	1.68e-04
AW [kg/m²$\sqrt{s}$]	5.00e-13	1.67e-13	0.00E+00	1.00e-12
μ [-]	1	0.017	0.950	1.050
$K_{l,eff}$ [s]	5.00e-13	1.67e-13	0.00E+00	1.00e-12
K_g [s]	1.00e-04	1.67e-06	9.50e-05	1.05e-04
D [mm]	60	1	57	63
Polypropylene (PP)				
ρ [kg/m³]	900	15	855	945
c [J/kgK]	1500	25	1425	1575
λ [W/mK]	0.200	3.33e-03	0.190	0.210
θ [-]	1.50e-06	2.50e-08	1.43e-06	1.58e-06
AW [kg/m²$\sqrt{s}$]	1.00e-06	1.67e-08	9.50e-07	1.05e-06
μ[-]	9000	150	8550	9450
$K_{l,eff}$ [s]	5.00e-13	1.67e-13	0.00E+00	1.00e-12
D [mm]	1	0.017	0.950	1.050
Gypsum board (G)				
ρ [kg/m³]	850	14.167	807.500	892.500
c [J/kgK]	850	14.167	807.500	892.500
λ [W/mK]	0.200	3.33e-03	0.190	0.210
θ_{por} [m³/m³]	0.650	0.011	0.618	0.683
θ_{eff} [m³/m³]	0.551	9.18e-03	0.523	0.579
θ_{cap} [m³/m³]	0.400	6.67e-03	0.380	0.420
$\theta_{80\%}$ [m³/m³]	7.20e-03	1.20e-04	6.84e-03	7.56e-03
AW [kg/m²$\sqrt{s}$]	0.277	4.62e-03	0.263	0.291
μ [-]	10	0.167	9.500	10.500
$K_{l,eff}$ [s]	6.26e-09	1.04e-10	5.95e-09	6.57e-09
$D_{l,eff}$ [s]	4.50e-06	7.50e-08	4.28e-06	4.73e-06
D [mm]	15	0.250	14.250	15.750

Table 2: The steady-state climate parameters, calculated with data from the MetOffice (UK Meterological Office, 2017), for the two weather stations (3 and 554) that were used in the HTS to simulate the wall.

Weather station		Temperature [℃]	Relative humidity [%]	Wind speed [m/s]	Precipitation [mm]
3	Fair Isle, Shetlands	8.34	84.73	7.56	0.4
554	Sutton Bonington, East Midlands	10.3	82.34	3.47	0.15

hand is much easier to implement as it needs only a minimum and maximum value. Tian (2013) concluded that the distribution choice should depend on the aim of the study, with hygrothermal studies using a normal distribution and building design studies using uniform distributions.

For both distributions the minimum and maximum values were kept equal, with a spread of possible values of 1 % above and below the mean value, see table 1. The standard deviation for the normal distribution was calculated according to the empirical rule (Marriott, 1990), where a spread of three standard deviations either side of the mean of a normal distribution captures 99.7 % of the values.

Number of simulation runs

The method of Morris with the extension by Campolongo was used for this UA/SA (Morris, 1991; Campolongo et al., 2007). It gives as a result the μ^* and σ for each parameter. The μ^* or elementary effect, gives the importance of each parameter to the outcome and ranking them will give an overview of the parameters where changes to that parameter will impact the model the most. The σ of each parameter indicates in what way the parameter is influenced by the other parameters (Saltelli et al., 2004). The number of samples (or the number of grid levels) are not fixed in an UA/SA (Saltelli et al., 2004). Literature suggests that a larger number of grid levels will lead to more robust results, a more accurate μ^* and σ. Saltelli et al. (2004) also suggests that a sample size of 4 should be taken as a minimum. For the SA in this paper, the number of grid levels has been set at this minimum. A higher number of grid levels would have only been beneficial if the number of samples increases significantly at the same time. The number of samples was set at 5 and thus quite small, but still sufficient to go over the four sampling steps for each model. Each number of samples increases the number of simulation runs with the number of parameters that are evaluated. Even at the low end, this would have added 35 simulation runs or over 26 core-hours of simulation time.

