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Use of sensitivity analysis to evaluate hygrothermal conditions in solid brick walls with interior insulation

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ABSTRACT

The paper describes conditions for an internally insulated solid brick wall. Refurbishment methods that in principle are the same might have a different outcome when applied on different buildings, e.g. internal thermal insulation without vapour barrier might result in mould growth behind the insulation in some houses, but not in all. One explanation could be that in practice the indoor and outdoor climates are not known beforehand as they vary with the weather, the habits of the inhabitants etc. The paper applies sensitivity analysis with the Morris method to find parameters that are negligible, linear and additive or non-linear. The effect of random input variables on the output of a simulation - the Sobol sensitivity indices - is also calculated. The calculation results show, that the dominating parameter for the moisture content in the innermost layer of the bricks is the wall orientation and driving rain. The effect of a vapour barrier is negligible, and the thickness of the insulation has only little effect. As a result the main focus when insulating solid brick walls should be on the resistance of the brick wall to driving rain and not on tightness of the vapour barrier or the insulation thickness as it has been traditionally.

1. Introduction

Solid brick-buildings dating from 1850-1920 have rich ornamented facades which are typical for that period. Such buildings contribute to the uniqueness of the local urban environment. To improve their energy performance, only measures that do not change the overall exterior architecture are acceptable; in practice this means interior insulation.

A higher moisture content in bricks poses a higher risk for instance for mould growth or frost damage. Analysis of moisture in an internally insulated wall has been performed before. Nielsen (1987) calculated condensation with Monte Carlo simulations based on diffusion. More advanced models are also used (Häupl, Jurk and Petzold 2003), (Scheffler and Grunewald 2003), (Vereecken and Roels 2011). In general the results show; that moisture problems behind internal insulation can be avoided if there is a tight vapour barrier on the warm side of the thermal insulation.

However, practice shows that mould growth can be a problem behind the internal insulation, even when there is focus on installing a tight vapour barrier. It is not always possible to foresee when internal insulation will cause moisture problems and when not. The solution seems to be risky. One explanation could be that indoor and outdoor climate as well as material parameters varies with the weather, the habits of the inhabitants and the quality of the material or work-manship. To investigate the influence of the stochastic variations, sensitivity analysis can be used.

Sensitivity analysis is used on many types of problems as described in Saltelli (2004) and Kleijnen (1995). Hagentoft (2011) has used it in an analysis of hygrothermal conditions in an attic. Analysis of condensation in a wall is found in Nielsen (1995). Sensitivity analysis has also been used in energy design of buildings (Wit and Augenbroe 2002), (Heiselberg and Brohus 2007), (Hopfe 2009).

2. Guidelines and recommendations

The Danish Building Research Institute has been involved in a number of cases with focus on energy refurbishment and improving the thermal envelope. They have included buildings with internally post insulated exterior walls of solid brick. Practical aspects of moisture design under Danish conditions are given in (Brandt et al., 2009).

Based on the results of these activities, guidelines were published by the Danish Building Research Institute on how to improve the thermal insulation of existing blocks of flats (Munch-Andersen 2008). The guidelines focus on typical building techniques used in Denmark.

The guidelines are supported by case studies including buildings constructed in the period between 1850 and 1920. Typically, buildings with a unique architecture, which demand customised technical solutions to improve the insulation standard of the thermal envelope. Measures are followed up by showing savings obtained by decreased energy demands. As moisture problems are known possible side effects of internal insulation, the case studies also address requirements of importance related to building physics to prevent degradation of the building envelope (Valdbjørn Rasmussen 2010). Building evaluations 1 and 5 years after completion of the energy refurbishment are presented through an on-going project (Co2ol Bricks 2011-13).

Most recommendations and chosen solutions in the case studies are based on simulations with climate data from a standard test reference year. However, they do not take stochastic variations into account. At the same time practice has shown examples of interior insulation without moisture problems, where calculations predicted problems and vice versa. Therefore, sensitivity analysis has been used in this paper in the endeavour to find the parameters that are important to consider when insulating solid brick walls internally.

Fig. 1. Example of old Danish brick building from 1901

3. Sensitivity analysis – example and method

The sensitivity analysis is illustrated by an example where the calculation is based on a 29 cm thick brick wall. The internal insulation can be up to 20 cm thick. The insulation material is mineral wool. The inner layer is a 12.5 mm coated gypsum board. There is a vapour barrier between the gypsum board and the insulation.

3.1 Material properties

The material properties for the wall consisted of

Gypsum

Thermal conductivity λ=0,198 W/(m K)
Vapour resistance Z=188*10^8 m/s
No liquid moisture transfer

Vapour barrier

No heat resistance
Vapour resistance Z=1250*10^8 m/s

Mineral wool

Thermal conductivity λ=0.04 W/(m K)
Vapour resistance for 10 cm: Z=5*10^8 m/s
No liquid moisture transfer

Bricks

Thermal conductivity λ=0.5 + w*0.0045 W/(m K)
w is the moisture content
The sorption isotherm, vapour diffusion coefficient and the liquid moisture permeability is taken from (IEA Annex 55 Exercise 2).

Note that mortar joints are neglected and the bricks are calculated as a homogeneous material.

