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Clustering approach for hygrothermal material properties of bricks in a tropical climate, based on three degradation risks.

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ABSTRACT

Architecture in Cuba has a rich and colourful history, where the colours are literally seen in the Old Havana streets. Several sites are declared World Heritage by UNESCO, such as the historical centre of Camagüey due to its peculiar urban form. Recent studies have shown that 30% of the world heritage sites in Cuba were constructed using earthly materials. Unfortunately, this number is rapidly decreasing where nowadays, only 10% is still standing and half of them show risks for biological deterioration, fungal growth, or salt crystallization. These degradation phenomena are at the root of the high collapsing rates and should be prevented at all costs. HAM-simulations have an added value in the research for renovation and restoration strategies. However, these simulations require a high accuracy for input variables. It is important to make correct assumptions for applied construction materials. For bricks, aspects as granularity, clay or sand content, compaction and firing techniques vary greatly in Cuba and have a major impact on the brick pore structures and consequently on its hygrothermal properties. In an early stage of a renovation project, exact building information is usually not provided, and in most cases a full material characterization is absent. This study investigates the potential to fill in the missing values of incomplete material data with a clustering approach for the Cuban climate. This methodology determines equivalently behaving bricks based on the impact of their properties on the hygrothermal behaviour regarding the mould growth, wood rot and salt crystallization.

KEY WORDS: Brickwork, Clustering Analysis, Heritage degradation, Hygrothermal response behaviour

1. INTRODUCTION

The old city of Havana in Cuba is noted for its history, architecture, and its monuments. The city was founded in the 16th century and declared World Heritage by UNESCO in 1982. Unfortunately, due to the combination of local building materials with the tropical climate, the colourful streets of Old Havana are at risk and measures are required to protect the earthly constructions.
Mud has been used as a construction material for centuries, and still plays a major role in developing countries. In Cuba, the adobe brick formed a solution after the material crisis of the 1990's [1]. The properties of the adobe bricks are highly dependent on the location. A different soil results in different granularity, clay content and coupled with the different brick preparations and compaction techniques will result in a large variability in material properties [2]. In recent years, the research on earth as a building material has gained more and more interest. One of the reasons for this is the growing awareness of the environmental impact and CO_2 impact of materials in the building sector. Recently, the comparison of older statistics and the recent updates from organizations such as UNESCO has shown a drop of earthly heritage buildings from 30% to 10% [2]. Even more concerning is that half of the remaining buildings is endangered and shows risks for collapse [2]. The warm and humid environment of Cuba coupled with the use of capillary materials results in a high humidity in walls for 80% of the damaged buildings [1]. A high humidity in walls can induce health risks for the occupants, since mould spores have the ability to activate and start their initial stages of growth [3]. Another risk is the possibility for cracks as a result of salt phase

changes. A study of Paradiso et al. [4] has shown a high concentration of smectic, a mineral which has an increase of crystal lattice with changes in humidity, similar to halite. Such an increase can induce stresses on the pore structure until the strength of the brick is insufficient and a crack occurs. Not only the mechanical performance of a brick is at risk when the humidity rises, the structural integrity of the whole building can be endangered due to the rotting of wooden elements embedded in the wall. These different types of pathologies lay at the base of the high collapsing rate in Cuba and should be prevented by means of renovation and restauration strategies. The severity of decay and the level of hygrothermal performances of a wall is highly dependent on the humidity profile in the wall. To estimate the profile, it is of great importance to have an accurate idea of the material properties. Especially since the high humidity in Cuban walls is affected by the capillarity of the adobe masonry [1]. Unfortunately, the large variety in brick types will entail a large uncertainty in the risk analysis. One solution is to characterize all properties for each project, but such processes are cost and time consuming. A partial characterisation is complicated by the fact that the material properties that are most important for degradation risk assessment are dependent on the pathology type, location, and risk zone in the wall setup [5], which are not always known. Another solution to cope with variability in brick properties was proposed by Zhao [6] and Vanderschelden et al. [7], namely the clustering analysis. Vanderschelden et al. proposed a fit for purpose clustering methodology to determine equivalency among bricks, which includes both physical characteristics and hygrothermal response behaviour. This approach allows to fill in missing material properties from the cluster showing the highest resemblance in characteristics [6]. Furthermore, for a specific case the clustering approach also facilitates to pinpoint which material property has the highest impact on degradation, and in turn the determination of this property will reduce the uncertainty in the risk assessment [7]. This paper executes the stepwise methodology for clustering as described above, and determines the most dominant brick property in Cuba for three different wall pathologies. First, a cluster schematic for each individual pathology was calculated and afterwards, to conclude, an easy to follow flowchart for 6 material clusters was drawn up for an overarching risk on pathologies. The analysis allows building practitioners to better understand how material characteristics affect degradation risks. With this knowledge, one can assess which renovation strategies can or cannot be carried out, in a more reliable way than if only a visual inspection is carried out or looked at with assumptions.

