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Improving hygrothermal risk assessment tools for brick walls in a changing climate

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Abstract. Due to the heritage value of historical buildings, the external facade can often not be modified. Therefore, heritage buildings require interior insulation when undergoing an energy renovation. However, interior retrofitting drastically changes the hygrothermal behaviour of a wall and can potentially cause moisture-related problems. Besides an interior retrofit, a changing climate might also trigger some of these damage mechanisms since parameters such as temperature and precipitation will change over time. It is proven that hygrothermal models can provide relevant insights into the risk of deterioration associated with these damage phenomena. Heat, Air and Moisture (HAM) tools are commercially available but rarely used in the building industry to study deterioration risks. Translating research into practical tools and guidelines is a challenge across the whole field of building renovation. This paper aims to tackle that challenge, by means of creating a hygrothermal risk assessment tool based on 48,384 HAM-simulations for the climate of Brussels, Belgium. Seven different performance criteria are addressed and discussed: freeze-thaw damage, mould growth, wood rot, corrosion, moisture accumulation, salt efflorescence and bio-colonisation. Subsequent to a sensitivity analysis, the study further investigates how these results can be translated into practice, providing building practitioners the most suitable insights and recommendations.

1. Introduction

It is indisputable that our historical building stock has high heritage significance, however it does not align with current energy reduction goals. Due to their often protected building facades, typically the only retrofitting solution is to place insulation at the interior side of the wall to reach energy renovation demands. As a result from the interior retrofit, the facade will have a lower drying potential and suffer from lower temperatures, inducing moisture related risks.

Next to interior retrofitting, also climate change can drastically affect the hygrothermal behaviour of a wall. Various studies have examined the impact of climate change for different regional models. Sabbioni et al. published the atlas of climate change impact on European cultural heritage [1] where different analyses, maps and management strategies can be found regarding different degradation phenomena. In the factorial studies of Vandemeulebroucke et al. [2,3], the impact of climate change is analysed on the hygrothermal behaviour of masonry walls for Brussels. They concluded that the impact of climate change on different performance criteria such as freeze-thaw risk, wood decay and mould growth are not the same for different representative concentration pathways or RCPs.

HAM tools have proven to be a valuable tool to assess the hygrothermal behaviour of building components. Although these tools are commercially available, their practical application remains limited due to the fact that they require specific knowledge to post-process and interpret the results. Calle et al. [4] stated that conducting a sensitivity analysis to gain insights from hygrothermal simulations has high potential, next to that Marincioni et al. [5] discussed whether decision-making for interior insulation can be assisted by probabilistic risk assessment. Decision trees can be useful to derive practical guidelines from simulation results and help the translation process from theory to practice [6].

Different attempts have been made to translate this academic knowledge to practice, each with their specific goals and pitfalls. In 2010, the Isolin-tool was launched by the government of Wallonia, Belgium [7]. This excel tool allows to fill in some variables, and in turn provides the hygrothermal analysis which was derived from the simulation software WUFI. However, it is imperative to fill in every single variable, since the tool does not work if any type of data is missing. The project Renofase [8] contains, inter alia, a diagnostic tool to help building practitioners with decision-making regarding renovation work, using a traffic light system for risk assessment. Furthermore, the project RIBuild [9] provides a lot of useful information on typical damages, checklists to fill in for your building, and discusses different insulation systems. Although the information provided is very comprehensive, it lacks a prediction model to foresee case-specific damage and suggest concrete further steps. The goal of this research is just that: to find a way to predict the damage phenomena for a specific case study.

2. Methodology

2.1. Simulation set-up

HAM software and HPC (High-Performance-Computing) The study setup consisted of 48,348 HAM simulations performed in Delphin 6.1. To reduce computational costs, 1D simulations were used. The model construction included the creation of a 1D cross-section of the wall and the assignment of boundary conditions and climate. The process for the simulation and calculation progress proceeded as such: first, all simulations were set up and run by an R script and the simulation tool via HPC. After a convergence check, the performance criteria were calculated by means of various R scripts on HPC.

