FROM SIMULATION TO PRACTICAL GUIDELINE: THE USE AND ADVANTAGE OF HAM-SIMULATIONS FOR THE CONSERVATION OF HERITAGE BUILDINGS IN HAVANA, CUBA

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ABSTRACT

Cuba, and more specifically Havana, is known throughout the world for its rich architectural heritage. The 214 ha centre of Havana, consisting of primarily housing, is inscribed as UNESCO world heritage. Nevertheless, is Cuba suffering from a major housing crisis. 70% of the built environment requires major repairs and 7% of the housing context has been declared uninhabitable. In order to tackle the degradation problem, while simultaneously protecting the historical heritage, there is an urgent need for tools and practical guidelines. These should provide insight into the approach to conserving Havana's heritage and the risks that could entail. The reasons for this deterioration and damage include different moisture-related problems due to the hot and humid climate of Cuba: mould growth, salt efflorescence and the rotting of wooden beam heads embedded in the masonry of the façade. Heat Air Moisture (HAM) models have been found a valuable tool to assess the risk on deterioration and premature failure of building components due to moisture-related problems. This paper demonstrates the process from hygrothermal simulation to practical guideline. The study focuses on the potential of the practical applicability of simulation output from Delphin 6, to produce practical schemes using classification trees. These results will improve decision-making for building practitioners and clarify which parameters have the biggest impact on the risks of deterioration, thus providing insights into the conservation of heritage buildings of Havana, Cuba.

KEY WORDS: HAM-simulation, conservation of heritage, degradation, guidelines.

1. INTRODUCTION

Cuba is known throughout the world for its rich architectural heritage with its colourful houses and picturesque streets. Their architectural environment is thus important, to the extent that the well-known city centre of Havana of over 214 hectares has been included in UNESCO's World Heritage List. Nevertheless, this unique site suffers from major degradation risks. The problems are so severe that they require major repairs on 70% of the built environment. A large percentage of this degradation is due to moisture-related problems such as mould, wood rot and salt efflorescence.

Hygrothermal simulations are proven to be a valuable tool for assessing the risk of moisture-related damage and premature failure of building components. Although tools for Heat Air Moisture (HAM) modelling are commercially available, their application in practice remains limited. However, the results of these models can provide important insight into the feasibility of energy renovation projects and risk assessment of both the present and the future. A major reason why hygrothermal simulations are not widely applied in practice is due to the fact that they require post-processing to analyse the obtained data and the need for people with expertise.

Therefore, the aim of this research is to investigate ways in which the insights of HAM modelling can be made available to the wider public/ construction industry in order to be beneficial to all parties. This can be done by presenting simple rules of thumb, listing certain conditions to prevent damage or by developing decision trees to allow consideration of the influence of a wider range of variables [1]. Degradation risks in masonry façades, and dwellings in general, are a widely discussed topic. Various studies have examined different deteriorations of masonry façades, e.g. mould [2], wood rot [3], salt crystallization [4], etc. Calle et al. [5] highlighted the potential of conducting sensitivity analyses to gain insights from hygrothermal simulations, whereas Marincioni et al. discussed whether a probabilistic risk assessment can assist decision-making for interior insulation [6].

The main objective of this research is to explore a methodology to translate theoretical insights on moisture-related damage into practice, in order to create a robust decision framework that can also incorporate the influence of climate change, which has been proven to have a major impact on the damage risks of masonry façades [7].

2. METHODOLOGY

Simulation set-up

27 648 simulations have been executed using Delphin 6.0 while varying 8 different parameters which are listed in Table 1. All the simulations are done for the location of Havana, more specifically Casa Blanca. The impact of different climate projections, orientations, albedo coefficients, wall assemblies, rain exposure coefficients and shortwave absorptions coefficient are investigated.

Table 1: Parameter variations for the sensitivity analysis

Parameter	Variations	Description
Climate (projection)	4	H, A1B, A2, B1
Orientation	8	N, N-E, E, S-E, S, S-W, W, N-W
Albedo	3	0.2, 0.5, 0.8 [-]
Wall thickness	3	150, 300, 450 [mm]
Wall Material	4	Brick clusters ZD and ZO, concrete, limestone
Interior insulation thickness	2	0 mm (uninsulated case) and 100 mm
Rain exposure coefficient	4	0.5, 1.0, 1.5, 2.0 [-]
Shortwave absorption coefficient	3	0.2, 0.5, 0.8 [-]