2. METHODS AND MATERIALS

In this study, the clustering methodology of Vanderschelden et al. [7] is applied for Cuba, which has a tropical savanna climate according to the Köppen-Geiger climate classification. The methodology provides a helping hand to fill in missing material properties during renovation projects. It defines equivalently behaving bricks with similar physical characteristics. The response behaviour and similarity in appearances is determined by means of clustering and sensitivity analyses with the results of hygrothermal simulations. During a hygrothermal (HAM)-simulation, the temperature and moisture contents throughout the wall construction is determined for predetermined timesteps. The calculation considers all transport equations and -functions as well as the storage in materials. The use of HAM-modeling is reliable, validated and provides more concrete insights than a visual inspection in the field. In this study, 15000 hygrothermal simulations were performed based on a latin hypercube sampling and the results were post processed to calculate the severity of three different pathologies.

SAMPLE CONSTRUCTION

For this paper, a single historic masonry leaf wall was used to investigate the hygrothermal response behaviour of different bricks. The masonry was abstracted to a single brick volume to reduce computational time. Typical masonry in Cuba is constructed with adobe brick, which entails a large uncertainty regarding the material properties. Since earthly materials are missing in hygrothermal databases and material characterization is limited, 15 German brick types from Zhao were adopted [6]. The analysis still holds value because no absolute degradation risks are calculated, the goal is to generate a comparative study between bricks. To increase the variability of the 15 bricks, a latin hypercube sampling was applied with variable water absorption coefficient, density, specific heat capacity, open porosity, effective moisture content, thermal conductivity, water absorption coefficient, vapor diffusion resistance factor and effective liquid conductivity. The original 15 bricks, on which the sampling is based, are listed below in Table 1. The original material files for simulations can be found in the IBK-database (Institut Bauklimat Dresden) by its accompanied ID number. The colour of the bricks is unknown but has a large impact on the surface temperature due to the level of solar absorption. The latter was studied by Martins et al. He concluded that for a tropical climate, such as Brazil, solar radiation is the most important parameter for thermal behaviour [8]. To incorporate the effect of coloured bricks, a uniform spread between 0.2 (light brick) and 0.8 (dark brick) for absorption of direct sun radiation was adopted [9].

Table 1: Summary of the applied brick types and historical finishing plaster in the IBK database

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

Two wall related properties were implemented in the sample construction; the wall thickness and rain exposure coefficient. The wall thickness varies from 150– 500 mm. With the rain exposure coefficient, it is possible to consider the variability of rain impingement on a wall and the effects of roof overhangs and rain runoff from above. In the sample, a uniform spread was used between 0 and 2.

CLUSTERING ANALYSIS

The first focus for equivalency is to find similarities in the physical appearances of bricks. Zhao showed the benefits of a statistical clustering to determine similar material properties [6]. In his work he created a clustering schematic for 27 bricks, including the 15 bricks from this study. The result comprises four clusters with similar appearances, for example cluster 1 includes bricks ZI and ZN which are characterized as modern bricks manufactured with new technologies. The methodology succeeds in the formation of clusters with similar physical profiles but the equivalency in hygrothermal response behaviour is not achieved. Vanderschelden et al. proved that bricks with similar properties may entail very different degradation risks: not all material properties are equally important, and for some properties there are threshold values that have a significant impact on the hygrothermal response. Hence, Vanderschelden et al, proposed a methodology to couple the statistical clustering with sensitivity analyses to determine equivalency in response behaviour [5,7]. The different analyses showed the importance of a fit for purpose clustering where regional materials, local climate conditions, typical construction methods, relevant material degradation or pathologies are considered. For the theoretical background of clustering methodologies, the authors refer to Zhao [6] and Vanderschelden et al. [5,7].

