Fit for purpose brick clustering for hygrothermal material properties: sensitivity to climate conditions.

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Abstract. Historic masonry has a rich and colorful history making it a treasured part in our society. To preserve and protect this heritage, adequate moisture control, retrofit and restauration strategies are required. However, due to the large range of material properties, inherent to historic brickwork, measuring every single parameter for every case and each material is unfeasible. In prior research, a clustering scheme was developed for 15 bricks, representing the wide variety in practice. The basic concept was that bricks with similar hygrothermal response behavior are clustered together based on their physical appearances. This could help improve existing retrofit practice by reducing characterization processes and minimizing expensive and time-consuming measuring tests. In the clustering process, a high dependency on the rain exposure was noticed. Climate and geographical location define the severity, duration and the number of rainfall events which have a direct impact on the liquid water penetration depth, the moisture content and distribution in the wall. Therefore, the aim of this study is to test the robustness of the developed methodology for brick clustering in different climate conditions. A comparison is made between the Test Reference Year of Essen, the Moisture Reference Year of Brussels and the climate conditions of Milan and London. The response behavior was evaluated based on hygrothermal simulations to see whether bricks in the same cluster show similar degradation risks under different climate conditions. Sensitivity analysis was used to study the response behavior based on three degradations risks: mould growth, wood rot and frost damage.

INTRODUCTION

Throughout Europe, valuable historic buildings are found in different forms and various places. Because of their rich history and the fact that they form an indispensable part of our society, the preservation and protection of these treasures against the harsh weathering conditions and climate change should be considered with great care [1], [2], [3]. This is not an easy task: historic brickwork is a very complex material which manifests itself in a wide variety of physical and aesthetic aspects [4], [5], [6]. Unfortunately, the characterization process of the materials complicates renovation and restauration projects. A reliable renovation study that quantifies the impact of a retrofit application requires the thermal as well as the hygric material properties, these can be determined by extensive laboratory tests, such as mercury intrusion, pressure plate, sorption isotherm test, etc. This is not self-evident since taking samples of historic buildings is not always possible or allowed. Additionally, a complete characterization of a material is a lengthy and very complex task as the accuracy of the transport and storage functions for moisture is challenging. On the other hand, a stochastic approach could be used to perform risk assessment and address both the uncertainty and variability of material properties [7]. Within this method, a dataset, based on latin hypercube sampled set of material properties, is simulated to incorporate the variability. The experimental as well as the stochastic method require a lot of time and effort for testing and computational expense respectively. Therefore, Zhao proposed a clustering analysis to reduce the characterization time for materials [4]. The analysis generates homogenous brick clusters which should behave in the same manner based on the physical appearances of the materials. His approach allows, using arithmetic averaging, the creation of a generic material which represents the whole cluster. This idea was later expanded and updated by Vanderschelden et al [8]. In the latter, it was pointed out that the creation of homogenous material clusters should not be developed by solely considering material properties. One should also include the response behavior of materials and the assembly. There, with sensitivity analyses, the relation between the physical properties and the response behavior was defined, and this updated clustering methodology led to a more precise and accurate response prediction within a cluster. The approach was tested for the climate conditions of Essen and showed a high dependency on the wind driven rain loads [7], [8]. Therefore, within this study the impact of the climate conditions on the methodology for clustering is analyzed, especially the impact of different wind driven rain loads. Four different locations in Europe were evaluated: Essen, Brussels, Milan, and London. The results confirm that the response behavior is highly related to the rain loads and, in this way, also to the climate type. It is recommended to use a fit for purpose analysis for the clustering methodology which considers regional materials, local climate conditions, typical construction methods, relevant material degradation or pathologies and local performance criteria.

