How to estimate material properties for external walls in historic buildings before applying internal insulation

E.J. de Place Hansen and E.B. Møller

Danish Building Research Institute, Aalborg University Copenhagen (AAU Cph), Copenhagen, Denmark. Email: ejp@sbi.aau.dk; evm@sbi.aau.dk

Abstract – Before deciding how to improve the energy efficiency of historic buildings by applying thermal insulation, an estimation of consequences, e.g. changes in heat and moisture flux, must be made. When applying internal thermal insulation to external walls, estimations are most likely made by hygrothermal simulations, which require information on material properties. These could be determined by tests, but full testing can be comprehensive. Instead, the planner is more likely to use materials already included in the simulation tool. But how to choose the best material? In the EU-project RIBuild, attempts have been made to cluster historic building materials; enabling a user to choose an appropriate material and include uncertainties. Brick clusters were created based on material properties, all equally important. However, these input clusters differed from clusters based on output from hygrothermal simulations, indicating that not all material properties were equally important. Unfortunately, the decisiveness of properties depended on whether e.g. conditions at external or internal surface of the brick wall were considered.

Keywords – clustering; failure mode; historic building materials; internal insulation; material properties

1. INTRODUCTION

Historic buildings built before 1950 make up 30 percent of the European building stock [1], and are often poorly thermally insulated, but with architectural or cultural values, especially related to solid external walls. In these cases, the possibilities for external thermal insulation are limited. This calls for robust and permanent, reversible energy-efficient internal solutions, otherwise the building owner will not be motivated to initiate energy savings unless he is forced. However, no matter whether internal insulation is promoted voluntarily or mandatory, it should be based on scientifically based risk assessment and Life Cycle Analysis [2].

The aim of the EU-project RIBuild (Robust Internal Thermal Insulation of Historic Buildings) [3] is to ensure robust solutions with internal thermal insulation in historic buildings and to guide a building owner when he considers renovating such a building. The building owner needs to know how much internal insulation it is safe to apply to a solid external wall. In engineering practice today, simple calculation methods are often used to access moisture risks; they require a minimum of material properties and boundary conditions, in some cases this might be sufficient. In RIBuild, a solid external wall will be used as reference for hygrothermal simulations. Results of simulations, including different kinds and thicknesses of internal insulation added to the reference wall, will be compared to threshold values for different failure modes to determine whether the solution is sufficiently robust or not. However, to create a tool that enables this, several steps must be taken: defining the wall structure, choosing the simulation tool, determining material properties needed for simulation, as well as location and orientation of the wall, and defining threshold values for different failure modes. This paper focuses on material properties using bricks as case, being the most common material in external walls of historic buildings [4].

2. CLUSTERING OF BUILDING MATERIALS BASED ON MATERIAL PROPERTIES

2.1 AVAILABLE MATERIAL PROPERTIES

Several material properties are needed to fully describe the hygrothermal behaviour of historic building materials. Moisture transport in building materials depend on numerous hygric properties, other properties describe heat transport, and finally heat and moisture transport are interlinked. RIBuild has shown that complete sets of material data required by hygrothermal simulation tools like Delphin [5] or WUFI [6] are rare; for most specific materials, a set of data was complete only if the material was found in a database used by such a tool [7]. Furthermore, calibrated material functions are needed, i.e. test results should be further processed before they can be used in the simulation tool.

The question is how a building owner can decide whether one of the materials included in the simulation tool represents the material that his building is made of. Often only a few properties are known, e.g. density, water uptake coefficient or other properties that are easy to determine. However, a complete test of all material properties, although minimising the uncertainties, is expensive and time consuming. This is why RIBuild used clustering of materials; to group materials with similar material properties, i.e. materials having more in common with each other than with the remaining materials, expecting their hygrothermal performance to be similar as well. By placing a specific type of brick with only a few known material properties in a cluster of bricks, it is possible to estimate the missing properties. However, by performing simulations based on clusters, the outcome will include uncertainties, making it clear what is lost when the high cost of complete testing is saved.