Parameter variation Table 1 provides an overview of the parameters that were varied in a full factorial approach. To cover the historical masonry building stock as much as possible, a fixed specific sampling distribution was applied to each variable. Each combination of parameters has been simulated, resulting in a total of 48,348 simulations.

Table 1. Parameter variation for the HAM-simulations.

Parameter	Variations	Description
Climate	4	Historical climate (1972-2005), Climate projections RCP 2.6, RCP 4.5 and RCP 8.5 (2066-2099)
Orientation	8	N, N-E, E, S-E, S, S-W, W and N-W
Wall thickness	3	150 mm, 300 mm and 450 mm
Brick	6	ZH, ZG, ZB, ZK, ZF and ZI
Insulation type	3	None, vapour open system with vapour control layer and a capillary active system
Insulation thickness	3	50 mm, 100 mm and 150 mm
Rain exposure coefficient	4	0.5, 1.0, 1.5 and 2 [-]
Shortwave absorption coefficient	3	0.4, 0.6 and 0.8 [-]

Material Six different bricks were selected, based on the clustering approach of Vanderschelden et al [10]. In this way, each cluster is represented in the total dataset. Three different wall thicknesses were chosen, namely 150 mm, 300 mm and 450 mm. Since 1D simulations are used, the influence of mortar joints have not been taken into account. Two different interior insulation systems were modelled, a vapour open system with a vapour control layer (VCL) and a capillary active system, the latter allows moisture to accumulate and be redistributed within the insulation by capillary action, and aims to dry out due to seasonal variations. Three different insulation thicknesses were simulated: 50mm, 100mm and 150mm. The vapour open system consisted of mineral wool insulation and a VCL with sd= 2.3 m, whereas the capillary active insulation system consisted of calcium silicate without a vapour barrier.

Climate The climate data were obtained from the ALARO-0 Regional Climate Model [11] for the grid point of Brussels, Belgium. They consisted of two 30-year periods. The historical climate data cover 1972-2005 and the future climate data 2066-2099. These future data were applied to account for climate change. 3 different RCPs were considered, namely RCP 2.6, RCP 4.5 and RCP 8.5.

Boundary conditions Eight different orientations were simulated for each case. To represent different colours of the outer surface, three different shortwave absorption coefficients were used, 0.4, 0.6 and 0.8, respectively representing light-coloured paint and exposed brickwork (0.4), muted paint (0.6) and dark paint or clinker brickwork (0.8) as provided by the German standard DIN 18599 [12]. EN ISO 6946 [13] was followed for the exterior boundary conditions regarding water vapour and heat transfer coefficients at the exterior surface. EN 15026 [14] was consulted to determine the indoor climate conditions. Four different rain exposure coefficients were applied: 0.5, 1.0, 1.5 and 2.0. This large range allows the integration of the effect of runoff, roof overhangs and malfunctioning gutters [4]. The reader can refer to the manual of the Delphin software [15] for more information about the setting up of a Delphin model.

2.2. Performance criteria

To understand the deterioration risk of the wall assembly in relation to moisture-related damage, seven different performance criteria were adopted. Please note that only existing performance criteria are used, obtained from literature.

Freeze-thaw damage Freeze-thaw damage takes place when water freezes in the pore structure of the brick. Due to hydraulic pressure and the ice lens mechanism, damage is induced. Whenever the ice mass density exceeds 25% of the open porosity, one FTC_{crit} was counted [16]. The number of critical freeze-thaw cycles (abbrev. *FTC*) was calculated at a depth of 5mm from the exterior surface. This is proven to be the critical depth in relation to freeze-thaw action [17]. Even though 25% may be a very low threshold, it is mainly used to a comparative assessment here.