HYGROTHERMAL RESPONSE BEHAVIOUR

The hygrothermal response behaviour is determined for the different bricks with Heat- Air and Moisture (HAM) simulations. HAM-modelling allows us to calculate the thermal and moisture balances through a wall under variable climate conditions. Hygrothermal simulations show their added value in the development of reliable renovation strategies, since they can simulate the response of façade systems under realistic climate conditions. A simulation starts with the division (discretization) of the assessed building component in smaller elements. Then, three balance equations: Heat, Air and Moisture are calculated, between each of the created elements, until a balance is found. This allows us to determine the temperature and moisture content in each element per time step. In this study, simulations were performed with Delphin 5.9. and postprocessed using Matlab and R-codes [9]. Post processing includes the application of numerical prediction models for pathologies at different depths in the wall setup. 15000 simulations were performed, each running 4 simulation years: three conditioning years and one evaluation year. The stepwise framework by Vanderschelden et al. [10] was adopted to construct the hygrothermal model. One of the steps focusses on the outdoor climate environment. The outdoor climate files were derived from METEONORM based on the historical information for the city centre of Havana. The file is a reference year comprised of hourly values for air temperature, relative humidity, wind velocity and direction, hourly total precipitation, direct and diffuse shortwave radiation, and longwave sky radiation. The reference year was constructed based on the average year of temperature and radiation, without consideration of the distribution of precipitation loads [11]. Indoor climate files can not be derived from METEONORM but were estimated by Vandemeulebroucke [11] based on the work of Baldoquin [12]. EN-13788 is not appropriate to use, since the indoor space of heritage is in most cases not conditioned by an HVAC-system (Heat Ventilation and Air Conditioning) [13]. Instead, in this study, the indoor temperature is set equal to the average outdoor temperature while the indoor vapour pressure is calculated as a 5% increased outdoor vapour pressure. This 5% considers the added moisture loads from occupants and various user activities.

As a result of the humid environment and the lack of systematic knowledge regarding the correct use and applications of adobe bricks, many Cuban buildings show pathologies and a high collapsing risk [1]. Within this study three different pathologies were analysed: mould growth, rotting of embedded wood and the phase transitions of salts.
The growth of mould is assessed at the inner surface of the plaster and predicted with the improved model by Viitanen [14]. Mould can endanger the occupant's health. A mould index between 0-6, with increasing severity, is calculated based on the surface temperature and relative humidity in time. For the calculation

a medium resistance to mould growth is assumed for the interior plaster, with a low decline of mould spores during the dryer periods.

The rotting of wooden beams embedded in the masonry contributes to the high collapse rate. The beams are a vital structural element and provide support for the flooring system. However, due to the high humidity, brown rot fungi will attack the cell wall material. To predict the severity of the attack, the model for brown rot by Brischke and Rapp is applied at the beam end located at 100mm from the inner brick surface [15]. The dose-response model calculates a daily dose with a temperature and moisture induced component. The decay rating from CEN 252 [16] is converted to a single year with the assumption to have no decay in 25 years. A decay rating of 4 represents failure and a value of 1 is considered a small attack. It is important that no damage occurs during the service life of the material, so a decay rating below 1 is advised.

The last pathology used in this study is the salt damage, both aesthetic as well as destructive deterioration was analysed. In certain humidity ranges and temperature conditions, crystallization-dissolution cycles occur and the number of cycles can be used as proxy for salt damage. The transitions are highly dependent on the type of salt solution which is different in various climates and for different geographical locations. In a study by Grossi et al [17], it was stated that the thernadite-mirabilite type is the most common hydrated salt type for humid climates whereas halite typically characterises the non-hydrated salts. The simulation output and climate parameters have an hourly temporal resolution. However, for the salt criteria, a daily resolution was used to incorporate heat and moisture buffering in materials. Two different criteria were calculated, hydrated and non-hydrated salt crystallization. For the non-hydrated, halite, a phase transition is counted when the daily humidity downward crosses the 75.3% critical threshold. For the hydrated salts, thernadite-mirabilite, the critical threshold is temperature dependent according to Function 1.

$$RH_{crit} = 59.11 + 0.87549.T \qquad when\ T < 22.5\ ^{\circ}C \qquad (1)$$

Aesthetic deterioration from salt crystallizations appears at the exterior surface of the wall, therefore the phase changes were calculated with the exterior surface temperature and relative humidity. For destructive deterioration, the phase changes were calculated at a depth of 5mm from the exterior surface.

SENSITIVITY ANALYSIS

To analyse the equivalency in response behaviour and to determine the most critical material property for each pathology, sensitivity analyses were addressed. In this study, three different types were used based on the study by Calle et al [18]. The Spearman Rank correlation, scatterplots (which provide the reader a quick grasp of the pathologies behaviour), and binary poison distribution trees, which reduce the assumptions of linearity and monotony to a minimum. A classification tree can be interpreted from top to bottom, where the most critical material properties will appear higher in the tree. Such trees can be used to derive practical guidelines for the building industry [19].

3. RESULTS

In the following section, the results of the clustering methodology (as described in section 2) are presented and discussed focussing on the three degradation models relating to mould growth, wood rot, and salt crystallization. A summary of the individual clustering results is shown in Figure 1 (a until f). Each individual graph represents one type of degradation. The results are visualized by means of a boxplot for the 1000 results of each individual brick and are ranked according to an individual clustering and sensitivity analyses, explained in the following paragraphs. The different clusters are marked by a red surrounding box. First, the degradation results are discussed individually for the three different performance criteria with the construction of their dedicated cluster schematic. Afterwards, the results are compared and an overarching clustering schematic coupled with the clustering of physical characteristics is proposed in the form of a flowchart.