The climate data used here are subtracted from the METEONORM tool. The Intergovernmental Panel on Climate Change (IPCC) defined different climate scenarios where each storyline considers different future developments. The Special Report on Emissions Scenarios (SRES) [8] considers scenario A1B (balanced energy technology), A2 (heterogeneous world with increasing global population) and B1 (convergent world with declining global population after mid-century). These different projections were compared to the historic period (H). To compare: the historic period (H) has a mean temperature of 25.19°C, whereas scenario B1's mean temperature equals 25.84°C, A1B's 27.76°C and A2's 28.19°C.
EN ISO 6946 [9] is consulted to provide the exterior boundary conditions such as heat and water vapour transfer coefficients at the exterior surface. Martins et al. (2016) [10] stated that the impact of solar radiation is of highest importance in Cuba related to thermal behaviour. Furthermore, the shortwave absorption coefficient and the albedo coefficient have a significant influence according to previous energetic renovation research in Cuba [11]. Therefore we incorporated three variations for each parameter to examine the impact on the hygrothermal behaviour of building components.
Rueda Guzmán (2003) [12] and de la Paz Pérez (2019) [13] stated that the critical orientation regarding overheating is the southeast. To elaborate further on the impact of orientation in terms of moisture-related damage, 8 different orientations are simulated. To incorporate runoff effects that lead to an increased moisture load due to low-absorptive materials above the wall of interest, we simulate a rain exposure coefficient (RE) of 0.5, 1, 1.5 and 2.
As prescribed in EN 15026 [14], the indoor climate conditions are derived from the outdoor air temperature. The first 4 years of the climate data are used to condition the wall assembly in order to simulate realistic starting conditions.
The uninsulated wall assembly consists of, from exterior to interior, a 5mm gypsum plaster, a load-bearing wall with a wall thickness of either 150mm, 300 mm or 450 mm and a 5mm gypsum plaster as interior finish. The insulated case replaced the gypsum plaster finish with 100mm insulation, represented by a thermal resistance factor of 2.5, a vapour barrier and a 12mm gypsum board as interior finish. Four different materials are simulated to represent the material of the load-bearing wall, namely concrete, limestone, brick cluster ZD and ZO. ZD represents a brick with a high absorption coefficient and ZO represents a brick with a rather low absorption coefficient.

Degradation criteria

The humid climate of Havana entails that mould growth at the interior side of a wall is a frequently occurring problem. The mould index (M) represents mould growth and is calculated using the VTT model [2]. This index quantifies the mould coverage on a certain surface, varying from 0 (when the spores are not yet activated) to 6 (corresponding with 100% mould coverage). A value of M=3 is a common threshold criterion, which equals a mould coverage between 10 and 30%. This value is chosen because everything above the value of M=3 results in a mould cover that is visually recognisable. However, the threshold value for the mould index in this research is M=1 for the fail-value. This value is described as 'small amounts of mould on surface (microscope), initial stages of local growth'[2] and is taken as a non-desirable growth rate. Because this study focusses on risk assessment and these models are not 100% accurate, only mould index values below 1 will be considered to entail a negligible risk.

It is possible for wood decay to occur when wooden beam heads are embedded in the wall which is common practice in historical dwellings. Therefore, the wood decay is measured at 100 mm from the inside of the load-bearing wall's surface, which relates to the minimal structural support for beams in the masonry. Degradation by wood-decaying fungi take place under certain boundary conditions. The dose-response relationship of Brischke and Rapp [3] quantifies the wood decay by the amount of mass loss of the beam head, which may eventually lead to structural failure. Note that this study conducts 1D simulations, therefore the beam itself is not modelled, thus the impact of the beam itself regarding heat and moisture behaviour is not accounted for. If we want to make sure that the wooden beam meets its requirement to have a minimum service life of 30 years [15], it is important not to exceed a mean decay rating of 1 over this 30-year period, which corresponds with a critical dose value of 15 doses for outcomes reported as a 1-year value. A mean decay rating is categorized in EN 252 (1989) [16] in 'no attack'(0), 'slight attack'(1), 'moderate attack'(2), 'severe attack'(3) and 'failure'(4). If the mean decay rating of 1 is exceeded over a 30-year period, we declare that the assembly fails our demands, thus receives a so-called 'fail-value' of 1.