Implementation

The UA/SA was implemented using SimLab, version 2.2.1 (European Commission, 2008) and Python, version 3.6, with the associated packages SALib, NumPy, Pandas and Matplotlib (Van Rossum, 1995; Python Core Team, 2017; Van der Walt et al., 2011; Herman et al., 2017; Hunter, 2007). SimLab was used to generate the grid levels and the samples.

Hygrothermal simulation (HTS)

The HTS was performed using Delphin, version 5.8 (Fechner et al., 2017), with the input files generated with Python. Delphin is HTS software that has been validated against the HAMSTAD Benchmarks for one dimensional cases and for two-dimensional cases according to ISO 10211: Thermal bridges in building construction - Heat flows and surface temperature - Detailed calculations (Sontag et al., 2013). The two-dimensional cases have only been validated for stationary boundary conditions.

Simulation settings

The HTS had stationary boundary conditions, because the software has only been validated for stationary boundary conditions and the focus of the UA/SA is on identifying the parameters that have the largest impact on the output of the hygrothermal simulation. The initial conditions for the wall were set at a temperature 20 ℃ and a RH of 80 %. The wind speed on both sides of the wall and the horizontal rain amount were started instantaneously from the start of the simulation. The simulation lasted for 100 days to cancel out the influence of the starting conditions and the initial fluctuations in the model outputs.

Computational grid

The computational grid was varied to match the variation in the dimensions of the wall structures. Delphin uses an orthogonal grid, with the possibility to set the height and width of the cells. The model was built in such a way that the number of cells between the different simulation runs was kept equal and the grid dimensions vary between the simulations. The number of cells for each material was set with a minimum of 5 cells for each material and whereby the maximum cell dimensions were 2 mm. Over each layer of material the size of the cells was kept constant.

Results and analysis

Outputs of interest

The UA/SA has been conducted with the aim to evaluate the effect of heterogeneity in the structure of a solid-brick wall on the hygrothermal behaviour of the wall. Therefore, the temperature and RH in the wall will be used as relevant outputs in the model. These

will be supplemented by the fluxes of heat and moisture through the wall:

- *Temperature*: the average temperature of the wall structure indicates the heat capacity of a wall. A higher heat capacity means less fluctuations in temperature of the interior of the building (Van der Linden et al., 2008). The average temperature will always be between boundary temperatures, thus depending on the weather scenario 8.34/10.3 ℃ and 23 ℃.
- *Relative humidity*: moisture build-up in the structure could lead to structural and health issues and should be avoided. Especially mould growth can start from a RH of 60 % or higher, respiratory problems on the other hand can occur with a RH below 30 %. The usual RH level of air in a dwelling is 46 - 56 % (Isaksson et al., 2010; Van der Linden et al., 2008).
- *Heat flux*: the heat resistance of the wall structure governs the amount of heat flowing through the wall. A lower heat flux will minimize the heat loss in a building. For a solid-brick wall the heat transmittance will typically be roughly 1 W/m²K (heat flux of approximately 4-7e10 J for the model in this paper), and roughly 0.5 W/m²K (2-3.5e10 J) for the insulated wall (Hens, 2011; Van der Linden et al., 2008)
- *Moisture flux*: analogous to the heat flux, a higher moisture resistance of the wall structure leads to less moisture exchange between the exterior and interior of a structure. In this paper rain is evaluated as one of the main parameters and thus a higher moisture resistance is beneficial. For a solid-brick wall the moisture transmittance will typically be roughly 1 m²/m² (moisture flux of approximately 13000 kg/h for the model in this paper), and roughly 0.25 m²/m² (3250 kg/h) for the insulated wall (Hens, 2011; Van der Linden et al., 2008).

Results: uncertainty analysis

Hygrothermal model

The structure of the wall has a significant influence on the four output variables. As can be seen in figure 3a for the heat flux, the MW wall has roughly half of the heat flux of the LM wall. The heat flux is thus reduced by applying the MW to the wall. More importantly, the absolute variation in results for the MW wall is smaller than that of the LM wall, a reduction of circa 30 %. The relative spread around the median for each of the cases on the other hand is equal between the different LM and MW cases. Similar results can be seen for the other three output variables, although with more overlap in the results of the eight cases, see figure 3b. In this figure the MW cases are still clearly grouped according to the weather scenario and wall structure, but the LM cases show an overlap. The differences in weather scenarios thus have a larger influence on the moisture flux of the MW wall than the LM wall. This could be caused by the overall lower resistance of the LM to moisture transport. With a lower resistance to moisture fluxes, small changes in the material properties will have a larger influence on the total moisture transport through the wall.