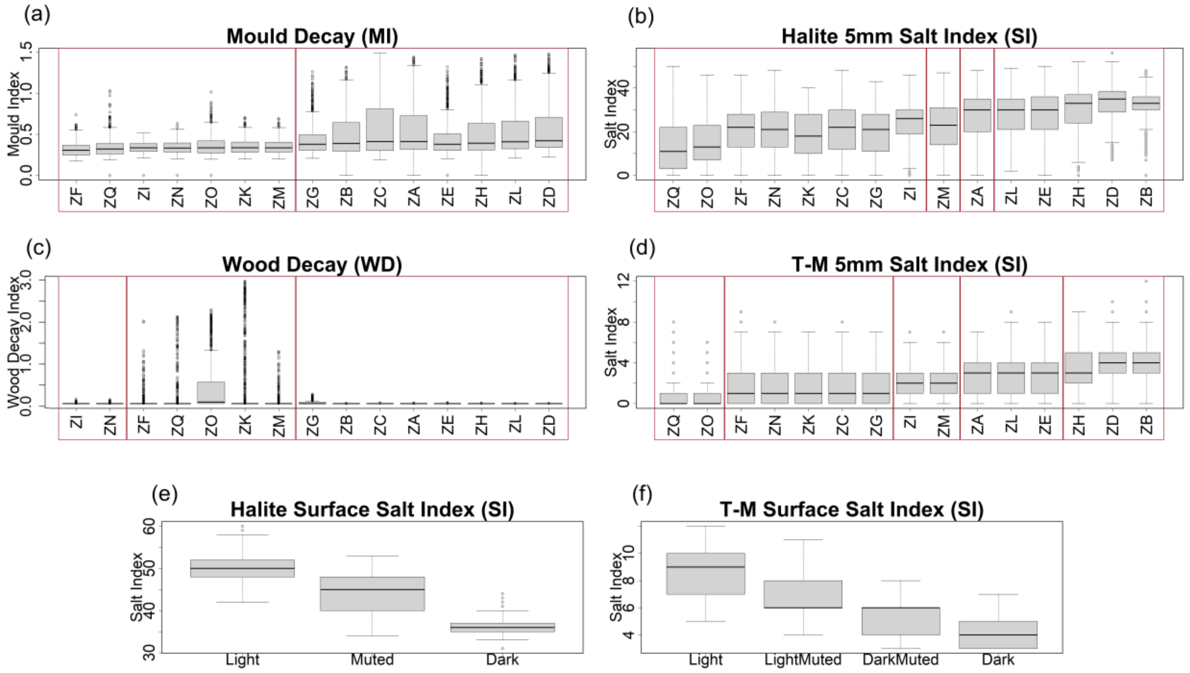

Figure 1: Summary of the response behaviour of the different bricks for the different pathologies by means of the clustering schematics: (a) Mould decay, (b) SI Halite 5mm, (c) Wood decay, (d) SI Thernadite-mirabilite 5mm, (e) Surface SI Halite, (f) Surface SI Thernadite-mirabilite.

Mould Growth

The classification tree for the growth of mould in Figure 2 shows the decreasing impact of parameters from top to bottom. The rain exposure is shown on top, so it appears to be most dominant. It defines how much rain is supplied to the wall surface during simulation. On a lower level in the tree, for a lower rain exposure, the solar absorption appears. Solar absorption improves the drying potential of bricks and is considered a highly influential material characteristic. On the same level, for a higher rain exposure, the first material property is visible, i.e. the water absorption coefficient. A split is noticed at 0.13 $kg/m^2s^{0.5}$, which in the original study by Vanderschelden et al. [7] was explained as the minimum value for which the waterfront reaches the interior surface. Below this threshold, the water is redistributed within the brick, and consequently reduces mould growth on the interior plaster. In Figure 1 (a), the boxplots of the mould results are ranked according to an increased water absorption. Two clusters are marked by a red surrounding box based on the 0.13 $kg/m^2s^{0.5}$ threshold. It is seen that the spread on the mould indexes is smaller below the threshold level than above. This could mean that, with a simple absorption test, one can already estimate the level of uncertainty and know a sense of the magnitude for mould growth. It shows that higher absorptive bricks need a higher level of material characterization to perform a reliable risk analysis.