Mould growth Mould growth can occur at the interior building surface or behind the interior retrofit under specific boundary conditions. The mould growth can be defined by the mould index (M) and calculated using the VTT model [18]. The mould index varies from 0 (spores not activated) to 6 (100% mould coverage). A common threshold criterion is M=3. This is equal to a mould coverage between 10 and 30% where the mould is visually recognisable. The mould index (abbrev. *M*) was calculated at the interior surface, behind the interior retrofit, and at the depth of an embedded beam at 100mm from the inside of the bearing wall. The decline rate was always set to 'no decline' and the mould sensitivity was varied between very sensitive (vs), sensitive (s), medium resistant (mr) and resistant (r) for the mould index at the interior surface of the wall.

Wood decay Wooden beams embedded in the masonry structure can be affected by wood rot. When a wall is internally insulated, the wooden beams are exposed to lower drying potential leading to higher moisture contents, hence they are more susceptible to wood decay. To determine the amount of mass loss at the beam head, the dose-response relationship of Brischke and Rapp [19] was applied. The wood decay was quantified at a depth of 100mm from the interior masonry surface which is the minimum structural support for a beam embedded in masonry. Because the study adopts 1D simulations, the beam itself was not modelled, therefore the influence of the beam itself was not accounted for. As stated in EN 252 (1989) [20], the mean decay rating (abbrev. *WD*) is classified as 0 (no attack), 1 (slight attack), 2 (moderate attack), 3 (severe attack) and 4 (failure). To limit the risk for wood decay the threshold value of 1 should not be superseded over a 30-year period.

Moisture accumulation Moisture can accumulate in between or on building layers due to condensation, when hot and humid air meets a building surface colder than its dew point, or due to infiltration because of highly capillary active bricks. Moisture accumulation can trigger other moisture-related risks and therefore it is important to avoid run-off. To quantify if this forms a risk, the hours of run-off were calculated (abbrev. *MA*), both for a criterium of 0.1 kg/m² and 0.2 kg/m².

Salt efflorescence Salt crystallisation is a prominent degradation risk triggered by the salt mixture behaviour inside the brick's pore structure. Salt degradation can be quantified by calculating the number of crystallization-dissolution cycles (abbrev. Salt). One phase transition is counted when the crystallization pressure exceeds the tensile strength of the material. Criteria for hydrated and non-hydrated salts are provided by Grossi et al. [21], represented by halite, a common salt in monuments, and thenardite-mirabilite (abbrev. T-M), a very damaging salt, respectively. The cycles were counted for three temporal resolutions: hourly values, 12 hourly values and daily values.

Corrosion Metallic reinforcements or steel components embedded in the masonry can be affected by corrosion when exposed to a certain level of humidity [22]. The corrosion rate R [μm/year] (abbrev. Cor) is calculated using the combined hygrothermal and corrosion model of Zelinka et al. [23] Note that the corrosion rate was calculated for galvanised steel, since only these corrosion parameters are provided. This may be accurate for current building practice but may differ significantly in historical structures. The threshold applied was not to exceed a current density i [mA/m²] of 1 as stated by Marra et al. [24], the Faraday law was used to calculate the transition from corrosion rate to current density.

Bio-colonisation Biological colonisation is the growth of microorganisms on the exterior surface of a wall. Fast-growing organisms settle on the exterior masonry surface first, after which slower-growing organisms get a chance of accumulating [25]. The bio-colonisation was calculated using the hours of optimal growth, both for bacteria (abbrev. *Bio_bacteria*), and fungi and lichen (abbrev. *Bio_lichen*). One hour of optimal growth was counted whenever the water activity of the exterior surface exceeds 0.98 for bacteria and 0.65 for fungi and lichen, as stated in Sabbioni et al. [1]. Furthermore, the species richness D (abbrev. Bio_richness) was calculated.