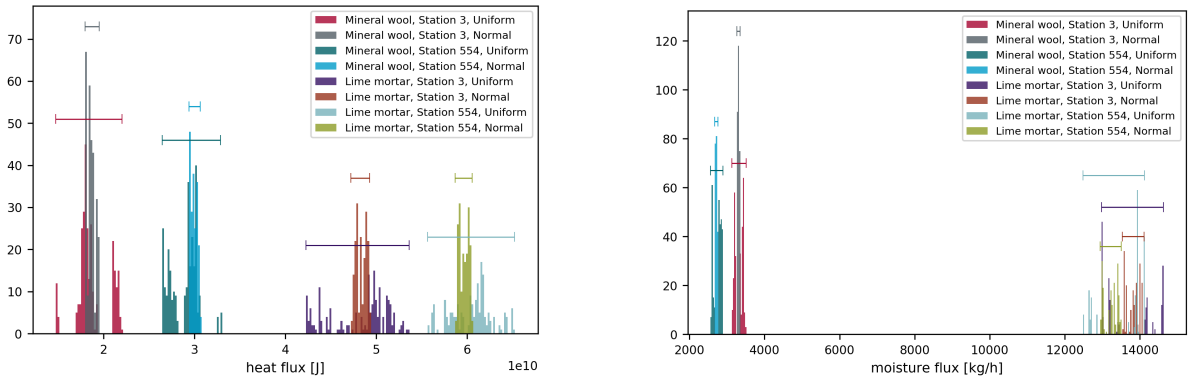
Weather scenario

The effect of the weather scenario is shown in figures 3 and 4. In the figures four distinct groupings can be seen, with two causes: the wall structure and the weather scenario.

The heat fluxes in the scenario with weather station 3 are lower than for weather station 554. This is counter-intuitive, since both the temperature gradient between the interior and exterior temperature and the wind speeds are higher for weather station 3. Looking closer to the results per simulation run this becomes clear. Due to the starting conditions, the heat flux peaks at approximately 500 hours of simulated time and than reduces to a near-linear behaviour. The peak in heat flux is therefore higher, because the heat flux after 2400 hours (100 days) is used in this analysis. After the peak the heat flux will drop to an equilibrium state since the boundary conditions are fixed. For station 3 this drop in heat flux happens quicker than for weather station 554 (a steeper angle of the near-linear behaviour), possibly due to the higher temperature gradient. At the end of the 100 day simulation the heat flux is not yet in equilibrium for both cases.

Related to the heat flux is the temperature of the wall, which is high for all cases, with wall-averaged temperatures between 19.7 and 19.9 ℃. With the boundary conditions this temperature is not completely impossible, but one would expect values closer to the average of the interior and exterior boundary conditions: 15.7 and 16.7 ℃ for weather station 3 and 554 respectively. The starting temperature of the wall is fairly high with 20 ℃ and with the high heat capacity of some of the materials and the HTS not fully achieving equilibrium, this is likely the cause of the high temperatures.

In figure 4 the correlation between the moisture flux and temperature of the wall are given. Here a higher temperature correlates with a higher moisture flux, which is in line with previous studies (Guizzardi et al., 2016). There is a distinction between the two wall structures, with the moisture flux being more dependent on the temperature for the LM wall than the MW wall. The vapour barrier of the MW wall is the likely cause of this difference. This layer is largely responsible for the moisture resistance of the wall as a whole and is placed on the warm side of the insulation. This means the temperature of the vapour barrier is mainly determined by the indoor temperature and thus very stable, where as the rest of the wall shows variations in temperature.



(a) Heat flux *(b) Moisture flux*

Figure 3: Distribution of the heat flux (a) and moisture flux (b) output from the HTS runs. The bin-width for the histograms has been fixed respectively at 2e8 J and 30 kg/h, the line above the histograms indicates the total spread in the outcomes.