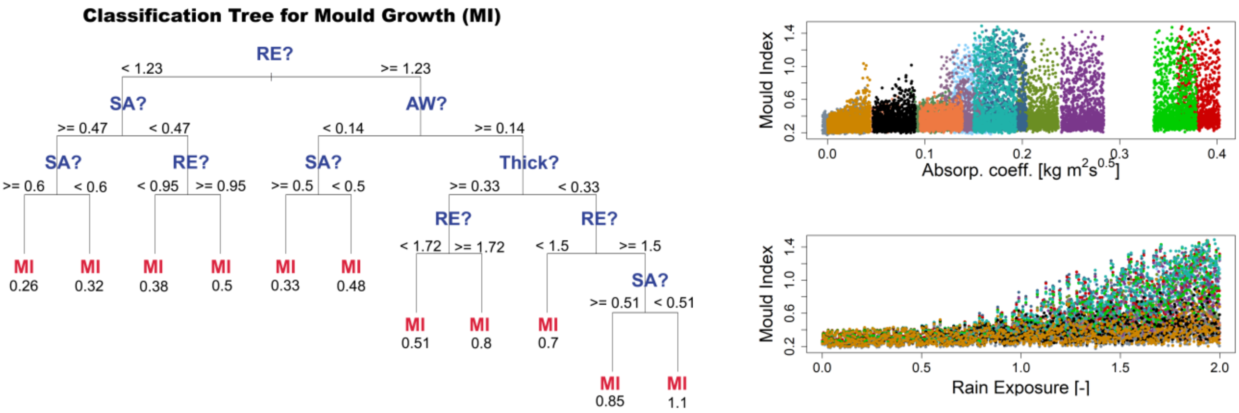

Figure 2: Sensitivity analyses for mould growth: decision tree on the left (RE: Rain exposure, SA: Solar absorption, AW: Water absorption, Thick: Thickness) and a scatterplot for water absorption and rain exposure on the right.

Wood decay

The wood decay rating was calculated based on the simulation results and visualized by the sensitivity analyses in Figure 3. The highest levels in the classification tree are established with the water absorption and the rain exposure. A threshold of 0.11 kg/m²s$^{0.5}$ was calculated for water absorption. As previously explained, a low water absorptive brick will store and redistribute liquid water in the brick and the waterfront will not reach the inner surface. Consequently, a wooden beam end in low absorptive bricks will be exposed to higher moisture contents and slower drying rates than in a case with high absorptive bricks. In the scatterplot in Figure 3 on the right, the critical water absorption of 0.11 kg/m²s$^{0.5}$ is confirmed. A large spread and high wood decay ratings below the threshold are found. In case of rain exposure, the scatterplot shows that an exposure above 0.5 and certainly above 1 entails a much larger uncertainty and magnitude of decay rating with a peak value of 3. As a result, a dedicated clustering schematic for three clusters was constructed with the threshold levels for water absorption and thermal conductivity from the classification tree. The schematic is visualised in Figure 1 (c).

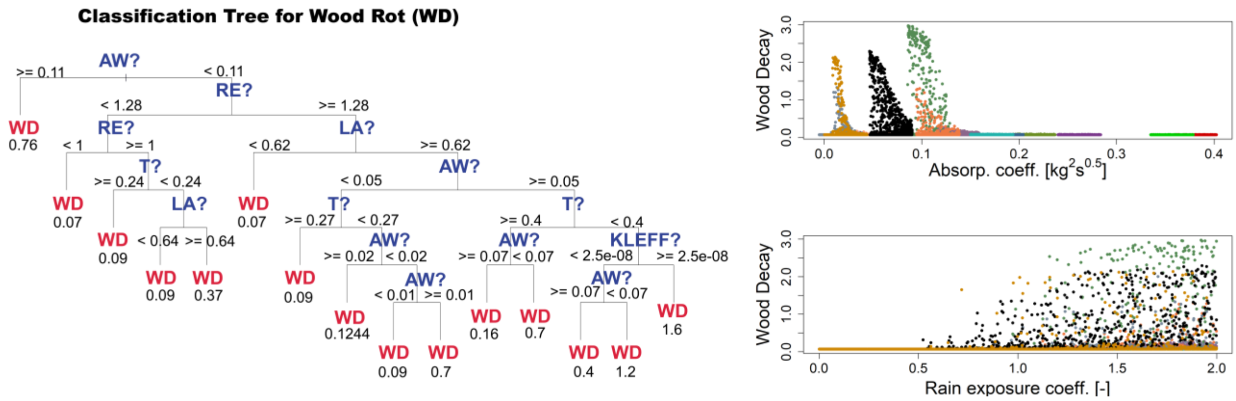

Figure 3: Sensitivity analyses for Wood rot: decision tree on the left (AW: Water absorption, RE: Rain exposure, LA: Thermal conductivity, T: Thickness, KLEFF: Liquid conductivity at saturation) and scatterplot for absorption coefficient and rain exposure on the right.