2.2 INPUT CLUSTERING

Clustering was based on twelve material properties (input data) of 44 bricks where a complete set of material properties were available, including ten properties studied by Zhao et al. [8], [9] as well as bulk density and water vapour permeability (wet cup value). All properties were represented by single numbers; properties that are normally expressed by sorption isotherms and suction curves were represented by single points on the curves. Further, they were all considered equal and the clustering itself was based on multivariate Gaussian distributions, where the covariance structure was allowed to vary as well as the number of mixture components [10], [11]. The number of clusters and the underlying covariance structure was selected based on the Bayesian Information Criterion (BIC).

Some material properties were expected to be more decisive at clustering than others. Identifying the most decisive properties could reduce the number of tests and would make it easier to place materials in the right cluster. To gain insight into the material property importance, as well as being able to classify new materials according to the identified clusters, a classification tree was trained to the un-weighed data [12]. If the classification tree was general for all bricks, and not only for the 44 with a complete set of material properties, other bricks with incomplete data set could be handled by imputing missing values by a principal component based method [13]. Five clusters of bricks were identified using this approach [7].

Cluster analysis based solely on un-weighed material properties as done in [8] and in this study, may lead to clusters that not necessarily perform hygrothermally alike, e.g. expressed by temperature, relative humidity or moisture content. Therefore, clustering based on output data from hygrothermal simulations were performed as well. If this analysis could identify the hygrothermally most decisive material properties, these could be weighed accordingly in an input clustering. In the end, a user will only have access to input, and should therefore be able to choose an appropriate input cluster based on a few available material properties.

3. IMPACT OF MATERIAL PROPERTIES ON HYGROTHERMAL BEHAVIOUR

3.1 TYPE OF ANALYSIS

Impact characterisation is often done by a sensitivity analysis, simulating the same situations with stochastic variations of one variable at a time, e.g. through Monte Carlo simulations. However, bricks are described by several properties, some of which are correlated. Random combinations of properties could therefore mean simulation with unrealistic bricks. Instead, a modified sensitivity analysis was done based on 44 types of bricks from the Delphin database, i.e. the only variation is the brick. The robustness of clustering based on output data from simulations, is evaluated by including two Danish locations (weather data) and two constructions; a solid masonry wall with plaster on the inside and the same wall with internal insulation, resulting in 176 simulations made with the software DELPHIN ver. 5.8.

3.2 BOUNDARY CONDITIONS

The walls included in the simulations are one and a half brick thick with no insulation and with 50 mm of a CaSi based insulation system, respectively. The walls were SW oriented using weather data from the EU-project Climate for Culture [14]. Two Danish locations were used. Internal climate corresponded to humidity class B [15]. Output from the simulation describing how materials in the wall behaved to the exposure were represented by temperature, relative humidity and moisture content at two specific positions within the wall; close to the external and internal surface of the brick wall, respectively, as shown in Figure 1.

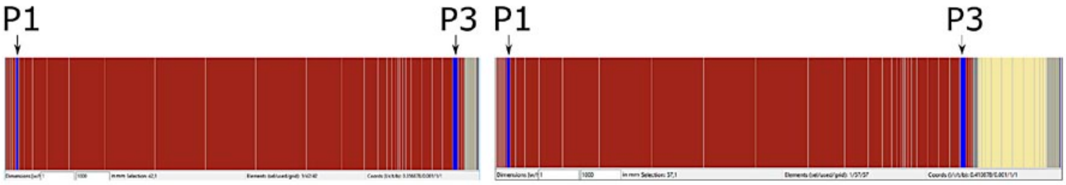


Figure 1. Delphin modes' construction detail. Not insulated wall (brick and plaster; left) and insulated wall (brick, glue mortar, CaSi insulation and plaster; right). Exterior to the left. Analysis of output data focused on results 9 mm from the exterior (P1) and 7.5 mm from the brick/plaster interface (P3).