3.2 Climate

The calculation was done with the Danish design reference year, DRY. The climate file with hourly values is described in (Jensen and Lund 1985). The selected monthly data give a good average for temperature and solar radiation. The solar radiation on the wall is taken into account using the equivalent outdoor temperature. The selected rain data in DRY are not necessarily a 30-year average value. The driving rain on the wall is calculated from wind direction, wind speed and rain on a vertical surface.

The indoor temperature was constant 20°C. The internal moisture load was 2.78 g/m^3 above the outdoor moisture level with a normal air-change rate of 0.5.

3.3 Simulation model

The simulation was done in MATLAB. The inner layers of gypsum board vapour barrier (PE foil) and mineral wool has little influence on the thermal and moisture inertia and were therefore simplified as thermal and moisture resistances. The brick was divided in 10 layers. In the following the results are presented for the innermost and outermost layer of the brick. If the temperature is below 0°C in one or more layers of the brick, then there is no moisture flow.

The model is similar to the model used by Hagentoft in (IEA Annex 55 Exercise 2). The model is written as a heat and moisture differential equation system and solved with the ode23 solver in MATLAB. It is an implementation of a Runge-Kutta method for solving differential equations. More about the simulation model are given in (Hagentoft 2011).

3.4 Statistical simulations

The statistical simulation is done with SIMLAB (Saltelli 2004) coupled with the MATLAB model of the case. SIMLAB has standard routines for different statistical distributions and can be used to make sensitivity analysis based on different methods.

3.4.1 Input parameter variations

The input parameters (Table 1) were selected to investigate the effect of larger insulation thickness on the moisture content. The air-change rate parameter is equivalent to a change in the interior moisture load from 1.39 g/m^3 to 4.17 g/m^3. The wall orientation for all directions are (0 = north, 90 = east and 180 = south). The driving rain parameter as well as the vapour barrier parameter give variations from none to full effect.

Table 1. Parameter variations – uniform

	from	to
Insulation thickness	1 cm	20
Insulation conductivity	0.03 W/mK	0,04
Air-change rate	0.5	1.5
Wall orientation	0 degree	360
Driving rain	0	1
Vapour barrier	0	1

3.5 Morris method

The Morris method (Saltelli 2004) is a screening method to find parameters that are important or negligible. The method varies one parameter at a time. Each parameter is divided into a discreet number of values that are chosen within the range of variation. The method calculates two sensitivity measures for each parameter. The measure for the overall effect, Morris my of the parameter on the output, can be called the mean value. The other measure, Morris sigma estimates the second and higher order effects in which the parameter is involved and can be called the standard deviation for the parameter.

The method calculates Morris my and sigma for each parameter. A high my indicates a parameter with an important overall influence on the output. A high sigma indicates either interaction with other parameters or a parameter that is non-linear. If both the my and the sigma are low then this parameter is negligible. The method tends to be qualitative as for ranking the input parameters in order of importance.

3.6 Sobol method

The Sobol method (Saltelli 2004) is a quantitative method that gives the percentage of total output variance that each parameter accounts for. The method is a variance based method to quantify the impact of uncertainties in random variables on the uncertainty in the model output. This method is more computationally expensive than the Morris method. The Sobol method for variance-based estimation is based on decomposition of the variance of a response to its variation sources. The Sobol method makes estimates of first-order sensitivity indices, higher–order indices and total indices using SIMLAB. The first-order term represents the partial variance in the response due to the individual effects of a random variable. The higher-order terms shows the interaction between two and more variables. The total effect relates to all direct and indirect variance from other variables.

4. Results of traditional calculations

A traditional calculation with fixed parameters was done for a whole year with hourly values for Danish climate. Calculation of moisture content for the original massive brick wall facing south is shown in Fig. 2 and Fig. 3. The calculation started on 1 July (0 hours). Therefore the winter lies between 3000 and 6000 hours in Fig. 2 and 3.

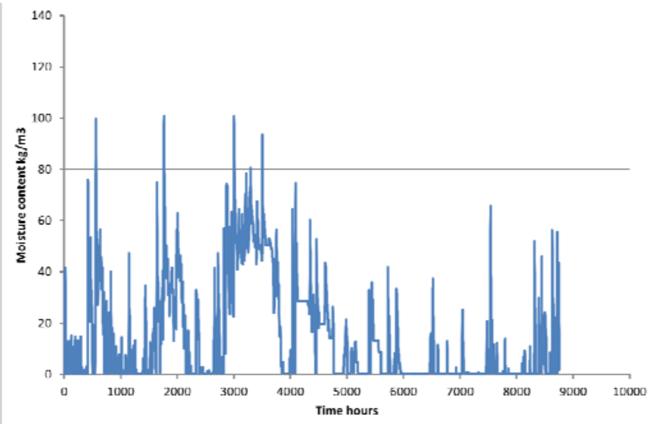

Fig. 2. Yearly moisture variation of outermost layer of the brick wall (hourly values)

The variation of the moisture content in the outermost layer (Fig. 2) of the brick is much influenced by the driving rain with high values in short periods. The variations in the innermost layer of the brick (Fig. 3) were lower and it is seen that the variations is much slower.