METHODOLOGY

To determine the similarities in physical properties of materials, cluster analysis can be used. A cluster provides the opportunity to generate generic materials which will be a representative material for the complete cluster. A cluster analysis is a multivariate procedure that defines the similarities between objects within a natural group and the difference with individuals of another group [9]. It is a widely used method in the field of biology, psychology, and market research to organize and process big data based on a classification approach. In the research by Zhao, the dissimilarity, and by extension the similarity, is measured by the distance between elements. The absolute distance between material properties was calculated with the Euclidean distance and the clustering was performed according to the Wards method [4]. The latter is in literature also referred to as the minimum variance method. It determines the objects, or already established clusters, in which a fusion will result in the lowest increase of the sum of the squared distances between the objects or cluster centroids. This approach by Zhao results in a clustering scheme that only considers the physical properties of the natural group. In the research by Vanderschelden [8], the cluster analysis was extended by considering the relation of material properties and their hygrothermal response behavior. The study was performed using binary Poisson distribution classification trees, as it showed promising results according to Calle [7]. Such a tree is derived from a top-down segmentation-based sensitivity analysis. A dataset or subset is divided with increasing homogeneity based on the variance of the (sub-)set. The step-by-step splitting is based on the parameter which causes the largest heterogeneity within the set. Hence, the most important variables, which consequently induce the largest variance in the output, appear on top in the classification tree [10]. In this study, the cluster methodology is extended with the impact of climate conditions. The impact of different climates and wind driven rain loads on the clustering methodology of Vanderschelden [8] was tested with the same stochastic approach. A sampled set of 7500 masonry wall setups was simulated for four different locations with Delphin 5.9. Within the samples set 11 parameters were considered variable: masonry thickness, rain exposure, brick type, density, specific heat capacity, open porosity, effective moisture content, thermal conductivity, water absorption coefficient, vapor diffusion resistance factor and effective liquid conductivity.

Sample construction

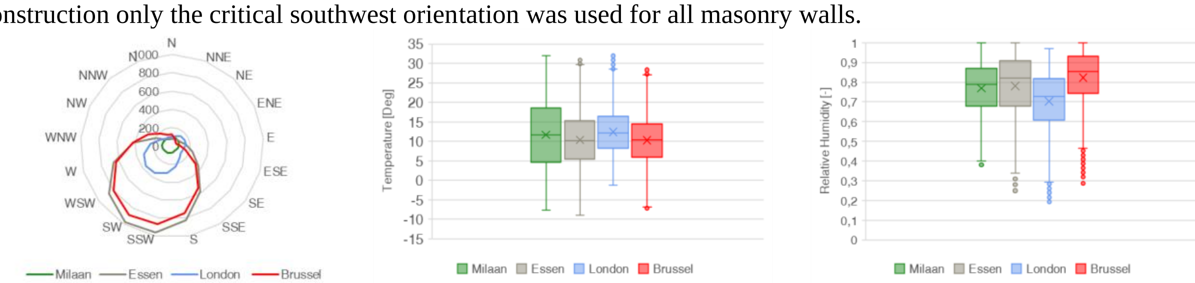
In this study, a historic masonry wall was selected as application to conduct the analysis. The assembly was constructed as a single leaf masonry with historic brickwork and an interior historical plaster without vapour barrier. The masonry was abstracted to a homogenous brick layer to reduce the computational expense. The variability in brick types was considered by adopting the 15 bricks reported by Zhao [4], which are available in the Delphin software. All materials are listed in Table 1. with their ID-number for the IBK database [11].

TABLE 1. Summary of the applied brick types and historical plaster with the ID number for the IBK database [11]

Material	ZA	ZB	ZC	ZD	ZE	ZF	ZG	ZH	ZI	ZK	ZL	ZM	ZN	ZO	ZQ	Plaster
IBK-ID	490	533	491	492	493	494	495	496	497	499	500	501	502	503	286	148

For each brick type a latin hypercube sampling of 500 samples was created to represent the natural variability in brick properties, which also includes the minor defects in experimental measuring processes. Furthermore, the wall dependent variables consist of wall thickness (T) and wind driven rain exposure coefficient (RE). The thickness was randomly varied between 150 and 500 mm. The rain exposure varies in practice depending on the wind direction, location on the façade, height, surroundings, and building geometry, and ranges in the model between 0 and 2. These limits are set to incorporate the effects of overhanging roofs and bad detailing of gutters respectively [7]. The simulations were performed in Delphin 5.9 according to EN 15026 [12], with post processing in Matlab and R- 4.1.2.