3. Results

3.1. Analysis

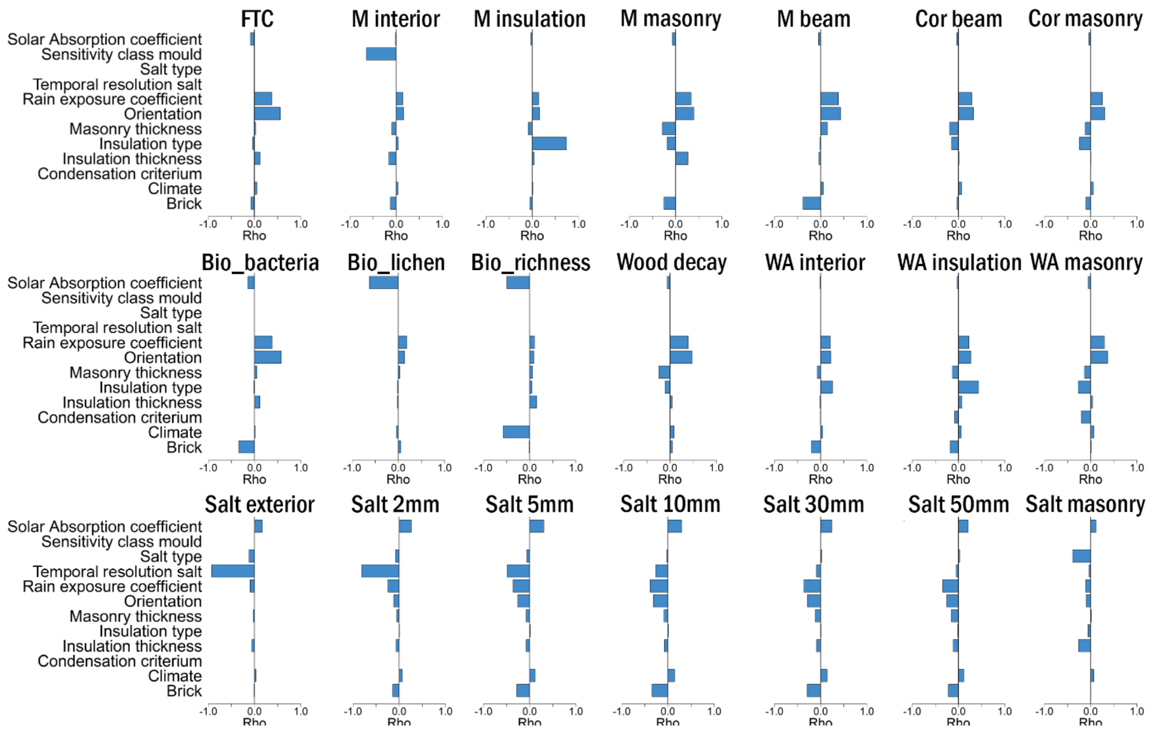

Figure 1. Spearman rank correlation for every performance criterion. The abbreviation of the performance criterium is followed by the place in the wall assembly (with masonry as the inside of the bearing wall).

First of all, understanding which parameters have a significant influence on the different performance criteria is essential. Figure 1 shows the Spearman rank correlation of the different variables in relation to the performance criteria. The higher the Rho-factor, the higher the variable is correlated with the damage criteria. A negative Rho factor implies a negative correlation and vice versa. Figure 2.a shows the correlogram of different performance criteria in a more numerical way, when blue, the correlation is positive and when red, negative. The denser the colour, the higher the correlation.

A lot of information can be derived from Figure 1 and 2.a Regarding freeze-thaw damage it is clear that the rain exposure coefficient (RE) and the orientation were the two most important factors. For mould at the interior surface (M interior), it is striking to see the importance of the chosen sensitivity class. This shows that varying this value is highly important when calculating a mould index. Please note that the decay rate was not varied. The type of insulation system was highly significant when looking at mould behind the interior insulation, together with the RE and the orientation. Notable when we look at salt cycles, is that the type of salt is most significant at the interior side of the masonry. The importance of the chosen temporal resolution decreases when going deeper into the masonry from the outside.