Salt damage can be parameterized using the number of crystallization-dissolution cycles, which can occur under precise heat and moisture conditions. Humid climates with high temperatures are at higher risk for potential salt damage [4]. These possible salt transitions are salt-dependent and can be related to climate types. Grossi et al. [4] stated that in humid climates salt transitions are primarily of the thenardite-mirabilite type. On the other hand, halite typically characterises non-hydrated salts. The number of phase transitions for a non-hydrated salt is assessed by counting the times when crystallisation occurs, this is whenever the daily relative humidity downward crosses the critical deliquescence point of 75,3% on consecutive days. For hydrated salts, it is measured by counting the number of times when thenardite would convert to mirabilite when a crystallization pressure greater than 10Mpa (which equals the tensile strength for most porous stones) is counted. Whenever the crystallization pressure exceeds the tensile strength of the material, damage may occur and a phase is counted. For stones this entails a 10MPa phase boundary at RH_{eq}, this equation can be found below.[4]

$$RH_{eq} = 59.11 + 0.87549\,T \quad when\ T < 22.5°C \tag{1}$$

If the phase transitions would be counted from hourly data, the number of cycles would be distinctively higher. However, the use of daily average data can account for the buffering effect of stone during the moisture behaviour. Since there is not a method to convert the number of phase transitions into the amount of damage, this research only examines the number of cycles and will be used for a relative comparison.

3. RESULTS

First, it is essential to understand which parameters have a significant impact on the performance criteria and whether they are positively or negatively correlated. By understanding to what extent a particular parameter influences the performance, some initial insights can be obtained. The Spearman rank correlation proves to be a suitable method to measure sensitivity for building physics simulations [17]. The results are shown in Figure 1. The higher the rho value is, the greater the impact of the parameter on the damage criterion under examination. The hypothesis that the variable has a significant impact on the damage phenomenon is confirmed if the p-value is lower than 5%, if the p-value is higher than 5%, the selected parameter marked with a red triangle in Fig.1.

The shortwave absorption coefficient has a large impact on the number of crystallization dissolution cycles of salt, as do the rain exposure coefficient (RE) and the orientation. This is illustrated in the first row (green), more specifically for Halite (H) and thenardite-mirabilite (TM) at the outer surface (ex) and at 5mm depth (5mm). The wall thickness, orientation and rain exposure coefficient have a big impact on the amount of wood decay (WDrating), illustrated in yellow.

It is noticeable that the impact of a parameter on a certain performance criterion does not necessarily remain the same for the fail-value of that same performance criterion. For example, the difference between the influence of the shortwave absorption coefficient (AC) for the mould index on the inner surface and the smoothed effect when looking at the failure value for this part of the structure. There, parameters such as RE, orientation and material of the load-bearing wall have a greater influence on whether the fail-value is exceeded. The explanation lies in the fact that the difference brought about by this parameter is not in a range between fail and no-fail.