Four different climate types were considered in this study, since climate and geographical location will define the severity, duration, and the number rainfall events which in turn have a direct impact on the liquid water penetration depth, and moisture content and distribution in the wall. The first climate considered was the Test Reference Year (TRY) of Essen, 2010 [11]. The Moisture Reference Year (MRY) of Brussel, 1987, was the second climate type. This MRY was determined by Vandemeulebroucke et al. as the 3rd most severe year in a 30-year period considering the wind driven rain as ranking criterion [13], [14]. It represents the climate conditions which will occur once every 10 years. The data for London was gathered by Met Office and analyzed by Lu [15]. The year 1999 was selected to represent the near-extreme reference climate, as the annual rainfall was closed to the 90th percentile of a 15-year dataset [15]. The data for Milan was derived from the climate database of Delphin [11]. The longwave radiation in the database was absent but was calculated according to the Boltzmann calculation [16], [17]. Even though the different climate files were constructed with different approaches, the intent of this paper is only to cover a relevant range of climates. A comparison for the most basic climate parameters, such as the outdoor temperature and relative humidity, is provided in Fig 1. In graph (a), in which the wind driven rain is compared, there is a large difference for the rain loads but the critical orientation for façade systems was similar for the different locations. Therefore, within the sample construction only the critical southwest orientation was used for all masonry walls.



(a) (b) (c)

FIGURE 1: Summary of climate variables: (a) comparison for the wind driven rain (b) comparison for the outer temperature (c) comparison for the outer relative humidity

Performance criteria

Three different performance criteria for the wall assemblies were adopted in the hygrothermal assessment. First, the risk on frost damage was quantified by the number of freeze-thaw cycles at a depth of 5 mm from the exterior wall surface. The threshold for the critical moisture content was set to 25% based on the study by Mesinga on Canadian brickwork [18]. In addition, mould growth was calculated on the interior surface since it could be harmful to the occupant's health. To quantify the relative difference in growth, the updated numerical prediction model developed by Hukka and Viitanen was used [19], [20]. In this model, the growth is categorized with a mould index value varying from 0 to 6 with increasing mould coverage, respectively from zero spore's activation up to a 100% mould coverage. The mould index is calculated with the surface relative humidity and temperature from the indoor plaster and includes an exposure time component. The time indication will determine if the mould is in a growing phase or in a delay of growth. The third and final performance criterion relates to the degradation of wooden beams embedded in historic masonry facades. Such beams are typically used to support the flooring system and are vital for the structural integrity of the building. The risk for wood rot was quantified at 100 mm from the interior surface to represent a sufficient support length. The dose response model by Brischke and Rapp was used to determine the mean decay rating according to EN 252 [21]. The model determines a moisture and temperature induced daily dose, which was fitted to the mean decay rating of samples in 23 different European test sites under different climate exposures [22], [23].

RESULTS

Fig 2 gives an overview of the risk assessment results for mould growth, wood rot and frost decay for each city. Essen shows the most severe risk followed by Brussels. A higher resilience for decay was seen for London and Milan. The same division is found in Fig 1 (a) with the comparison of wind driven rain loads (WDR) for 16 different orientations. The critical WDR for Essen and Brussels is almost three times larger than in London and Milan. This means that the main moisture source in Essen and Brussels is assumed to come from rain loads on the façade system. In London and Milan, the moisture source in the façade could be more determined by the indoor moisture loads since the WDR is much lower. This hypothesis was confirmed by the sensitivity analysis for mould growth in Fig 4 and 5. In Fig 4, it is seen that for the high WDR climates (Essen and Brussels) the most significant parameters are related to the rainfall exposure and absorption of liquid water. For the more moderate climates with a low WDR (London and Milan) in Fig 5, the classification tree displays the parameters related to the risk of interstitial condensation i.e., the thickness and thermal conductivity. It highlights that in these dryer areas the dominant moisture source in the wall is the indoor moisture load and the clustering methodology should be performed for each climate type.