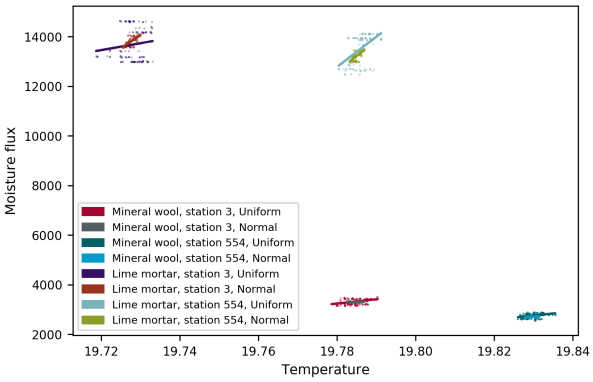


Figure 4: Regression plot of the outcomes for the moisture flux and temperature.

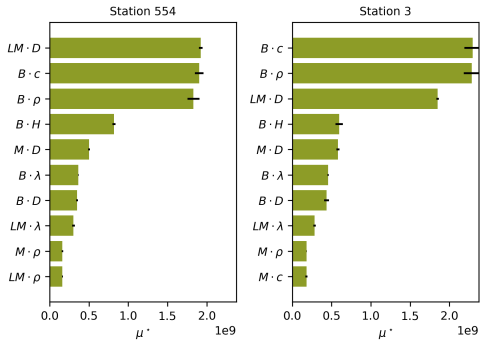


Figure 5: Comparison between the elementary effects of the two weather scenarios, for the heat flux of the lime mortar wall with a uniform distribution

Parameter distribution

Compared to the differences in the outcomes caused by the wall structure and the weather scenario, the differences as a result from the two different distributions of the parameter means are limited. Notable are however the spread in the results, see figure 3. For all the cases the spread in the outcomes of the normal distribution is roughly 25-30 % of the uniform distribution. The difference in the outcomes can largely be explained by the manner SimLab samples both distributions. The distribution is split into the number of samples (in this case 4) of equal size and the middle point of each split is takes as the value for the UA/SA. This causes the values for the uniform distribution to be equally spaced between the minimum and maximum values, but the values of the normal distribution are more clustered towards the mean.

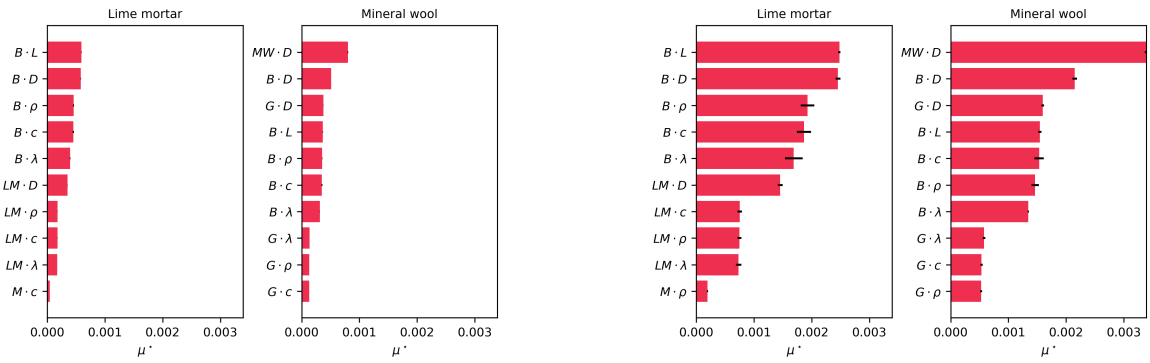
Results: sensitivity analysis

When looking at the μ^* of the parameters it can be seen that the weather scenarios have no influence on the order of the parameters (within a 95 % certainty). The differences in magnitude of the μ^* are also limited (up to 20 %, with the relative difference between parameters unchanged), see figure 5, meaning that the two weather scenarios chosen do not significantly alter the sensitivity of the wall structures. Which parameters and the sequence of these parameter with the largest μ^* (within its uncertainty) does not change when using the different parameter distributions, compare as an example figures 6a and 6b.