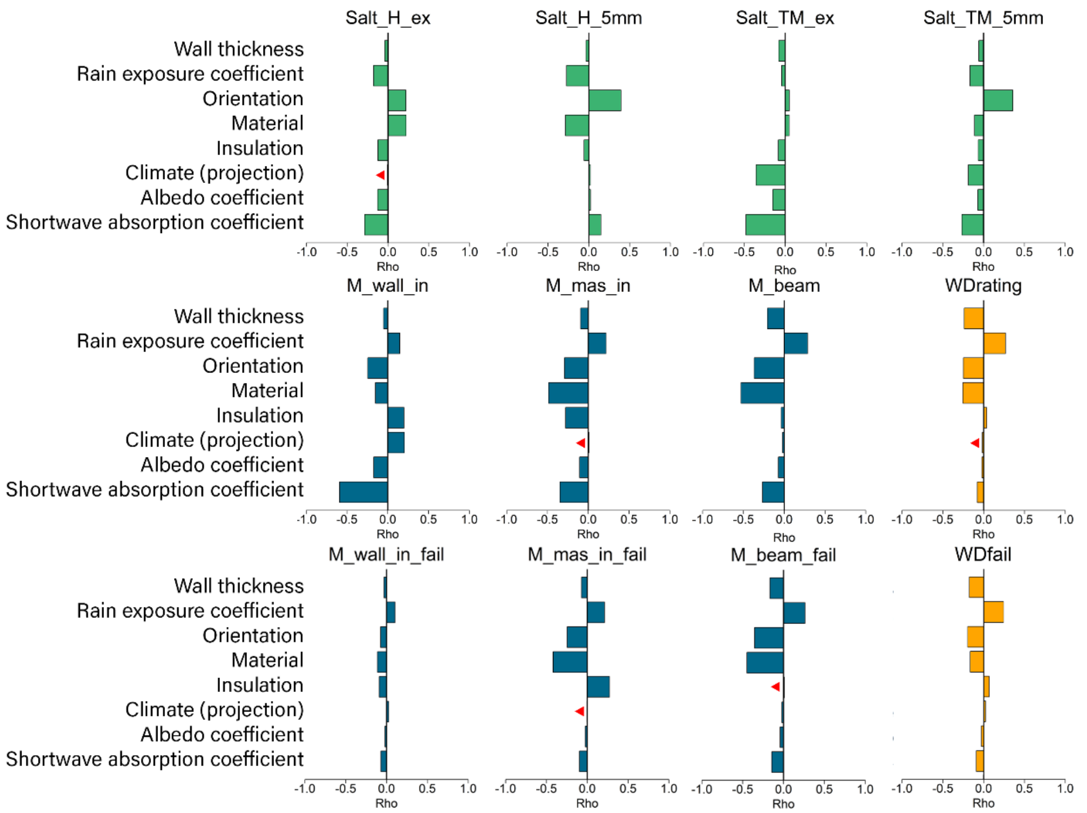


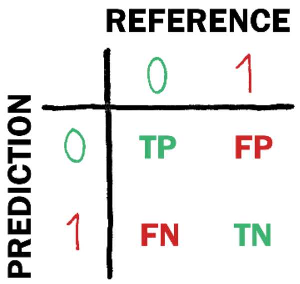
Figure 1: Standardized Spearman rank correlation coefficient (Rho). Parameters with a p-value greater than 0.05 are marked with a red triangle. Abbreviations: see page 9.

In order to develop a predictive model on which practitioners can rely for decision-making, the data is split into a training and testing set. Therefore, the model is constructed using the training set and the different models are evaluated using the testing set, revealing which model performs best. A value of 1 is achieved when damage is expected and a value of 0 when no damage is expected.

Common practice is to measure the performance of a trained model in terms of its accuracy (equation 2). However, this would lead to a situation where a false negative case (FN), where damage is predicted when it is not, is given the same weight as a false positive case, where damage is not predicted when in fact there is.

Therefore, the models will be compared by their decay accuracy rate, introduced here as the K-rate (equation 4). This rate takes into account that false negative (FN) cases are not harmful because damage is predicted, but in fact there is none. The false positive (FP) cases should really be avoided, they can appear without being foreseen and can inflict considerable damage. Therefore, it is essential to eliminate these false positive (FP) cases from the model as much as possible.

Another factor to compare is the specificity (equation 3). This rate shows what fraction of all negative cases are correctly predicted.



$$\text{Accuracy} = \frac{\text{TP+TN}}{\text{TP+TN+FP+FN}} \quad (2)$$

$$\text{Specificity} = \frac{\text{TN}}{\text{TN+FP}} \quad (3)$$

$$\text{K-rate} = \frac{\text{TP+FN+TN}}{\text{TP+TN+FP+FN}} \quad (4)$$

Figure 2: Confusion matrix which compares the predicted model built with the training dataset with true class, namely the testing set. With TP (true positive), FP (false positive), FN (false negative) and TN (true negative).

6 models are compared to decide which prediction model can best be applied to obtain the best results, i.e. to obtain the highest K-rate. The section underneath describes the comparison in relation to mould growth on the inner surface.

As explained above, the data set is split into a training set and a test set. The training set is used to build the model and the test set is used to verify how robust and precise the prediction model is.

The first method tested is a basic classification tree, a regression model with a general structure following a two-stage procedure. The obtained models can be represented as binary trees [18]. Further pruning of the obtained classification tree is carried out using the most appropriate complexity parameter, this is used to select and control the optimal size of a tree to achieve its highest accuracy.

All other methods belong to the ensemble methods, whereby weak learners are combined sequentially or in parallel to obtain more accurate predictive models. The random forest and bagging models extract a majority vote from a large number of decision trees to reduce the prediction variance. The boosted decision trees subsequently add ensemble members to correct the prediction of the previously created models, whereupon a majority vote is generated based on these predictions [19].