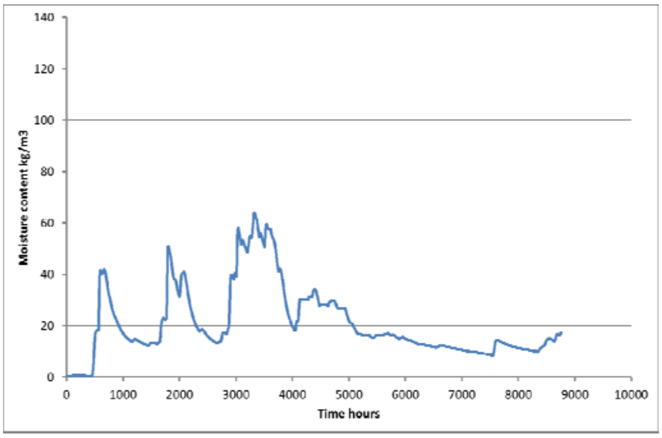

Fig. 3. Yearly moisture variation of innermost layer of brick wall (hourly values)

Similar calculations are done for a case with 10 cm internal insulation, moisture barrier and gypsum, as shown in Fig. 4 and Fig. 5.

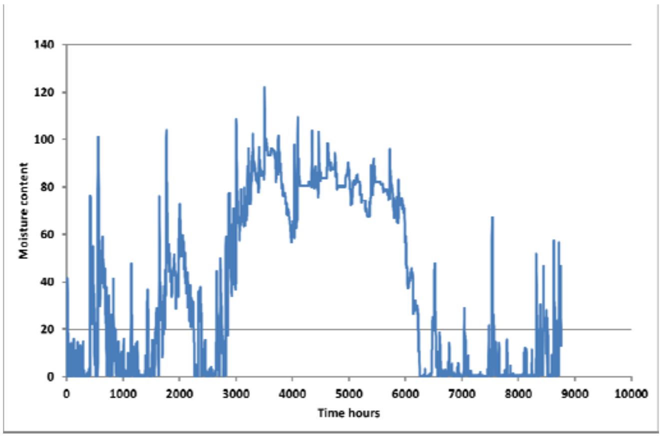

Fig. 4. Yearly moisture variation of outermost layer of bricks for an insulated brick wall (hourly values)

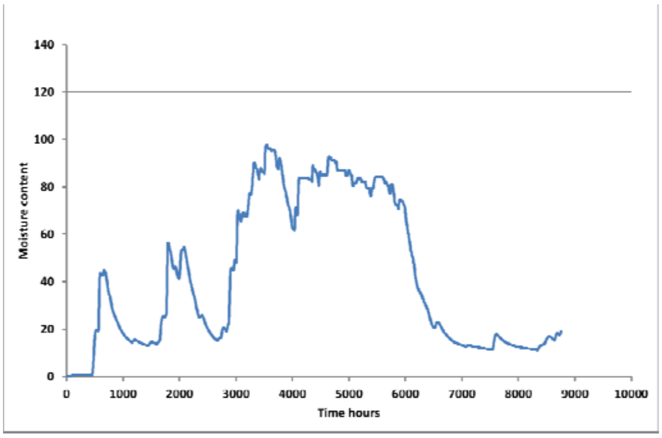

Fig. 5. Yearly moisture variation of innermost layer of bricks for an insulated brick wall (hourly values)

The variations of the moisture content in the insulated wall are similar to the wall without insulation (Figs. 2 and 3) but the moisture level is higher; 80 kg/m^3 versus 60 kg/m^3 for the innermost layer. The high moisture content is also on a high level in a longer period for the insulated brick wall. In short, we can expect higher moisture levels in the insulated wall.

5. Statistical simulation

In the statistical simulation, different input parameters were varied as described in Table 1. The simulations are made for January in order to reduce the computing time. The temperature and the moisture content are the interesting output parameters. These are calculated for each hour (744 values) at 10 points through the brick wall. All these points are not interesting. The selected values in this paper are the temperature and moisture content in the outermost and innermost layer of the brick wall as an average value for the whole month. These output parameters are used for the following analyses.

Selecting results from one case makes it possible to look in more detailed at the temperature and moisture conditions inside the brick wall for the calculation period.

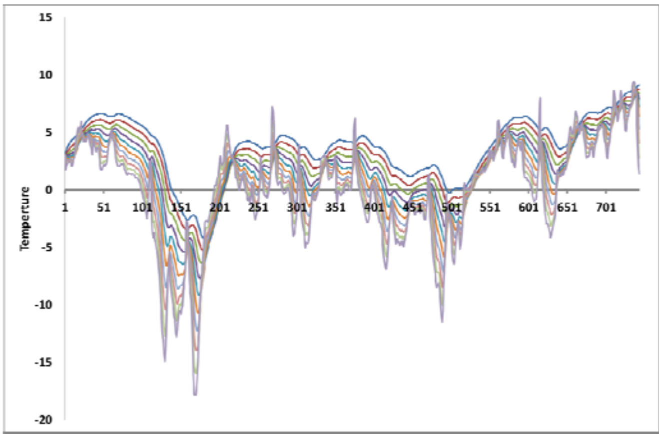

Fig. 6. Temperature variation in the 10 layers of the brick wall in January

Fig 6 shows, that the temperature difference from the inner side to the outer side of the brick wall can be more than 10 °C.