Surface Salt transitions

The severity of the aesthetic deterioration by salts was analysed on the exterior surface. The phase transitions for two salt solutions were calculated with the surface relative humidity and temperature. The sensitivity analyses, in Figure 4, and the plots (e) and (f) at the bottom in Figure 1 show that the surface crystallization in Cuba is highly dependent on the colour of the brick. The latter is implemented in the

HAM-simulations by means of the solar absorption coefficient. For both hydrated and non-hydrated salt solutions, respectively Halite and Thernadite-Mirabilite, a lighter brick will show higher deteriorations with an increased number of phase transitions. This can be explained by the fact that a darker colour translates to a higher solar absorption, which in turn increases the surface temperature and evaporation rate during sunnier periods. In the bottom graphs (e) and (f) of Figure 1, the number of phase transitions for both salt solutions were clustered according to the solar absorption with the classification tree. The clustering splits were calculated based on the classification trees in Figure 4. In case of Halite, the clusters were determined as follows: light bricks with a solar absorption between 0.2 and 0.4, mutted bricks between 0.4 and 0.6 and dark bricks entailing an absorption of 0.6 until 0.8. A different scheme was obtained when analysing a thernadite-mirabilite solution, namely light bricks from 0.2 to 0.35, light mutted from 0.35 to 0.47, dark mutted bricks from 0.47 to 0.55 and dark bricks representing an absorption from 0.55 up to 0.8.

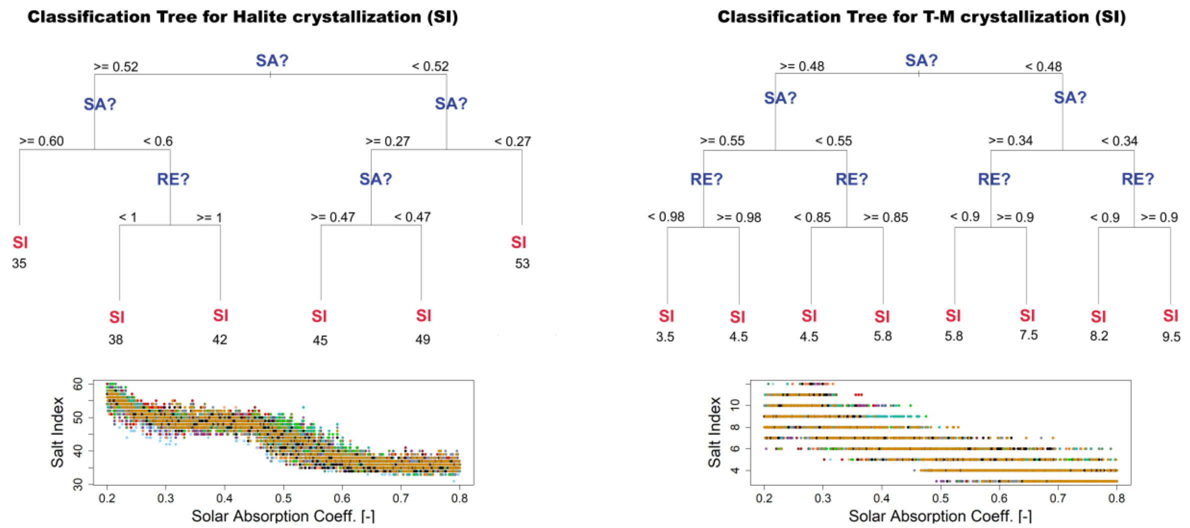

Figure 4: Sensitivity analyses for Surface salt crystallization, decision tree on top (SA: Solar absorption, RE: Rain exposure) and scatterplots for solar absorption on the bottom.

Salt transitions at 5mm

The analyses of the number of phase transitions at a depth of 5mm was used as a proxy for destructive deterioration by salt solutions. The sensitivity analyses, in Figure 5, showed similar results for hydrated as non-hydrated solutions. The vapour resistance appeared in the top two levels of both classification trees. The dominant behaviour is confirmed in the scatterplots of Figure 5, and in Figure 1 (b) and (d), where the number of phase transitions was ranked with a decreasing vapor resistance from left to right. The plots show a decrease in the number of salt phase transitions for a decreasing vapor resistant brick. The high dependency of the vapor resistance could be explained by the drying behaviour of porous materials. The drying of bricks occurs in two phases. The first phase is represented by a linear mass loss over time and is material independent. This part happens at a fast rate, as the waterfront is still at the surface and the drying occurs by evaporation. In the second stage, the waterfront recedes inwards of the brick. Consequently, the drying is now impacted by the vapor transport through the material and is therefore material dependent [6]. With this knowledge, one can reason that the drying behaviour in a more vapor resistant material is much slower than in a low vapor tight material. This results in a relative humidity which has less fluctuations around the critical phase transition humidity and less salt crystallization-dissolution events occur. The clusters in Figure 1 (b) and (d), for the phase transitions at a depth of 5mm, are marked by red surrounding boxes and the values for the splits were calculated with the classification trees.