Table 2 shows the accuracy (equation 2), specificity (equation 3) and K-rate (equation 4) for each prediction method. Overall, the Pruned Tree method performs best with respect to predicting mould at the interior surface. Although all methods perform well, except the random forest model with the ranger package that scores insufficient specificity, the method of a pruned classification tree is applied in the remainder of this study. It can be assumed that the ideal prediction method is highly data-dependent, for best practice always compare performance for different predictions

Table 2: Comparing the performance of predictive methods for mould at the interior surface

Method	**Accuracy**	**Specificity**	**K-rate**
Classification tree	0.9974	0.7500	0.9981
Pruned tree	0.9984	0.8833	0.9991
Bagging	0.9973	0.8276	0.9988
Ada Boosting	0.9975	0.8621	0.9990
Random Forest	0.9979	0.7931	0.9985
Random Forest (ranger package)	0.9953	0.3448	0.9953

Figure 3 and 4 illustrate the classification trees that indicate whether damage is expected or not, for wood decay and mould damage at the interior surface respectively. The last node shows the outcome of 0 (no damage) or 1 (damage) and the number below the outcome indicates the probability of getting this result if you arrive at this node. The higher a parameter appears in the decision tree, the more important the variable is. Through examining the classification tree, many insights can be derived about whether or not damage is likely to occur.

For instance, if a wall has a south to north orientation, one can assume that no wood rot will occur in the embedded beam in that wall. However, if the wall is oriented between N-E and S-E, the next decisive factor would be the rain exposure coefficient. Whereas the orientation of your wall is fixed, an adjustment could be provided to ensure that the rain exposure coefficient remains below 1 in order to avoid the risk of wood decay. There is simply no use to change the RE from 2 to 1.5 if the wall is orientated east regarding wood decay.

These decision trees succeed in providing many practical insights for building practitioners. In order to supply even more straightforward guidelines, a list of conditions is presented below to ensure that the probability of damage remains below 5% if one of the listed conditions is achieved for your wall assembly.

To avoid wood decay (1 suffices)

- Wall orientation between south-west-north
- Rain exposure coefficient less than 1
- Bearing wall consists of concrete and is thicker than 300 mm
- Bearing wall consists of limestone and is thicker than 150 mm

To avoid mould at the interior surface (1 suffices)

- Wall orientation from south-west-north
- Interior insulation thickness is at least 100 mm
- Wall orientation from south-east to north and a RE<1.5
- Wall orientation from south-east to north and a shortwave absorption coefficient > 0.5
- Wall orientation from south-east to north and a historic or A1B projected climate
- Material of the bearing wall is either concrete, limestone or a brick clustered as ZO
- The shortwave absorption coefficient > 0.5 and RE < 1.5