Notable for all the results is that the parameters with a high μ^* for all structures are mainly the dimensional parameters and the parameters determining the thermal properties of the materials, see figure 6 and table 1. Variations in hygric properties and especially the porosity of the materials seem to have negligible effect on the outcomes of the temperature, relative humidity, heat or moisture flux.

Discussion

The study described in this paper is a step to better understand the uncertainty and sensitivity concerning the hygrothermal behaviour of a solid-brick wall, both uninsulated and insulated with mineral wool. From the UA it is clear that small differences in the



(a) Normal distribution

(b) Uniform distribution

Figure 6: Side-by-side comparisons of the top-10 rankings between the two wall structures for temperature outcomes under weather scenario 3. (a) shows the comparison for the normal distribution of the input parameters and (b) for the uniform distribution of the input parameters

input (up to 1 %) can cause significant differences in the outcomes. The SA has further shown that of all the parameters that were varied, the dimensions and the thermal properties of the elements should be defined as exact as possible in the model to achieve reliable outcomes of the HTS.

The boundary conditions will further have a different effect on the two wall structures, with the LM wall structure showing a larger impact of changes in weather conditions. The differences between the two static boundary conditions were relatively small, due to the choice to use mean values. During a year far greater differences may occur, showing a more distinct effect on the two wall structures. This in turn means that effects of weather on one wall structure cannot be projected onto another wall.

The differences in the two distributions used is notable, with the normal distribution showing less uncertainty than the uniform distribution. A normal distribution is more similar to the actual distribution of material parameter means, thus it can be concluded that the robustness of a model may be underestimated when a uniform distribution is used. A small caveat has to be placed here, because the normal distribution in this study was synthetic, as the actual minimum and maximum values of the material parameters were unknown. The purpose of the HTS could however be the determining factor what distribution to use, with a different conclusion than Tian (2013). When the only purpose is to find the parameters that have the largest effect on a model, an uniform distribution will yield the same results as the normal distribution, with less information required. But if more information is available, a normal distribution seems to yield more accurate results.

Last but not least, there is balance to be found between the accuracy of the results and the time spent on the HTS, i.e. the simulation runs. Because steady boundary conditions were used in this study, the simulation time was limited to 100 days. This was insufficient to come to a full equilibrium in the outputs. Some of the outcomes were at first glance therefore counter-intuitive, and a more detailed analysis of the underlying data was needed. For a study as this, where comparisons are made, this is defensible, but this is not sufficient for conclusions about the actual hygrothermal properties of the wall structures.

Conclusion

The study presented a comparison between two wall structures with two distributions of parameter means in an uncertainty and sensitivity analysis under two weather scenarios. From the results it can be concluded that the variations in dimensional and thermal properties of the wall determine the sensitivity of the parameters, with limited effect of the weather scenario and applied distribution. The uncertainty on the other hand will be affected by the weather scenario and the choice between a normal of uniform distribution. Depending on the purpose of the study either distribution can be used, with the normal distribution needing more information, but leading to less uncertainty of the outcomes of a model.

Nomenclature

ρ	Bulk dry density [kg/m^3]
μ	Water vapour diffusion resistance factor [-]
μ^*	Mean of absolute elementary effects [n/a]
λ	Thermal conductivity [W/mK]
σ	Standard deviation of the elementary effects
θ	Porosity, with subscripts $_{por}$ for open porosity, $_{eff}$ for effective saturation, $_{cap}$ for capillary saturation content and $_{80\%}$ for hygroscopic sorption at a RH of 80% [m^3/m^3]
c	Specific heat capacity [J/kgK]
AW	Water uptake coefficient [kg/m$^2\sqrt{s}$]
$D_{l,eff}$	Liquid water diffusivity at effective saturation [s]
K_g	Air permeability [s]

$K_{l,eff}$	Liquid water conductivity at effective saturation [s]
D	Depth or width of a material, depending on material orientation [mm]
L	Length (specifically bricks) [mm]
H	Height (specifically bricks) [mm]

References

Campolongo, F., Cariboni, J., and Saltelli, A. 2007. An effective screening design for sensitivity analysis of large models. *Environmental Modelling and Software*, 22(10):1509–1518.

European Commission 2008. SimLab - Sensitivity Analysis.