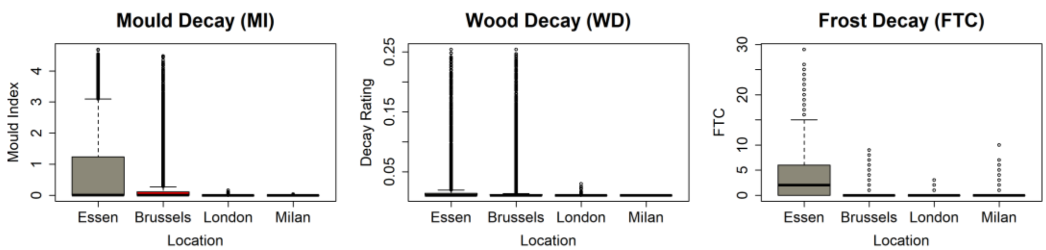


FIGURE 2. Overall performance results for three different performance criteria: mould growth (MI), wood decay (WD) and frost decay (FTC) for four different locations, respectively Essen, Brussels, London, and Milan

The results of the hygrothermal simulations were first used to test the original clustering method and generic materials of Zhao [4]. The same conclusion as in Vanderschelden et al [8] was derived in all four cities, where the generic material cannot be considered as representative material in terms of hygrothermal response behavior. Next, the updated material clustering methodology of Vanderschelden et al [8] was applied in the four cities.

It is seen that, the response behavior and climate are strongly intertwined, which entails that the full potential of a clustering analysis is only addressed in a fit for purpose approach where regional materials, typical construction methods, relevant degradation risks, and local climate conditions are consider. In this study, the individual clustering analyses are compared among cities with similar wind driven rain loads i.e., high, or low loads. For the higher rain climates, Essen and Brussels, the updated clustering schematic for brick types from Vanderschelden et al. [8] was applied and displayed in Fig 3. The distribution of the 500 simulation results for each individual brick type is ranked according to the clustering scheme [8]. The different clusters are color-coded and delineated with a dotted grey line. A clustering scheme can be considered reliable when the distribution of the results for risk predictions is similar for all elements in the clusters.

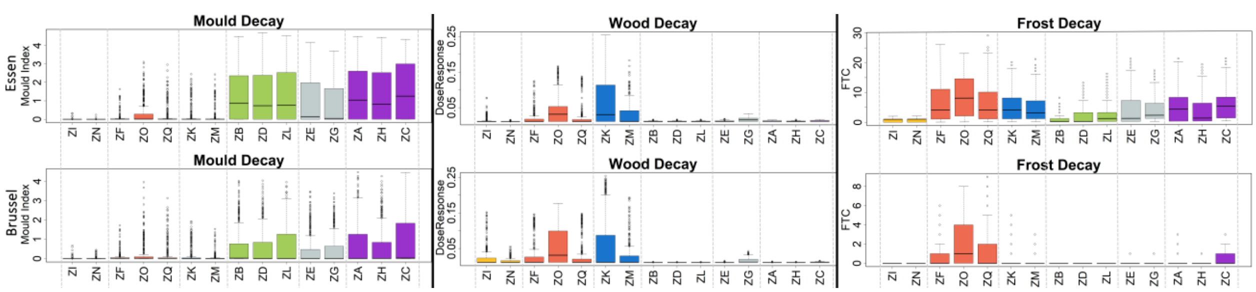


FIGURE 3. Clustering schematic for mould growth, wood rot and frost decay risk in a High Wind Driven Rain (HWDR) environment