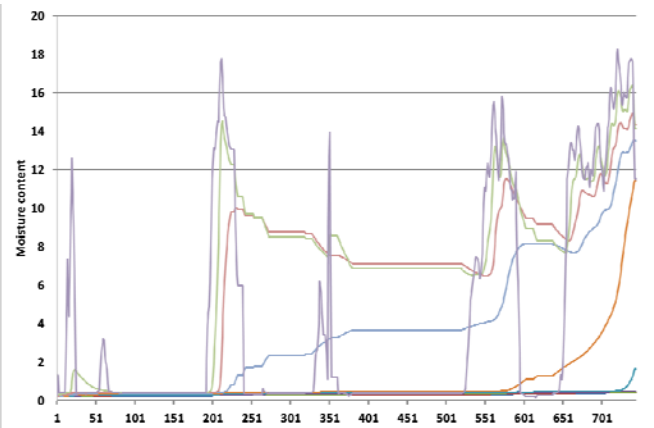

Fig. 7. Variations in moisture content in the 10 layers of the brick wall in January

Fig 7 shows how periods with driving rain on the surface of the brick wall result in high peaks in the moisture content. The moisture content decreased as the moisture is transported into the brick. It is also possible to see that the moisture content is constant in periods with frost, when comparing with Fig. 6.

6. Morris analysis

Results for the Morris analysis on the average moisture content and the average temperature are shown in Fig. 8 to 11 as mean value versus standard deviation. Parameters with high mean value have a high influence on the output. High standard deviation means interaction with other parameters or a non-linear parameter. If the points (Morris my, Morris sigma) are below the line in the diagram, the parameter are linear. If they are above they are non-linear. Points with my and sigma below 0.1 can be ignored as they had little influence.

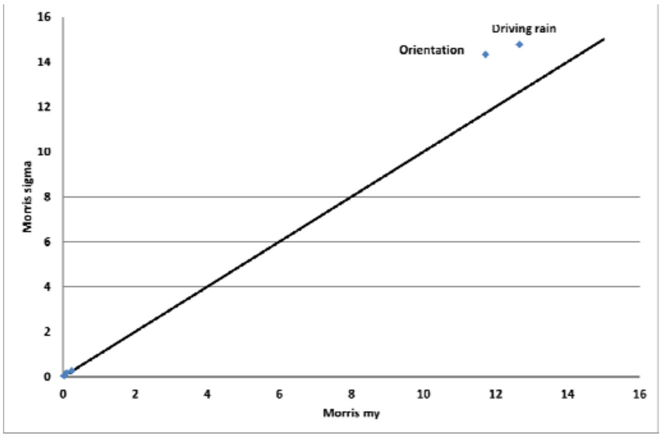

Fig. 8.Morris analysis for average moisture content in the innermost layer of the brick wall

The results for the average moisture content in the innermost layer of the brick (Fig. 8) showed that most parameters are non-linear or interacted and that driving rain and wall orientation are the most important parameters.

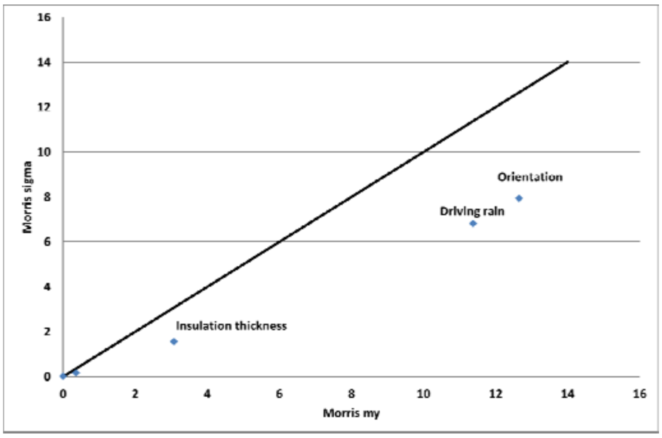

Fig. 9. Morris analysis for average moisture content in the outermost layer of the brick wall

The results for the average moisture content in the outermost layer of the brick (Fig. 9) show that the parameters have a linear influence on the moisture content and that driving rain and wall orientation are the most important parameters.

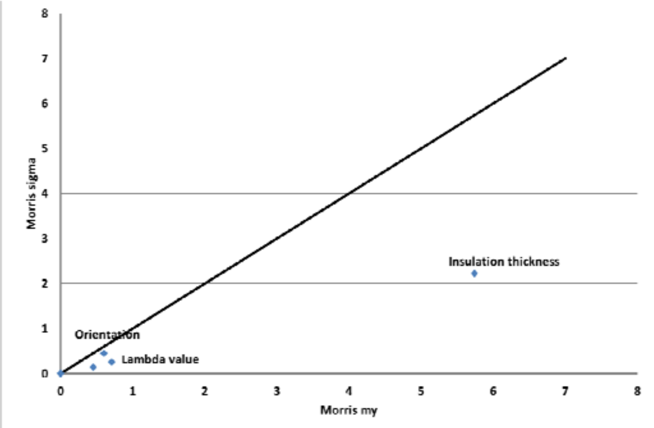

Fig. 10. Morris analysis for average temperature in the innermost layer of the brick wall

The results (Fig. 10) for the average temperature in the innermost layer of the brick wall show that most parameters are linear and that the insulation thickness is the most important parameter.