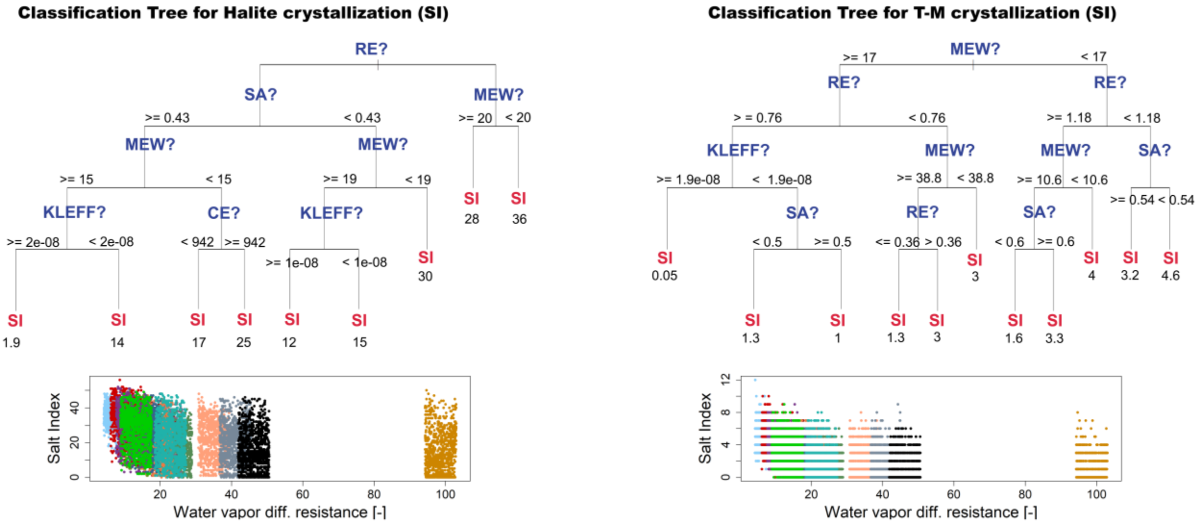

Figure 5: Sensitivity analyses for salt crystallization at 5mm: decision tree on top (MEW: water vapor resistance factor, RE: Rain exposure, SA: Solar absorption, CE: Heat capacity, KLEFF: Liquid conductivity at saturation) and scatterplot for water vapor diffusion resistance on the bottom.

Clustering schematic

In the previous sections, a clustering schematic was established for each individual pathology, representing equally behaving bricks. In this part, the schematics are compared and coupled back to the characteristics and physical appearances of the bricks. The latter was performed with the statistical clustering of Zhao [6]. A single clustering flowchart, including the different pathologies, was created in the format of an overarching classification tree. 6 Different clusters where established, where each cluster represents a group of bricks with similar physical appearances and an equal response behaviour. The analysis was summarised in an easy to read flowchart, shown in Figure 6. The bottom of the flowchart shows the different clusters with their associated physical characteristics and pathology risks. Figure 7 shows the degradation results according to the derived flowchart for masonry in Cuba.

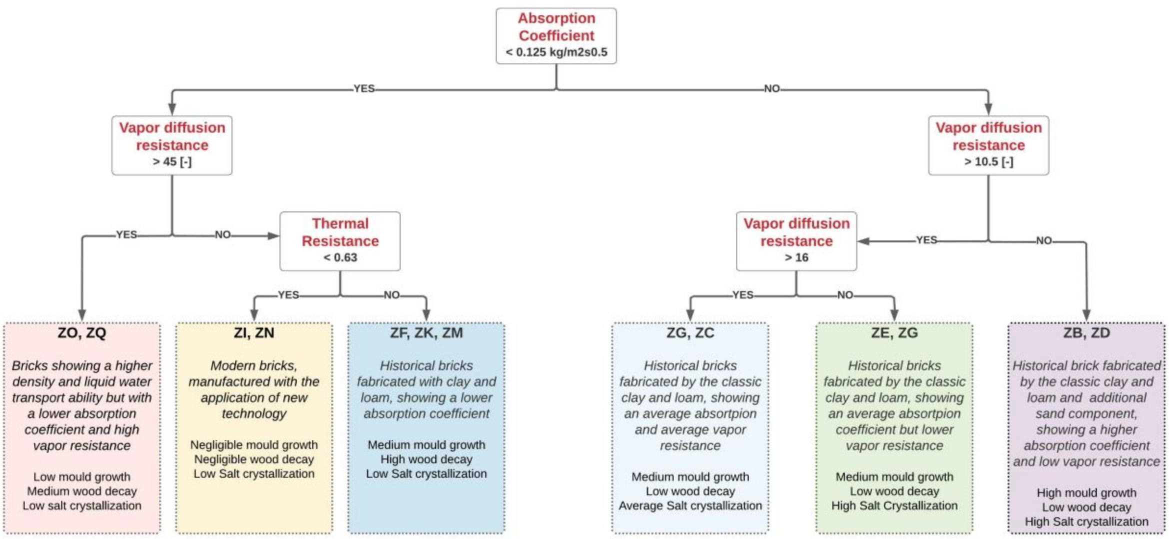

Figure 6: Clustering flowchart for bricks in Havana and a summary of the physical characterizations and the risk for the different pathologies.