The clustering results for Essen and Brussels in Fig 3 shows a visual similarity. The clustering scheme is able to cluster similar response behavior with a meaningful physical appearance in both cities. In Fig 4 a more, in-depth sensitivity analysis was applied on the results to determine the dissimilarities. The binary Poison distribution trees were established for Essen and Brussels for all considered performance criteria. In this paper, the criterion related to

mould growth will be discussed in detail. A large similarity is seen at the top of the classification trees and the only difference appears in the lowest level. So, the most significant parameters to quantify risk, are equal for the higher WDR climates. The most significant parameter is the rain exposure followed by the absorption coefficient, and the thickness of the masonry wall. The tree shows the degree of relevancy; however, it does not show the trendline. Therefore, a scatterplot is displayed for the most relevant properties on the right of Fig 4. It is clear that the risk for mould growth on the interior surface will increase when the assembly has a higher exposure to WDR. A clustering threshold value of 0.13 $kg/m^2s^{0.5}$ for the water absorption coefficient was calculated for Essen as well as for Brussels. It can be concluded that the updated methodology for clustering is valid and reliable for high wind driven rain climates concerning the mould growth risk on the interior. The conclusion was confirmed in an additional test for the colder climate of Fichtelberg in Germany for a similar rain load as Essen.
When focusing the differences on the tree, it is seen that the response behavior for Essen is furthermore defined by the liquid absorption of the brick whereas for the dryer climate of Brussels, the thickness will define the response behavior. It can be hypothesized that, the clustering in climates with higher rain loads is dominated by the rain exposure and the water absorption coefficient whereas for dryer climates the thickness and thermal conductivity will have a larger role.