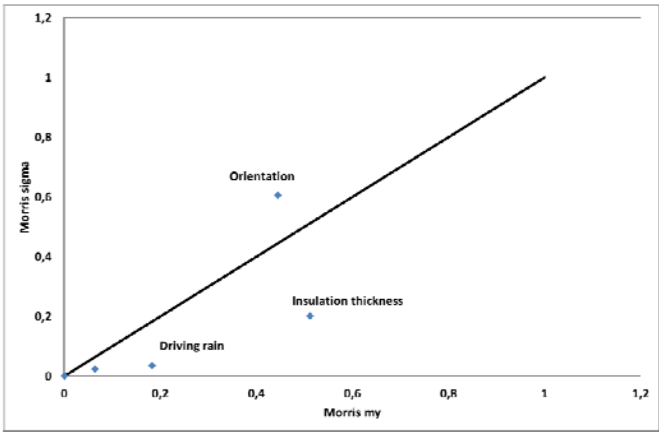

Fig. 11. Morris analysis for average temperature in the outermost layer of the brick wall

The results (Fig. 11) for the average temperature in the outermost layer of the brick show that all parameters except wall orientation have a linear influence on the temperature. Insulation thickness and wall orientation are the most important parameters. The wall orientation has its non-linear influences from the solar radiation on the wall surface. It is interesting to see that there is quite a difference between the inner and outermost layer of the wall.

The results of the Morris analysis showed that the most important parameters on the average moisture content and the average temperature are driving rain, wall orientation and insulation thickness. Other parameters might be ignored, which is important if there are many parameters and a need to reduce computing time. In this case, we had few parameters so the quantitative analysis with the Sobol method was done with all parameters.

6.1 Parameter variations

The Morris analysis gave information on the important and unimportant parameters. This can also be seen from the plot of the parameter variations against for instance the moisture content. The simulation used 400 cases, which are presented in the next figures.

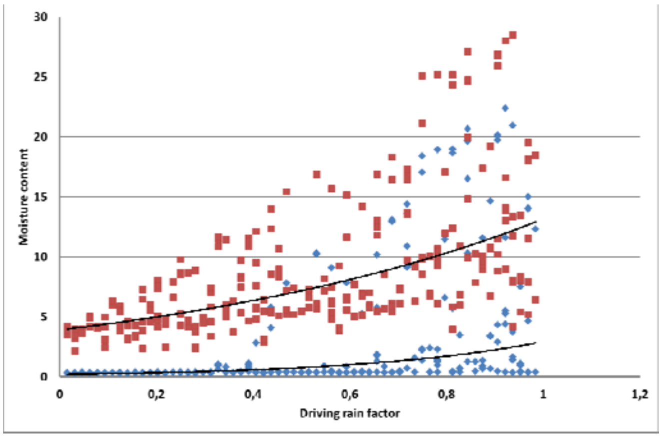

Fig. 12. Moisture content in outermost (square points) and innermost (rhomb points) layer of brick wall versus driving rain parameter

Fig 12 shows that driving rain is an important parameter for the moisture content throughout the brick wall as a reduction in driving rain reduces the moisture content. A low amount of driving rain gives low moisture content in the bricks. The two lines in the diagram are trend lines for the outermost and innermost moisture content of the brick. A reduction in the driving rain will have a very important effect on the moisture levels.

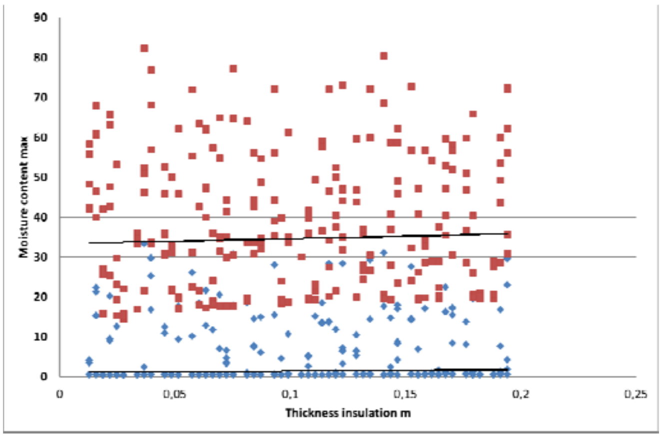

Fig. 13. Moisture content in the outermost (square points) and innermost (rhomb points) layers of brick wall versus insulation thickness

Fig. 13 shows that the insulation thickness is not an important parameter for the moisture content as the trendlines are almost constant.

Fig. 14 shows that the wall orientation is an important parameter as the values change with direction and also that it is non-linear. We can see that certain wall orientations will have a higher risk of getting high moisture content in the brick wall.

Fig. 15 shows that the air-change rate is not an important parameter. The air-change rate variations are the same as a variation in the indoor moisture level as mentioned in section 3.4.1. The two lines in the diagram are the trend lines for the moisture content at the innermost (the lowest line) and the outermost layer of the brick.