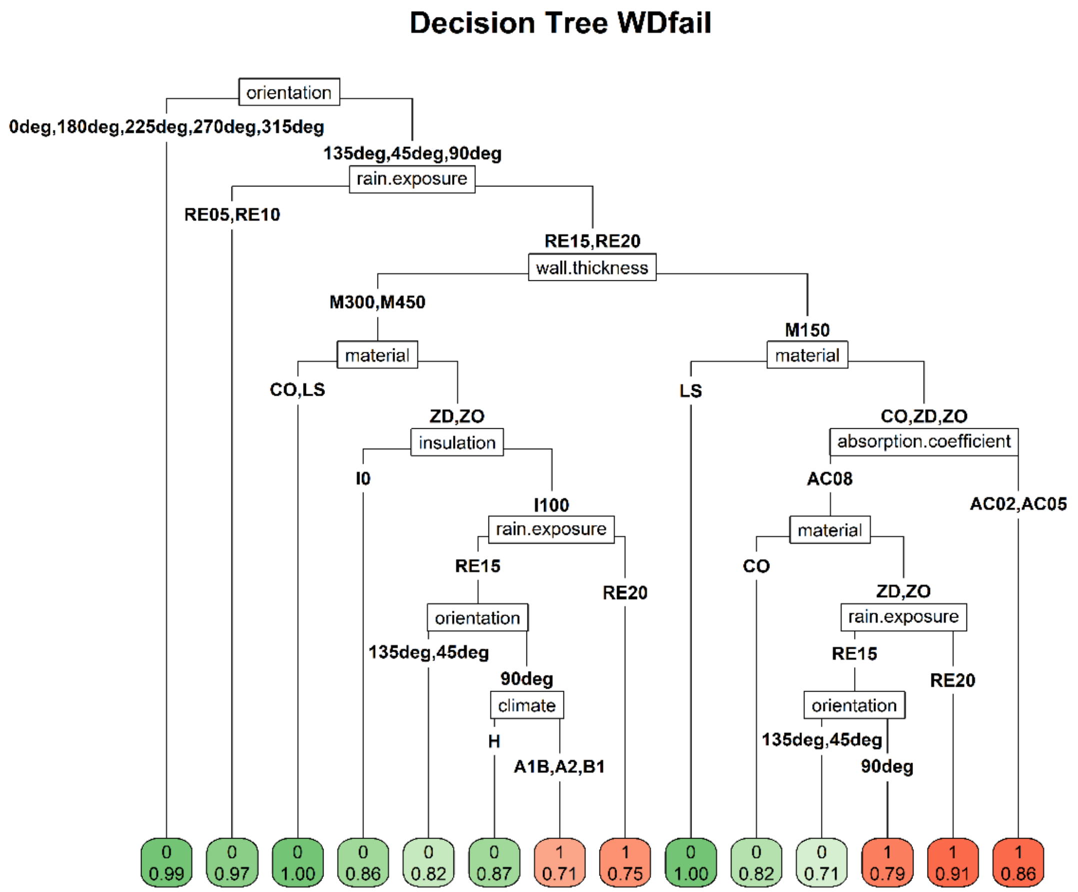


Figure 3: Decision tree fail-value wood decay (WDfail). Abbreviations: see page 9.

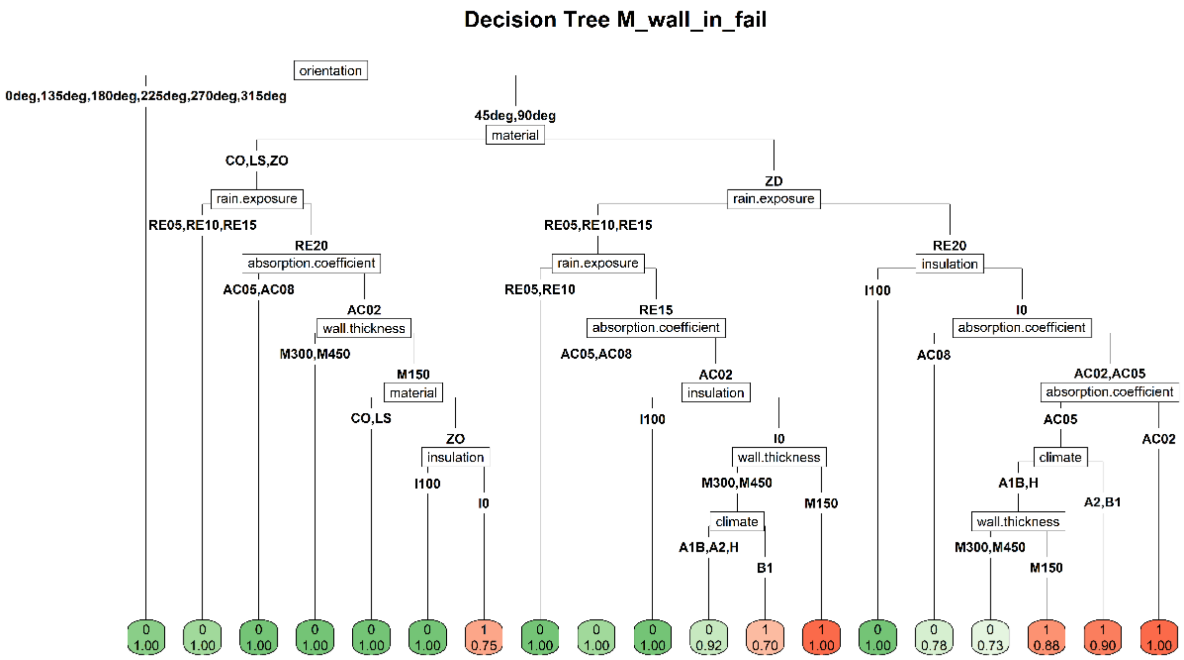


Figure 4: Decision tree mould damage at interior surface (M_wall_in_fail). Abbreviations: see page 9.

Considering salt damage, there is no way to convert the amount of phase transitions of salt to the amount of damage through, for example, a dose-response model, we focus on the absolute change in the number of cycles for the climate projections compared to the historic climate data. Figure 5 illustrates clearly that the mean absolute change (in blue above the graph) is not very large. However, the cases are scattered over a wide range, especially for halite.