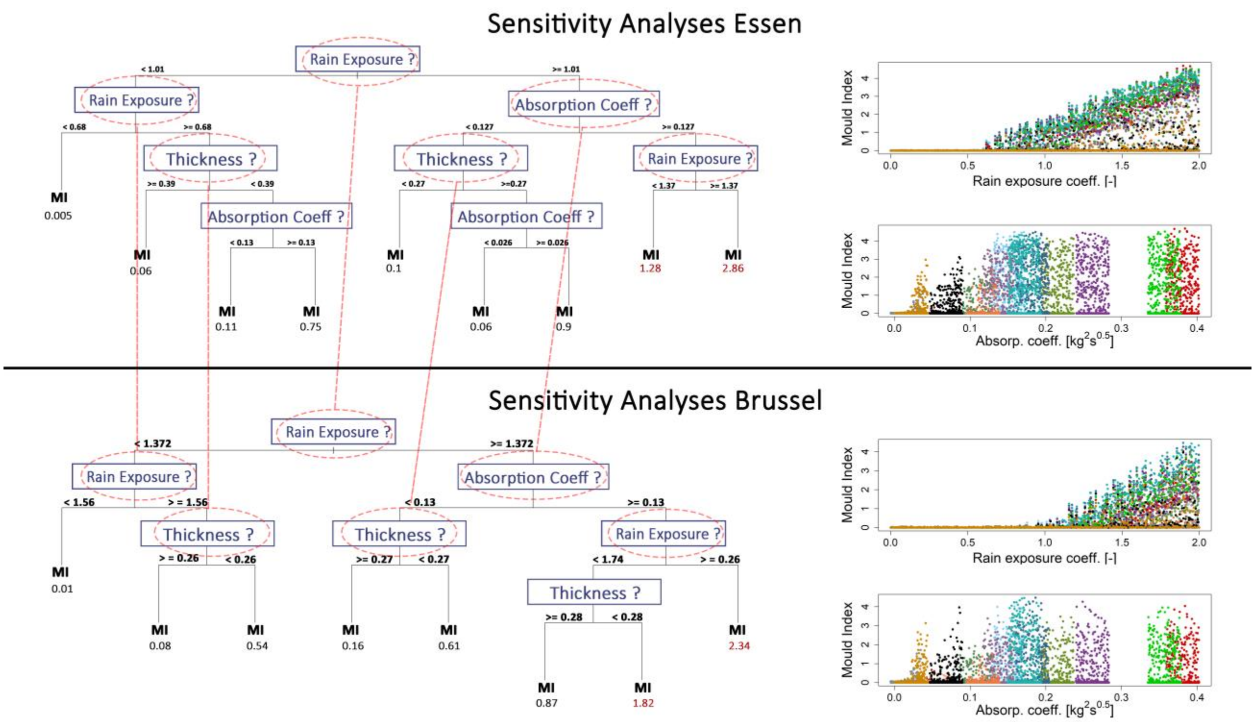


FIGURE 4. Sensitivity analyses for high Wind Driven Rain climates (Essen and Brussels), classification tree on the left and scatterplots on the right to assess which parameters affect mould growth risk (the 15 colors relate to the 15 brick types).

The low WDR climates, London, and Milan, show much lower risk for wood rot, frost damage and mould growth. Wood degradation even appeared absent in Milan and frost damage risk showed to be negligible in London. The latter is evident since the outdoor temperature only surpassed the freezing point 23 hours over the whole year with an extreme value of -1.3 degrees, Fig 1 (b). The performance results for the low WDR show large discrepancies with the high WDR climates. Therefore, the methodology for material clustering described in Vanderschelden et al. [8] was applied for the low WDR climate separately. The results are summarized in Fig 5 with the classification trees on the left and the scatterplots of the most significant parameters on the right. For both cities, within the low WDR climate, the absorption coefficient did not play a major role in the response behavior of the wall system. Instead, the thickness showed to be dominant, followed by the thermal conductivity of the brick. Both parameters have a direct impact on the temperature profile through the wall. The impact of the masonry thickness is most evident in the scatterplot for Milan: here, a general trend amongst the different bricks can be observed for which the highest risk coincides with the thinnest walls. In contract, the thermal conductivity shows an inverse correlation: the highest brick conductivity will entail the highest risk for mould growth.

In the scatterplots for London, some irregularities are noticed for the bricks with lower thermal conductivity (Fig 5, mould index > 0.015 in the scatter plot for London). Further analysis showed that the specific combination of thin walls, a high exposure to WDR, and high absorptive bricks yields extremer mould growth risks. In these cases, the moisture source is not only derived by the indoor environment but also partly by rain ingress, explaining the outliers.

After the analyses, it was concluded that for low WDR climates, the thermal conductivity is the most significant material property and should be used to define the different clusters.