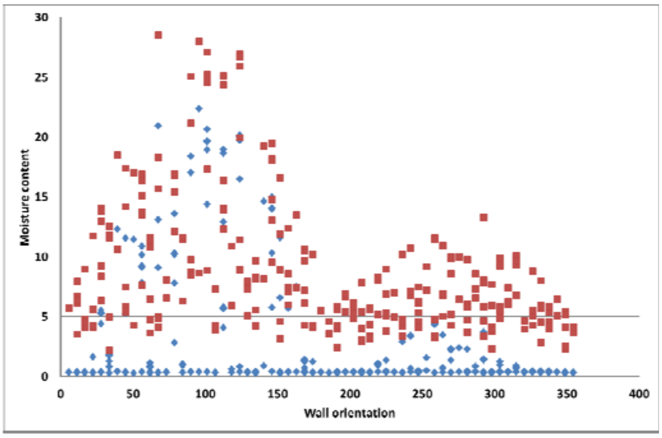

Fig. 14. Moisture content in the outermost (square points) and innermost (rhomb points) layers of brick wall versus wall orientation

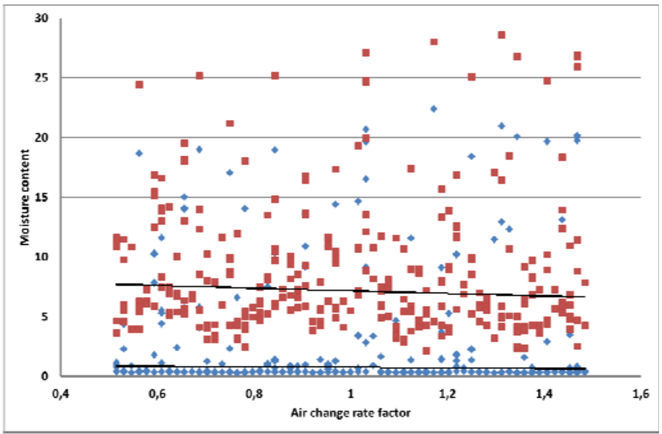

Fig. 15. Moisture content in the outermost (square points) and innermost (rhomb points) layer of brick wall versus air-change rate

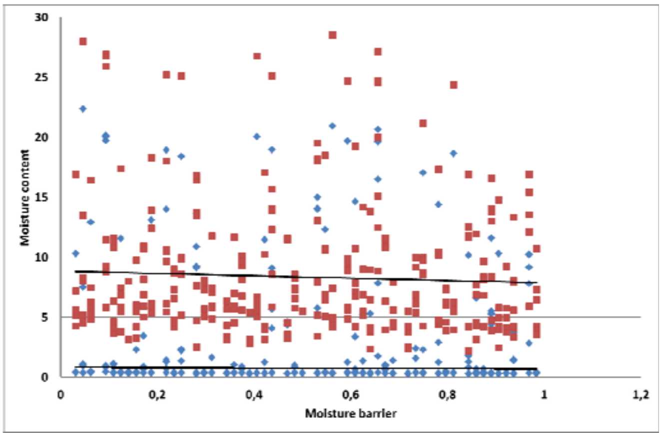

Fig. 16. Moisture content in the outermost (square points) and innermost (rhomb point) layer of brick wall versus moisture barrier

Fig. 16 shows variations in the moisture resistance for the moisture barrier from none (0) to normal barrier (1). As seen from the statistical evaluation there is a very small effect of the moisture barrier but it has an influence on the air-tightness that could be important.

Fig. 17 shows that the insulation thickness is an important parameter for the temperatures in the brick wall. As expected, the temperature in the innermost layer of the brick wall decreases when the insulation thickness is increased. The effect does not change much from 10 to 20 cm.

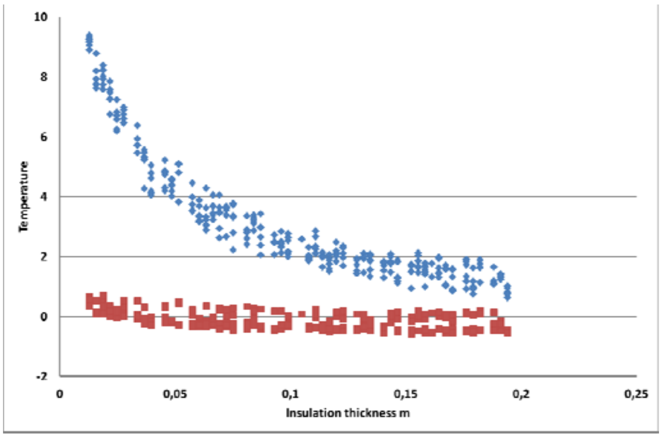

Fig. 17. Temperature in the outermost (square points) and innermost (rhomb points) layers of brick wall versus insulation thickness

7. Sobol analysis

The Sobol analysis calculates the percentage of output variance that each parameter accounts for.

Table 2 is for the average temperature in the outermost layer of the brick. Insulation thickness is the most important parameter both for first order and total indices. Two parameters do not have any influence; air-change rate and resistance of the vapour barrier.

Table 2. Sobol indices for temperature in outermost layer

	Sobol First	Sobol total
Insulation thickness	1.1504	1.2132
Insulation conductivity	0.0040	0.0110
Air-change rate	0	0
Wall orientation	-0.0963	0.0156
Driving rain	0.0038	0.0068
Vapour barrier	0.0002	0

The analysis is also done for all combinations of two parameters to find the combination with the largest effect. Sobol total for pairs for the case in Table 2 had the highest value for the combination insulation thickness and driving rain with a coefficient of 1.33.

Table 3 shows the Sobol indices for average moisture content in the outermost layer of brick. The wall orientation and the driving rain are the most important parameters. The moisture from the inside has little influence as air-change rate and vapour barrier had low indices.