Moisture content was chosen as the decisive parameter in the output clustering analysis as it showed the highest variability. Furthermore, moisture is more decisive than temperature in most failure modes, and by using moisture content, instead of relative humidity, the temperature dependency is avoided. Further details about input and output data are given in [7].

3.3 CLUSTERING BASED ON OUTPUT DATA

To create clusters, the bricks were ranked after 'Sum of moisture content' representing the area under the moisture content vs time curve for a given time period, or the median of the moisture content for this period. Figure 2 shows an example using these approaches.

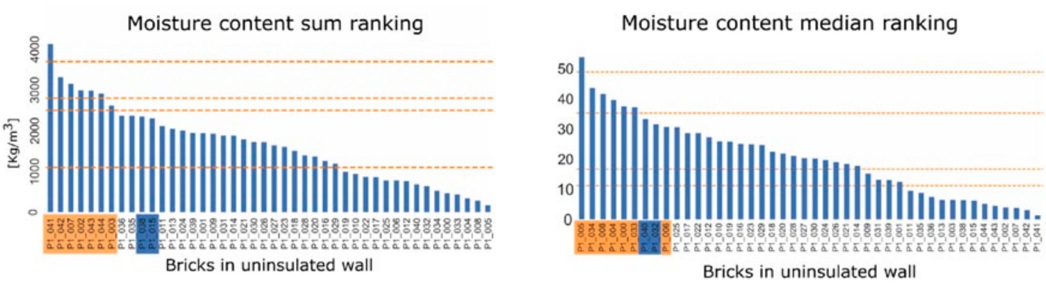


Figure 2. Ranking of bricks based on sum of moisture content (left) and moisture content median (right) at the exterior of a SW oriented 1½ brick thick wall without insulation. Location Copenhagen, winter 2026–2027 (Dec 1 to Mar 1). The seven highest-ranking brick types in the sum diagram (left), marked with orange, are in the median diagram (right) mixed with two other brick types marked with blue in both diagrams.

Focus was on winter conditions and bricks with high moisture content, as they are probably most important when it comes to failure modes. Six of the seven highest-ranking brick types in the left part of Figure 2 (sum of moisture content) were also highest-ranking in the right part (median); i.e. sum and median approaches resulted in similar clustering, which in general was the case in this study.

However, comparing results at different positions within the wall, showed that the clustering was dependent on whether it was based on output at the external or internal surface, cf. Figure 3. This indicates that the failure mode would be important, as high moisture content at the external surface (P1, Figure 1) is critical in relation to frost damage, and high moisture content in bricks close to the brick-plaster interface (P3) is critical when it comes to mould growth.

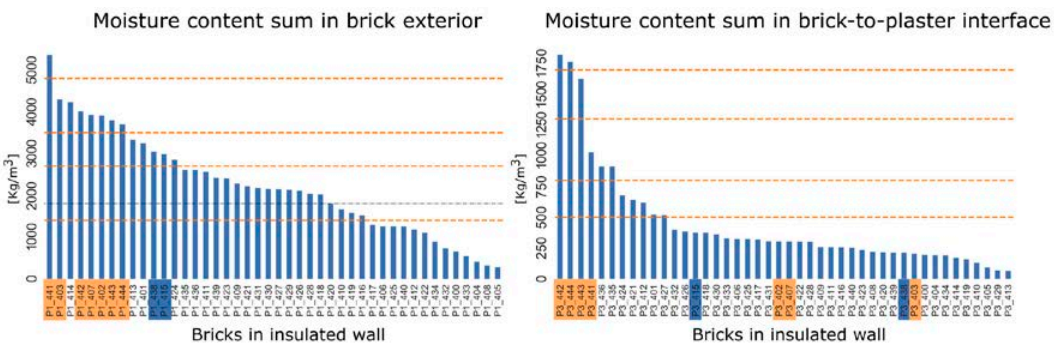


Figure 3. Ranking of bricks based on sum of moisture content at the exterior (left) and the brick-plaster surface (right) of an insulated 1½ brick thick SW oriented wall. Location Copenhagen, winter 2026–2027 (Dec 1 – Mar 1). Bricks marked with orange and blue boxes refer to the highest-ranking bricks in Figure 2.