In Figure 2.b the impact of climate change on the risks and performance of the wall is reported. For RCP 2.6, in general, all degradation phenomena are expected to increase compared to the values derived for the historical climate. A big difference in between the different RCPs can be noticed. This confirms the importance of using different climate projections.

Figure 3.a shows the number of salt cycles throughout the masonry wall section. We can see that the crystallization dissolution cycles are expected to be the highest in the first centimetres of the masonry, after which it decreases quickly. However, we can see a significant increase in cycles when looking at the inner surface of the masonry for Halite. The increase at the interior side however, is rather modest compared to the amount of cycles on the exterior side relatively speaking.

When looking at calculating mould growth, most of the time a sensitivity class '(very) sensitive' is used just to account for the worst-case scenario. Looking at Figure 3.b, it is evident that this highly influences the outcome. It would be better to variate the class if the exact classification of the material is unclear. This way an over or underestimation can be avoided.

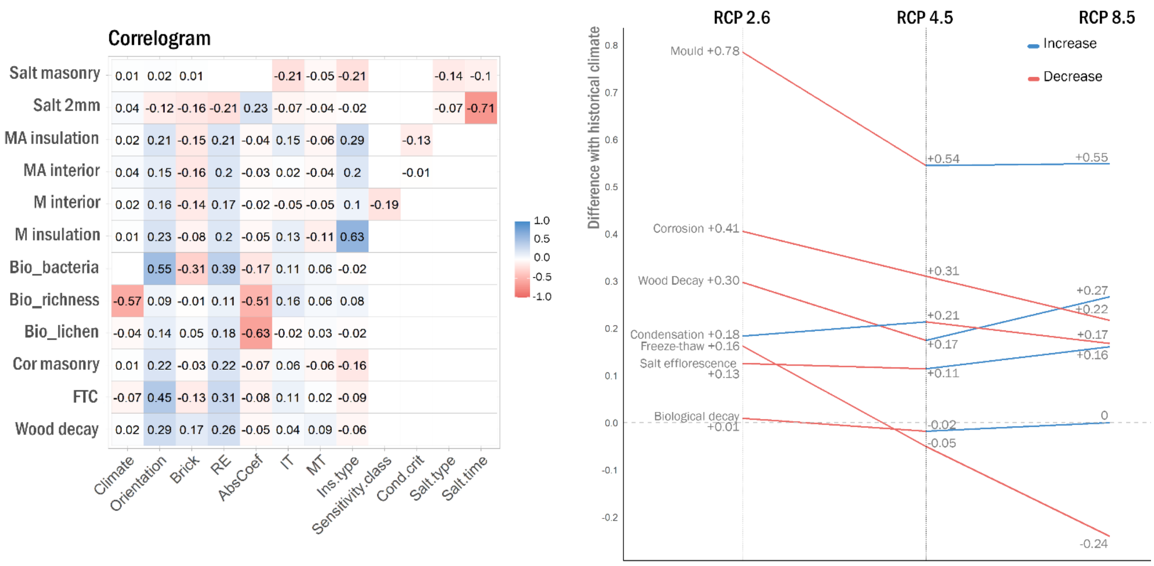

Figure 2. Left: Correlogram for the performance criteria and the variables **(a).** Right: Increase or decrease of the performance criteria for the 3 RCPs in comparison with the historical climate **(b).**