Table 3. Sobol indices for moisture in outermost layer

	Sobol First	Sobol total
Insulation thickness	-0.0631	0.0548
Insulation conductivity	0.0021	0.0004
Air-change rate	-0.0001	0
Wall orientation	0.5549	0.8417
Driving rain	0.3672	0.8692
Vapour barrier	0	0

Sobol indices for pairs for the case in Table 3 give the greatest influence from the combination wall orientation and driving rain with a coefficient of 1.58.

Table 4 shows Sobol indices for moisture content in the innermost layer of the wall. Again the wall orientation and the driving rain parameter are the most important parameters. The Sobol indices are different from the outermost layer, but the conclusion is the same

Table 4. Sobol indices for moisture innermost layer of brick

	Sobol First	Sobol total
Insulation thickness	-0.0165	0.0117
Insulation conductivity	0.0010	0
Air-change rate	-0.0004	0
Wall orientation	0.5190	1.0183
Driving rain	0.1270	1.0498
Vapour barrier	0.0015	0

7.1 Example – east facing wall

Except for the very early design phase the wall orientation is known in most practical cases. This means that this parameter is fixed. The results of an analysis with 140 calculations using the Sobol method executed for an east facing wall is shown in Table 5 and Table 6. Table 5 gives the Sobol indices for the average temperature in the outermost layer of the brick. The result is similar to Table 2 with the insulation thickness as the most important parameter.

Table 5. Sobol indices for temperature outermost layer of brick in an east facing wall

	Sobol First	Sobol total
Insulation thickness	0.8536	0.8935
Insulation conductivity	0.0058	0.0091
Driving rain	0.1260	0.0758

Table 6 shows the Sobol indices for the average moisture content in the outermost layer of the brick. The most important parameter is the driving rain parameter, which was also found in Table 3.

Table 6. Sobol indices for moisture outermost layer of brick in an east facing wall

	Sobol First	Sobol total
Insulation thickness	0.0748	0.0452
Insulation conductivity	0.0027	0.0003
Driving rain	0.7887	0.7444

7.2 Variation of indices with time

The previous part has looked at the average moisture content in bricks. What happens if we look at the moisture content at a fixed time? This is done for an east-facing wall after 120, 220, 320,420,520, 620 and 744 hours.

Table. 7 Sobol indices for moisture in the innermost layer of brick in an east facing wall at 744 hours

	Sobol First	Sobol total
Insulation thickness	1.0501	1.0405
Insulation conductivity	0.0287	0.0099
Air-change rate	-0.0013	0
Driving rain	-0.0026	0.045
Vapour barrier	0.0004	0

The indices are exactly the same for other times. So it is not important if we select a specific time for average moisture content in the innermost layer of the brick.

The Sobol indices for moisture content in the outermost layer are shown in Table 8. The results for other times are listed in Table 9.

Table. 8 Sobol indices for moisture in the outermost layer of brick in an east facing wall at 744 hours

	Sobol First	Sobol total
Insulation thickness	0.2290	0.3038
Insulation conductivity	0.0147	0.0025
Air-change rate	0.0003	0
Driving rain	0.6812	0.5538
Vapour barrier	0.0004	0

Table. 9 Sobol first indices for moisture in the outermost layer of brick in an east facing wall at different times

Time (hours)	Thickness	Conductivity	Driving rain
120	0.0049	0.0011	1.1112
220	0.0294	0.0056	1.0373
320	0.0007	0.0129	1.0180
420	0.0421	-0.0028	0.5463
520	0.0421	-0.0028	0.5463
620	0.0671	0.0054	0.4411
744	0.2290	0.0147	0.6812

It is seen that the driving rain is the most important factor, but that the numerical values of the indices vary. This is probably caused by the sudden peaks of driving rain. So the statistical analysis will be uncertain near the outer surface, but have no problems at the inside of the brick.

8. Discussion

8.1 Decisive parameters

The sensitivity analysis show that the insulation thickness is the most important parameter for the temperature level in a post-insulated brick wall. This was also expected from (Nielsen 1987). The most important parameter for the average moisture level was the driving rain and the wall orientation – two interacting parameters. More secondary effects are the indoor moisture level and the moisture resistance of the internal vapour barrier. A previous statistical simulation by (Nielsen 1987) showed that the vapour barrier was the most important parameter. But that analysis did not include driving rain.

The simulation, the Morris analyses and the Sobol indices all showed the same results; driving rain and wall orientation are the most decisive parameters for the moisture content throughout the wall. The effectiveness of the vapour barrier is not important. While insulation thickness is only important for the temperature in the wall, the influence is weak at the outside for higher thicknesses but always strong at the inside.

The results are strongly influenced by the moisture transport mechanisms. Therefore further investigations should be made on how different material properties affect the results; e.g. moisture properties should be treated as variables. An interesting observation is that the statistical coefficients vary with time at the outer surface from the highly un-linear behaviour of driving rain.

8.2 Risk of condensation and mould growth

The analysis results for moisture level showed that the condensation risk is not the most important factor as driving rain is the dominating factor in a massive brick wall. Previous studies have reached the same conclusion e.g.