To investigate this aspect, Figure 6 shows the decision tree for the absolute change in phase transitions for halite at the exterior surface. Note that the range of absolute change lies between a 25-cycle decrease and a 34-cycle increase; given this wide range, it is critical to understand which parameters are expected to entail the most significant increase.

It is striking that the parameter 'climate' appears rather low in the tree and does not yield clear statements, since climate projection B1 gives both a positive and a negative absolute change. We can conclude that the cycles for halite are expected to decrease if the wall assembly complies with one of the following propositions:

- The solar absorption coefficient is bigger than 0.8 and the bearing wall consists of concrete or limestone.
- The solar absorption coefficient is smaller than 0.5 and the wall is oriented from north to east
- The solar absorption coefficient is bigger than 0.5 and the bearing wall consists of concrete
- The solar absorption coefficient is smaller than 0.2, the wall consists of a brick that can be clustered as ZO and the future climate can be represented by projection B1

Furthermore, walls already affected by salt crystallisation due to halite, containing a bearing wall out of materials such as concrete or limestone with a solar absorption coefficient lower than 0.2 and an orientation from south to north-west, will face severe difficulties if the future climate follows the B1 projection. In that case, the cycles are expected to increase by 13 to 34 cycles, which may cause an increase in salt damage.

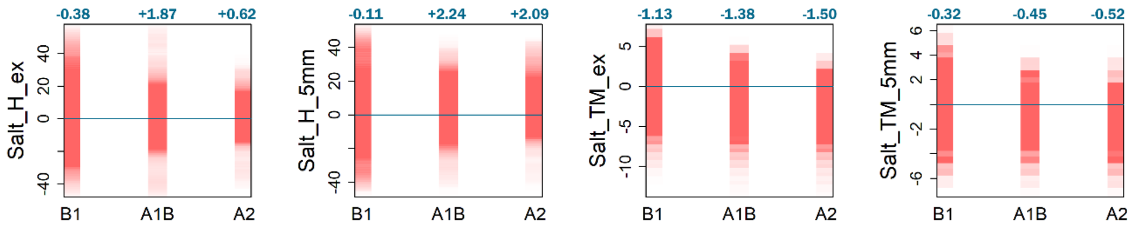


Figure 5: Change in phase transitions for different climate projections compared to the historic period. In blue above the graphs: the mean absolute change for this projection. Abbreviations: see page 9.

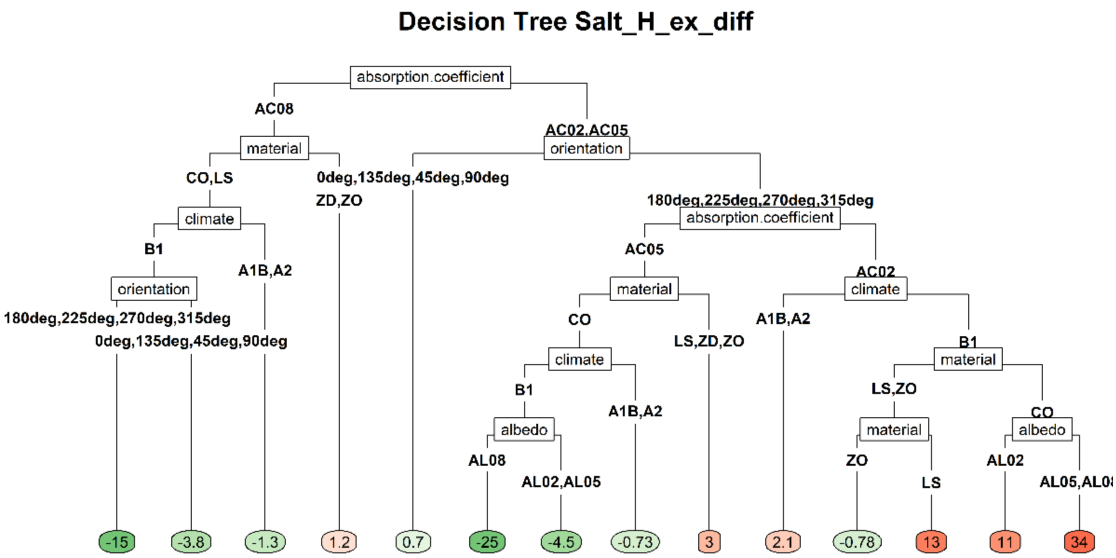


Figure 6: Decision tree change in phase transitions for halite at the exterior surface (Salt_H_ex_diff). Abbreviations: see page 9.