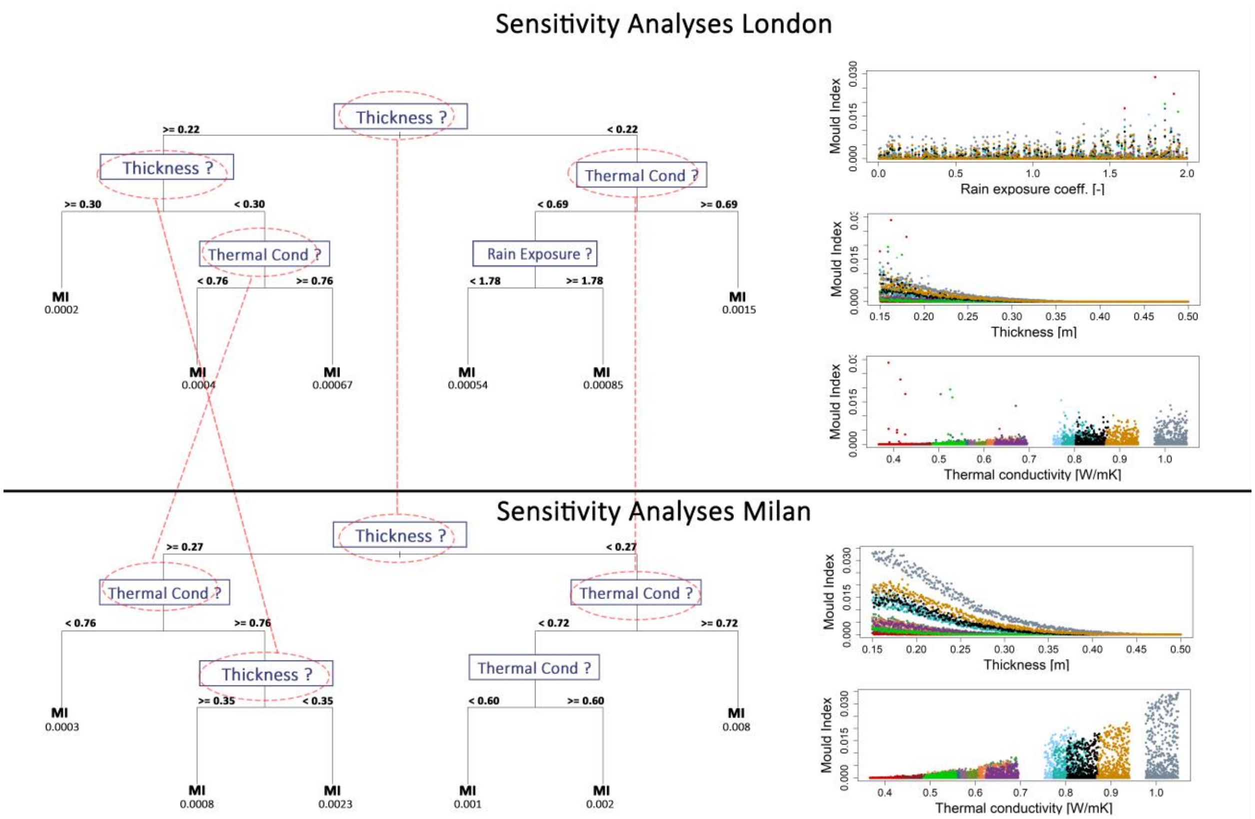


FIGURE 5. Sensitivity analyses for low Wind Driven Rain climates (London and Milan), classification tree on the left and scatterplots on the right to assess which parameters affect mould growth risk (the 15 colors relate to the 15 brick types).

The findings from the sensitivity analyses were used to derive a separate clustering schematic for both cities within the low WDR climate which is visualized in Fig 6. Three different clusters were defined based on the thermal conductivity of the bricks. For the mould growth, a good fit was achieved to represent similar behavior. For the wood rot initiation, it is seen that a low WDR climate could not benefit from clustering, since the severity of the wood decay risk is negligible or absent i.e., Milan. For frost damage, the thermal conductivity facilitated the clustering of bricks with similar behavior, however, some irregularities were noticed. It could be resolved by means of a more in-depth observation and analyses of the material properties in front of the clustering analyses in the classification tree.

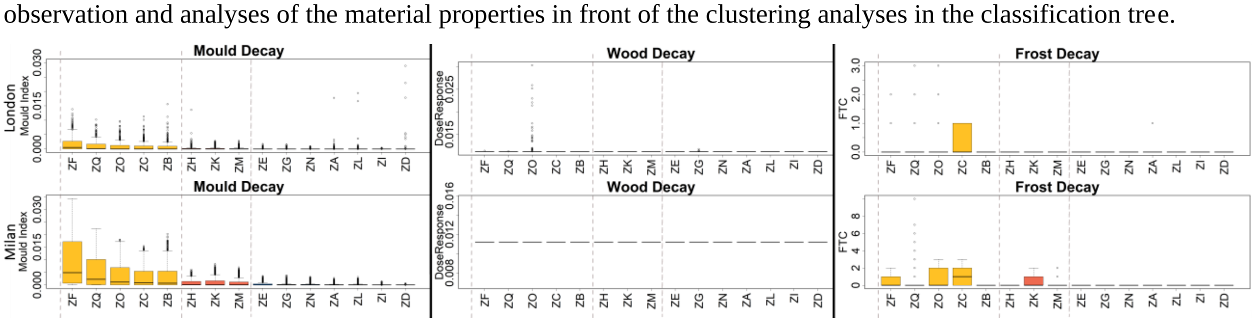


FIGURE 6. Clustering schematic for mould growth, wood rot and frost decay risk in a low Wind Driven Rain climate defined by the thermal conductivity