3.4 IMPACT CHARACTERISATION

If bricks in a specific cluster, identified as described in section 3.3, have a considerable lower variation in certain properties than for bricks in general, these properties are likely to have a high impact. Figure 4 shows the result of this approach used at open porosity, thermal conductivity, specific heat capacity and effective saturation moisture content. A prerequisite for the approach is that a high moisture content in bricks is important when evaluating the robustness of internal insulation systems.

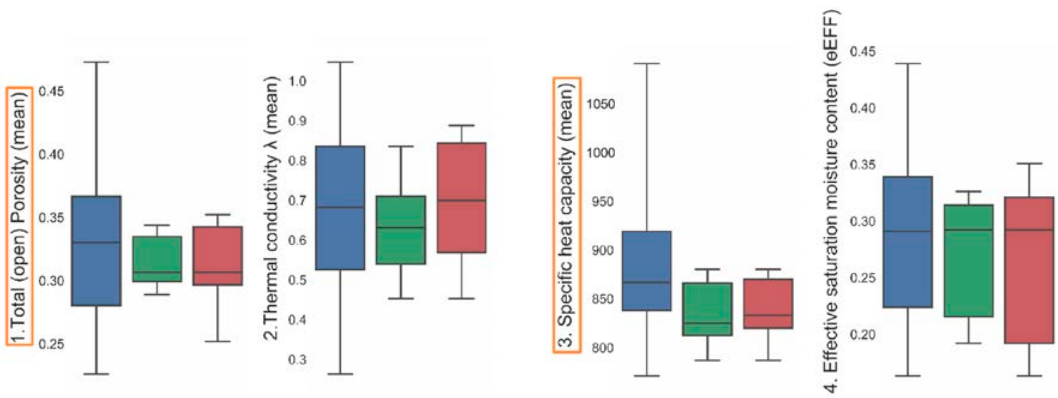


Figure 4. Variation of open porosity, thermal conductivity, specific heat capacity and effective saturation moisture content for 44 types of bricks in total (blue boxes), the upper cluster consisting of six types of bricks in a not insulated wall (green), and the upper cluster consisting of eight types of bricks in an insulated wall (red). Boxes mark 25 and 75 % quantiles. Upper clusters are identified as shown in Figure 2 and Figure 3.

Figure 4 indicates that open porosity and specific heat capacity do have more impact than thermal conductivity and effective saturation moisture content. In the two first cases, the variation for the upper clusters (green and red boxes) was considerably lower than for the bricks in total (blue boxes), while this was not the case for the two other parameters. Further, bulk density was identified as having a high impact [7].

4. DISCUSSION

4.1 MOISTURE PROPERTIES AND FAILURE MODES

The decisive material properties presented in section 3.4 are only true in the described situation and only when considering moisture content. If e.g. temperature is considered, thermal conductivity is probably of high importance as well. It is therefore likely that the importance of the material properties depend on what output is considered, which leads to the discussion of which failure mode should be considered. Opposed to the findings in section 3 concerning decisive material properties or not, the HAMSTAD project [16] found that HAM results depend strongly on the detailing and quality of material characterization. The discrepancies might be caused by different focus. While HAMSTAD is more focused on the accuracy of simulations, the aim of this paper is more practical; to facilitate the use of HAM simulations by making it easier for users to choose the right materials for simulations and help deciding what is the most important material properties to test.

Further simulations are suggested before discarding the idea of some material properties being hygrothermally more decisive than others, at least in some critical situations or failure modes. Likewise, simulations including other building materials than bricks could help defining within what range material properties seem to be less important than e.g. the weather. However, for the time being, in practice it may be of less importance which brick is chosen compared to other parameters, as long as the material parameter of the brick is within a certain range.