4. DISCUSSION AND CONCLUSION

The application of HAM simulations has not become widely adopted in practice yet, in part due to the complexity of the models, the uncertainties of the material properties and simplified approximations for damage criteria. Therefore, this article aims to explore the trajectory from simulation to practical guidance. Although, naturally, this process is not without its challenges.

First, it should be noted that there is still considerable uncertainty about how to quantify damage for performance criteria such as mould, wood rot and salt. This research applies the available methods, but does not aim to improve the quantification of damage. Instead, this research applies the available methods to investigate ways to translate them into practice. Secondly, the simulations carried out are all 1D simulations. Evidently, This entails simplifications because the wall construction is abstracted into a homogeneous brick construction without mortar joints or embedded beams. This simplification has been done to reduce the computational time and the costs, which increases dramatically when 2D simulations are performed. Where now the different parameters are varied in a full factorial approach, future research will require an efficient sampling technique for continuous and categorical values.

Decision trees are a useful tool to indicate which specific combinations of parameters entail a higher or lower risk for a certain damage criterion. These trees can be used as a flow-chart when all the variables have been quantified to understand the associated risks. In practice however, not all variables are quantified or some are surrounded by uncertainties, nevertheless the trees provide a high level of insight into the risks posed by a particular wall construction or retrofit. In addition, this information can inform building practitioners about exactly which parameters to address or which adjustments to introduce in order to prevent damage.

This paper notes that performing a sensitivity analysis is essential to quickly understand the influence of certain parameters on a given performance criterion. Furthermore, testing different prediction methods is beneficial to determine which type of model would perform best in regards to the given data. For damage prediction, the models performance is best measured by quantifying the K-rate rather than the accuracy. For this data, a pruned classification tree came out as the most effective way to translate the simulation results into a useful decision-making tool.

From these classification trees, we can derive a list of conditions where the wall assembly must comply with, in order to have only a 5% chance of damage. The trees can be built up more precisely if it is desired to reduce this fail-percentage, although this would imply that the conditions should also be stricter. In addition, for damage criteria whereby there is currently no method of quantifying the damage, it is nevertheless feasible to obtain comprehensive knowledge by carrying out a sensitivity analysis and by comparing the relative changes for a future climate regarding the historic climate in a decision tree. This allows for example to detect which wall constructions might be facing a significant increase in salt efflorescence due to climate change.

We can state that the development of a methodology for translating the results of hygrothermal simulations to practice can be of great value. Consequently, theoretical insights will not only remain within the academic world, but will also achieve an impact and application in the building industry.

ACKNOWLEDGMENTS

This research was funded by the Research Foundation Flanders (FWO), grant number 1S71922N (Kaat Janssens) and 1S90420N (Isabeau Vandemeulebroucke).

ABREVIATIONS

Salt_H_ex	Number of phase transitions for halite at the exterior surface
Salt_H_5mm	Number of phase transitions for halite at a depth of 5mm
Salt_TM_ex	Number of phase transitions for thenardite mirabilite at the exterior surface
Salt_TM_5mm	Number of phase transitions for thenardite mirabilite at a depth of 5mm
M_wall_in	Mould index at the interior surface
M_mas_in	Mould index at the interior surface of the load bearing wall
M_beam	Mould index at the place of an embedded beam
M_wall_in_fail	Fail-value of mould at the interior surface
M_mas_in_fail	Fail-value of mould at the interior surface of the load bearing wall
M_beam_fail	Fail-value of mould at the place of an embedded beam
WDrating	Wood decay rating
WDfail	Fail-value for wood decay
AC02	Shortwave absorption coefficient equal to 0.2
AC05	Shortwave absorption coefficient equal to 0.5
AC08	Shortwave absorption coefficient equal to 0.8
AL02	Albedo coefficient equal to 0.2
AL05	Albedo coefficient equal to 0.5
AL08	Albedo coefficient equal to 0.8
RE05	Rain exposure coefficient equal to 0.5
RE10	Rain exposure coefficient equal to 1.0
RE15	Rain exposure coefficient equal to 1.5
RE20	Rain exposure coefficient equal to 2.0
H	Historic climate
A2	Climate projection A2
A1B	Climate projection A1B
B1	Climate projection B1
CO	Concrete
LS	Limestone
ZD	Cluster ZD
ZO	Cluster ZO
TP	True positive
FP	False positive
FN	False negative
TN	True negative

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