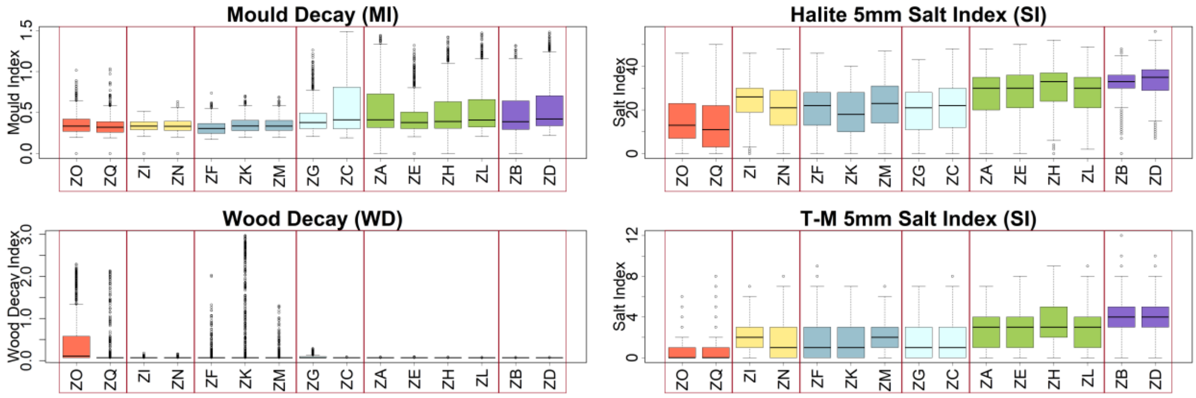

Figure 7: Hygrothermal response behaviour for the different clusters according to Figure 2 in regard to the risk for mould, salt and wood decay.

4. CONCLUSIONS AND DISCUSSION

In this fit for purpose clustering approach, a representation for brick materials was applied in a local climate environment, to analyse relevant degradation pathologies in Cuban heritage. Clustering is proposed as a way to cope with uncertainties among bricks, and in a broader spectrum this could be applied to all types of building materials. The methodology has led to 6 different clusters with similar characteristics and equal risk for degradation. The similarity in physical appearances was calculated according to Zhao with a statistical clustering methodology. To compose clusters with bricks entailing similar pathology risks, the methodology from Vanderschelden et al. was applied. Three different pathologies were adopted in this study: mould growth, wood rot and salt crystallization. The results are summarized in an easy to read flowchart, in Figure 6. During the clustering of the response behaviour for the individual pathologies, some particular conclusions were made.

The water absorption showed to be the most critical material property, defining the severity of mould growth. The magnitude as well as the spread on the mould index is determined by water absorption. A threshold level of 0.13 $kg/m^2s^{0.5}$ was found, for which a more absorptive brick shows a larger spread and magnitude than lower absorptive bricks. This means that a simple absorption test already provides an insight in the uncertainty and magnitude of mould growth.

In case of wood degradation, similarities with mould growth were noticed. The water absorption showed to be most dominant and decisive for the severity of wood rot. A critical value of 0.11 $kg/m^2s^{0.5}$ was observed in the sensitivity analyses. The 1D approach for masonry largely minimizes the computational time and can be considered as a conservative approach [21]. However, in applications with anisotropic materials such as wood, one should consider the use of 2D and even 3D- modelling.

The deterioration due to salt transitions was divided in aesthetic and destructive deterioration. The aesthetic deterioration was analysed on the exterior surface of the masonry. The conditions of an exterior façade in Cuba are highly influenced by the level of radiation, which in turn results in a dominant impact of the brick's solar absorption. Absorption of radiation for bricks is related to the colour of the brick and is implemented in the simulations by the solar absorption coefficient. It was clear that a darker coloured brick had a smaller number of salt transitions than lighter bricks.
The number of phase changes at a 5mm depth was used as a proxy for the destructive deterioration by salt transitions. The sensitivity analyses showed a high importance of the vapor resistance of the brick. The physical origin could relate to the difference in drying rates between a vapor tight and a more vapor open brick. For a more vapor open material, the drying will proceed at a faster rate and higher oscillations occur, which entails that the number of phase transition around a critical humidity will increase.

It is important to note that in this research, state-of-the-art numerical degradation models were applied. The authors acknowledge that these models still have large uncertainties, but the aim of this research was not to test or improve the models. Furthermore, the results were not analysed in terms of absolute values but only used in a relative and comparison matter.

The research of hygrothermal behaviour in heritage buildings for a tropical climate was performed with material properties which can differ from local adobe bricks. Therefore, in future research it would be beneficial to compare the simulated bricks with local bricks or materials.

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