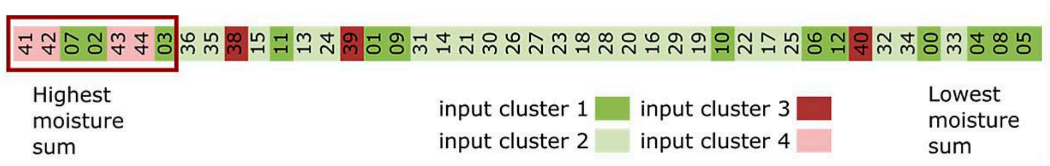
4.2 SETUP OF CLUSTERING

Moisture content [kg/m^3] was chosen as the best measure to compare bricks that perform hygrothermally alike, cf. section 3.2. The findings concerning clustering rely solely on a high moisture content in the winter and the output (moisture content) near the exterior surface. This leads to a ranking biased towards moist conditions and may thereby only be valid for the walls' behaviour under very humid conditions. However, a biased result is justifiable assuming that the relevant failure modes prevail under high levels of moisture content.

The ranking of the bricks varied in the different scenarios although the same outcome (moisture content) was considered. It was therefore by falsification shown, that the decisiveness of material properties is not unique. However, further simulations can be made by varying several parameters, using quasi Monte Carlo methods. In this way, trends toward which material properties are the most decisive for some failure modes, could appear.

4.3 IMPACT CLUSTERING

For the input clusters twelve material properties were used (section 2). The impact characterisation was based on bricks ranked according to simulation outputs followed by output clusters (section 3.4). Had output and input clustering matched, all material properties would have been equally important. Figure 5 illustrates that this was not achieved.



Ranking of bricks is according to sum of moisture content and therefore a representation of output clustering. Brick with highest and lowest sum of moisture content at left and right, respectively, referring to the ranking at Figure 2, left. Box represents upper output cluster, marked with orange at Figure 2, left. Colours represent input clusters. Ranking of bricks do not compile with input clustering.

A second location with a slightly different climate combined with a higher precipitation catch ratio and a lower drying potential, expressed by a lower absorption coefficient (short wave radiation) giving more extreme conditions, was included to test the robustness of the clustering presented in section 3.3. It showed another ranking of bricks with a high moisture content, indicating that changes in boundary conditions, e.g. microclimate, with the current methodology influence the clustering and possibly conclusions drawn from this.

In Delphin, bricks are not only described by the twelve material properties represented by single numbers; additional functions (calibrated material functions) are used to describe the materials. This could explain some of the differences between input and output clusters, especially because very moist conditions have been used in the examples. One of the findings in input clustering was that neither sorption nor suction curves were important [7], which may be because they are represented by one single point each. Adding more points as single material properties would probably not change this, as each point would be considered as a material property. Maybe the curves should be represented in another way. One possibility could be to present them as simple functions like in [17] and use the coefficients as parameters.

Clustering requires a threshold value or any other clustering criteria. The current study has not aimed to define such criteria; a simple threshold value has been used (sum of moisture content). This may provide inappropriate clusters as important details may escape, e.g. a failure mode that priorities long duration of relative high moisture content rather than short duration of even higher moisture content.

5. CONCLUSIONS AND FURTHER STUDIES

It has been investigated whether and how decisive material parameters for hygrothermal simulation outputs can be identified for historic building materials (bricks). It was found that:

1) Clustering of materials based on un-weighed material properties (input clusters; section 2) did not correspond to clusters based on moisture content close to the exterior of a masonry wall (output clusters; section 3), indicating that not all material properties were equally important.
2) Clustering based on moisture content at a specific depth in a masonry wall may not correspond to clustering based on moisture content in another depth; indicating the specific failure mode to be an important parameter. The cluster analysis did focus on extreme situations, e.g. situations in which failure modes may occur.
3) Other parameters in hygrothermal simulations may be more important than material properties, assumedly when the properties are within a tolerable range, e.g. weather or longwave radiation and precipitation catch ratio

At present it is not possible to tell the user of a simulation tool which material properties are the most important when choosing a material from the material database. Further clustering may reveal tendencies or even the possibility to determine the most decisive material properties if some of the more complex material functions e.g. can be represented by functions rather than single points on curves.