(Häupl, Jurk and Petzold 2003). A high moisture content in the innermost layer of the brick could cause mould growth. However, it is not possible to conclude that the vapour barrier can be left out if driving rain is prevented or reduced in a rainy and windy location like Denmark. This will require further analysis.

The example used in the paper is a solid brick wall. However, since the 1920s hollow walls (two brick walls with air space of 5 to 12 cm between) have become more common. As there is no direct connection between the two walls, except in single points, moisture from driving rain cannot be transported by capillary suction from the outer to the inner wall. The influence of driving rain on the moisture content of the inner wall is therefore expected to be eliminated or strongly reduced.

Is it a problem to have a high moisture content in the inner part of the brick? At the inner side of the brick wall, there could - in practise - be old wall paper, wood studs for the gypsum board or wooden floor beams i.e. nutrition for moulds. An effective vapour barrier could reduce the health risk posed by mould growth in the construction.

8.3 Risk of frost damages

The analysis can also predict whether an increased insulation thickness possess a higher risk of frost-damaged bricks as moisture levels and the number of freeze-thaw cycles could be found, as shown in Fig. 6.

9. Conclusion

The sensitivity analysis presented in this paper is a suitable method for identifying the important parameters and their influence on the temperature and moisture content in a typical construction. Such analyses could be relevant in the design and execution phase. Internal insulation of old brick walls is known to be risky and the walls should not have any defects (e.g. faulty joints). However, focus has been on the vapour barrier, and quality insurance has been concentrated on this point. The presented simulations show, that the effectiveness of the vapour barrier is not so important. The main effort should be on preventing the driving rain.

References

Brandt E (ed.) (2009) Fugt i bygninger (SBi-anvisning 224) (Moisture in buildings, SBi Guidelines 224), Danish Building Research Institute, Aalborg University, Denmark.

Co2ol Bricks, Co2ol Bricks – Climate Change, Cultural Heritage & Energy Efficient Monuments, Baltic Sea Region project COOL Bricks 2007- 2013, Social Affairs and the Priority 1: Fostering Innovations of the Baltic Sea Region Programme 2007 – 2013.

Hagentoft C-E. (2011) Probabilistic analysis of Hygrothermal conditions and mould growth potential in cold attics. Impact of weather parameters, building systems and construction design characteristics, XII DBMC, International Conference on Durability of Building Materials and Components, Porto, Portugal.

Häupl P, Jurk K and Petzold H (2003) Inside thermal insulation for historical facades, Research in Building Physics and Building Engineering, Taylor Francis group, London, 345-352.

Heiselberg P and Brohus H (2007) Application of sensitivity analysis in design of low energy office buildings, Department of Civil Engineering, Aalborg University, Denmark.

Hopfe C J (2009): Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization, Doctoral thesis, Eindhoven University, The Netherlands IBPT International Building Physics Toolbox, Users guide to the IBPT – A brief manual (2002), Danish Technical University and Chalmers University of Technology.

Jensen JM and Lund H. (1995) Design reference year, DRY – et nyt dansk referenceår (Meddelelse 281), Thermal Insulation Laboratory, Danish Technical University.

IEA annex 55. Reliability of energy efficient building retrofitting – probability assessment of performance and cost (RAP-RETRO) www.iea-rapretro.org

Kleijnen J P C. (1995) Sensitivity Analysis and Related Analyses – a Survey of Statistical Techniques, International symposium SAMO95 – Theory and applications of Sensitivity Analysis of Model Output in computer simulations, Italy.

Nielsen A. (1987) Fuktteknisk dimensjonering med statistikk. En metode for vurdering av risiko for byggskader. [Moisture design with statistics. A method for evaluation of building damages], BFR, Sweden R89:1987

Nielsen A. (1995) Use of statistics for prediction of condensation in a wall construction, International symposium Indoor Air Quality in Practice, Moisture and Cold Climate Solutions, NIF, ISIAQ, Oslo, Norway.

MATLAB version 7 with SIMULINK www.mathworks.com

Munch-Andersen J. (2008) Efterisolering af etageboliger (SBi-anvisning 221), (Improving Insulation of Multi-storey Houses, SBi Guidelines 221). Danish Building Research Institute, Hørsholm, Denmark.

Saltelli A et al (2004) Sensitivity Analysis in Practice. A guide to Assessing Scientific models, John Wiley & Sons, England, ISBN 978-0470-87093-8.

Scheffler G and Grunewald J. (2003) Material development and optimisation supported by numerical simulation for a capillary-active inside insulation material, Research in Building Physics, A A Balkema Publishers, 463-469.

SIMLAB version 3.2.9 simlab.jrc.ec.europe.eu

Valdbjørn Rasmussen, T. (2010) Post-insulation of Existing Buildings Constructed Between 1850 and 1920. In R. Karney (Ed.), Buildings XI, International Conference, Thermal performance of the exterior envelopes of the whole building XI, December 5-9, 2010.

Vereecken E and Roels S. (2011) A numerical study of the hygrothermal performance of capillary active interior insulation systems, 9th Nordic Symposium on Building Physics, Tampere, Finland, 365-372.

Wit S and Augenbroe G (2002) Analysis of uncertainty in building design evaluations and its implications, Energy and Buildings, 34 (2002) 951-958.

Zhao J et al (2011) Stochastic study of hygrothermal performance of a wall assembly – The influence of material properties and boundary coefficient, HVACR Research, 17:4, 591-601.