In the cities with a the low WDR climate, the analyses were performed for degradation risks that are almost negligible. This concludes that a clustering should be performed with a fit for purpose approach where relevant performance criteria are considered. In cities with a low WDR climate the performance problems could be more related to the thermal shock, salt crystallization, corrosion, thermal spalling, or bio-deterioration [23].

DISCUSSION

A single result for material clustering cannot be considered as universally valid. The clustering facilitates a fit for purpose analysis as it allows to balance regional materials, typical construction methods, relevant degradation risks, and local climate conditions. Therefore, in future research a broader spectrum of different climate types, such as colder or tropical climates, should be considered to determine the significant properties for different purposes. It was seen that for low WDR climates the impact of indoor climate was dominant. This renders the results only valid for the considered setup i.e. an uninsulated single-leaf masonry wall without vapor barrier. So, the updated material clustering methodology should be applied on different typical constructions methods and for different types of retrofitting.

Furthermore, it became clear that not only the severity of the risk is highly related to the geographical location but also the types of degradation. It is necessary to define the possible risks based on the boundary conditions and sensitivity of the applied materials. For example: a wall setup in a low WDR climate is not subject to severe mould growth or woot rot but problems can occur related to the thermal shock, salt crystallization, corrosion, thermal spalling or bio-deterioration.

In relation to the regional climate and material factors of the analyses, the fit for purpose analysis should include regional materials for a higher reliability. Such materials should, in a larger study, be fully characterized for a range of material types in different locations of Europe.

CONCLUSIONS

In this research, the updated clustering approach of Vanderschelden et al. [8] was adopted for four cities with different climate types and exposure conditions. It was concluded that the clustering methodology could be applied for all considered cities. The four geographical locations in this study allowed to test the robustness of the updated clustering methodology regarding different levels of wind driven rain and its exposure. The latter already showed to be a crucial element for hygrothermal simulations and risk assessment, [8]. In this study, it became clear that depending on the wind driven rain load the clustering result could be divided into two groups, the high wind driven rain climates, with cities Essen and Brussels, and the climates with lower wind driven rain climates, London and Milan. It was concluded that for both climate types, the clustering methodology was able to establish clusters with similar response behavior. For the higher WDR climate, the clustering schematic from Vanderschelden et al. [8] was relevant for both cities. For the climates with lower WDR the updated clustering methodology provided a different schematic. It was seen that for the higher WDR, the rain exposure was dominant for the risk assessment, followed by the water absorption coefficient. For the low WDR, the impact of the absorption coefficient was insignificant, given that the wind driven rain was much lower. Here, the primary moisture source was considered to be the indoor environment. As the indoor moisture load became crucial, the properties which define the temperature profile through the wall dominate the sensitivity analyses, i.e., the masonry thickness and the thermal conductivity. The two cities per level of WDR could be furthermore divided in a similar way based on their moisture load. It became clear that the result of material clustering, and in this study the clustering of historical brickwork is not only determined by the material properties and response behavior but is highly dependent on the outer climate conditions and the relevant performance risks. One should consider a fit for purpose approach when performing clustering analyses which considers all factors of the hygrothermal exposure and resistance of a wall assembly. This fit for purpose material clustering will be beneficial for regional risk-analyses and will reduce the time expensive material characterization or stochastic approach.

ACKNOWLEDGMENT

Prof. Nathan Van Den Bossche would like to gratefully acknowledge the financial support for his visiting stay in Italy from the Research Foundation Flanders (FWO, grant V413921N).

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