Fechner, H., Ruisinger, U., Nicolai, A., and Grunewald, J. 2017. *Delphin: Simulation program for the calculation of coupled heat, moisture, air, pollutant, and salt transport, version 2.8*. Bauklimatik-Dresden, Dresden, Germany.

Guizzardi, M., Derome, D., and Carmeliet, J. 2016. Water uptake in clay brick at different temperatures: Experiments and numerical simulations. *Journal of Building Physics*, 39(4):373–389.

Hamilton, I., O'sullivan, A., Oreszczyn, G. T., Shipworth, D., Summerfield, A., and Davies, M. 2017. Old and cold? Findings on the determinants of indoor temperatures in English dwellings during cold conditions. *Energy and Buildings*, 141:142–157.

Hens, H. 2011. *Applied Building Physics*. Verlag fur Architectur un technische Wissenschaften GmbH und Co, Berlin.

Hens, H. 2015. Combined heat, air, moisture modelling: A look back, how, of help? *Building and Environment*, 91:138–151.

Herman, J., Usher, W., Mutel, C., Tridade, B., Hadka, D., Woodruff, M., Rios, F., and Hyams, D. 2017. SALib - Sensitivity Analysis Library in Python.

Hopfe, C. J. and Hensen, J. L. M. 2011. Uncertainty analysis in building performance simulation for design support. *Energy and Buildings*, 43(10):2798–2805.

Hunter, J. D. 2007. Matplotlib: A 2D graphics environment. *Computing in Science and Engineering*, 9(3):99–104.

Isaksson, T., Thelandersson, S., Ekstrand-Tobin, A., and Johansson, P. 2010. Critical conditions for onset of mould growth under varying climate conditions. *Building and Environment*, 45(7):1712–1721.

Macdonald, I. and Strachan, P. 2001. Practical application of uncertainty analysis. *Energy and Buildings*, 33(3):219–227.

Marriott, F. 1990. *A dictionary of statistical terms*. Harlow.

McLeod, R. S. and Hopfe, C. J. 2013. Hygrothermal implications of low and zero energy standards for building envelope performance in the UK. *Journal of Building Performance Simulation*, 6(5):367–384.

Morris, M. D. 1991. Factorial Sampling Plans for Preliminary Computational Experiments. *Technometrics*, 33(2):161–174.

Nielsen, A., Møller, E. B., Rasmussen, T. V., and Hansen, E. J. d. P. 2012. Use of sensitivity analysis to evaluate hygrothermal conditions in solid brick walls with interior insulation. In *5th International Building Physics Conference (IBPC)*, pages 377–384, Kyoto.

Oreszczyn, T., Ridley, I., Hong, S., and Wilkinson, P. 2006. Mould and winter indoor relative humidity in low income households in England. *Indoor and Built Environment*, 15(2):125–135.

Prada, A., Cappelletti, F., Baggio, P., and Gasparella, A. 2014. On the effect of material uncertainties in envelope heat transfer simulations. *Energy and Buildings*, 71:53–60.

Python Core Team 2017. Python: A dynamic, open source programming language.

Saltelli, A., Tarantola, S., Campolongo, F., and Rotto, M. 2004. *Sensitivity analysis in practice*. John Wiley & sons Ltd, Chichester.

Sontag, L., Nicolai, A., and Vogelsang, S. 2013. Validierung der Solverimplementierung des hygrothermischen Simulationsprogramms Delphin. Technical report, Technische Universitat Dresden, Dresden.

Tian, W. 2013. A review of sensitivity analysis methods in building energy analysis. *Renewable and Sustainable Energy Reviews*, 20:411–419.

UK Meterological Office 2017. Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853 -current).

Van der Linden, A., Erdtsieck, P., Kuijpers-van Gaalen, I., Zeegers, A., and Selten, T. 2008. *Building Physics*. ThiemeMeulenhoff, Utrecht, 7th edition.

Van der Walt, S., Colbert, S. C., and Varoquaux, G. 2011. The NumPy array: A structure for efficient numerical computation. *Computing in Science and Engineering*, 13(2):22–30.

Van Rossum, G. 1995. Python tutorial, Report CS-R9526. Technical report, Centrum voor Wiskunde en Informatica (CWI), Amsterdam.