6. ACKNOWLEDGEMENTS

RIBuild has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 637268. Associate Professor Torben Tvedebrink and Research Assistant Simon B. Jørgensen, AAU have performed the clustering presented in this paper.

7. REFERENCES

[1] European Commision. Energy-efficient Buildings PPP. Multi-annual Roadmap and Longer Term Strategy. Brussels, 2010.

[2] E.J. de Place Hansen. "Improving the energy performance of historic buildings with architectural and cultural values" in Interdisciplinary perspectives for future building envelopes, Proc. 8th International Conference on Building Envelope Systems and Technologies. A. Tavil and O.C. Celik, Ed. Istanbul: Istanbul Technical University, 2017, pp. 648–658.

[3] Robust Internal Thermal Insulation of Historic Buildings. Available: www.ribuild.eu [Feb. 1, 2018]

[4] A. Blumberga, D. Blumberga, E. Kamendere, A. Kamenders, K. Kass, R. Purvins and G. Zogla. Report on historical building types and combinations of structural solutions. RIBuild Deliverable D1.1, 2015. Available: www.ribuild.eu [Feb. 1, 2018]

[5] J. Grunewald. Diffusiver und konvektiver Stoff-und Energietransport in kapillarporosen Baustoffen. PhD Thesis, TU Dresden, Dresden, 1997.

[6] H.M. Künzel. Simultaneous Heat and Moisture Transport in Building Components. One- and two-dimensional calculation using simple parameters. Fraunhofer IRB Verlag Stuttgart, 1995.
[7] E.B. Møller. Report on material properties. RIBuild Deliverable D2.1, 2018. Available: www.ribuild.eu [Feb. 1, 2018].
[8] J. Zhao, R. Plagge, N.M.M. Ramos, M.L. Simões and J. Grunewald. “Application of clustering technique for definition of generic objects in a material database.” Journal of Building Physics, vol. 39, no. 2 pp. 124–46, 2015.
[9] J. Zhao, R. Plagge, N.M.M. Ramos, M.L. Simões and J. Grunewald. “Concept for development of stochastic databases for building performance simulation. A material database pilot project.” Building and Environment, vol. 84, pp. 189–203, 2015.
[10] C. Fraley and A.E. Raftery. “Model-based Clustering, Discriminant Analysis and Density Estimation.” Journal of the American Statistical Association, vol. 97, pp. 611–631, 2002.
[11] C. Fraley, A.E. Raftery, T.B. Murphy and L. Scrucca. mclust Version 4 for R: Normal Mixture Modeling for Model-Based Clustering, Classification, and Density Estimation, 2012.
[12] L. Breiman, J.H. Friedman, R.A. Olshen and C.J. Stone. Classification and Regression Trees. Wadsworth. 1984.
[13] J. Josse and F. Husson. “missMDA: A Package for Handling Missing Values in Multivariate Data Analysis”. Journal of Statistical Software, vol. 70, no. 1, pp. 1–31, 2016. doi:10.18637/jss.v070.i01
[14] D. Jacob and L. Kotova. High-resolution datasets for the different IPCC scenarios for selected Case Study areas as input data for hygrothermal building simulation and complete high resolution dataset over entire Europe. Hamburg, 2013. Available: https://www.climateforculture.eu/index.php?inhalt=download&file=pages/user/downloads/project_results/D_01.2_final_publish.pdf [Feb. 1, 2018].
[15] EN 15026:2007. Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation. Brussels: European Committee for Standardization, 2007.
[16] HAMSTAD. Determination of liquid water transfer properties of porous building materials and development of numerical assessment methods. Available: https://cordis.europa.eu/project/rcn/53129_en.html [Feb. 1, 2018].
[17] K.K. Hansen. Sorption isotherms. A catalogue. Technical report 162/86. Lyngby: Technical University of Denmark, Dept. of Civil Engineering, Building Materials Laboratory, 1986.