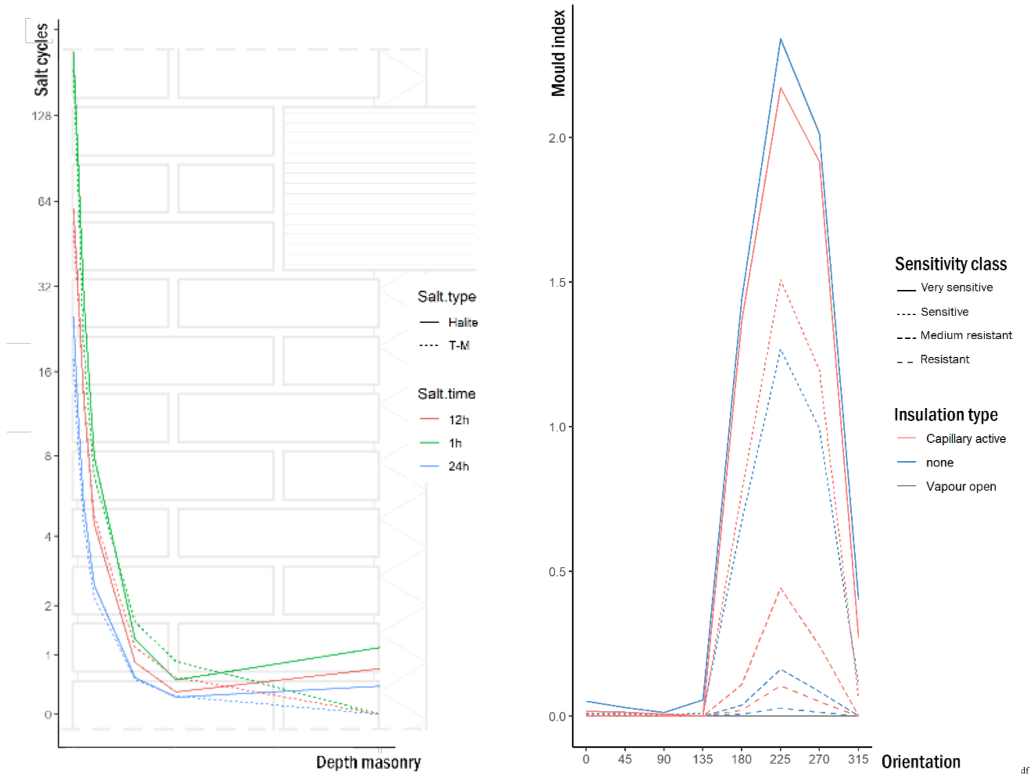

Figure 3. Left: the number of salt cycles through the depth of the masonry wall **(a).** Middle: The mould index on the inside surface of the total wall assembly as a function of wall orientation **(b).**

3.2. Translation to practice

Although HAM-tools are commercially available, we see that they are barely used in practice. We want to overcome this problem by creating a webtool which is easy to use and provides the user with a case-specific decision frame. This webtool, made in Shiny [26], starts from data already simulated in Delphin 6.1. The data is subdivided by the use of a questionnaire that the user can fill in. The results of this questionnaire automatically divide the data, thus the provided information which is generated will be case specific as seen in the flowchart (Figure 4). After the available information is filled in, the webtool provides, next to dynamic decision charts, advice and next steps which would be smart to take (Figure 5). For instance: the user has a S-W facade with a light colour and the brick's absorption coefficient is 0.1 $kg/m^2s^{0,5}$, he or she wants to know what interior insulation is best to use. Automatically all the cases with other orientations than S-W are omitted, only cases with a solar absorption coefficient of 0.4 are kept, and only brick clusters ZI, ZF and ZK are still considered. To point out the most important parameters, a graph such as Fig. 1 and 2.a contains most information but these are not as comprehensible for people unfamiliar with statistics. A pie chart, on the other hand, is proven to be easy to read and ties in with the advice, aiming to provide the user information in layman's terms.

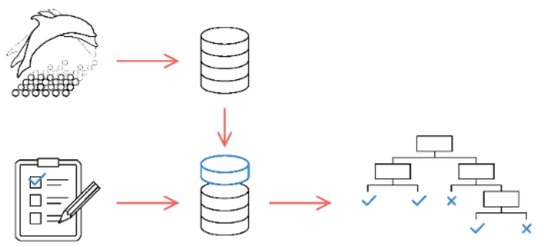

Figure 4. Left: Flowchart of the web tool's process.

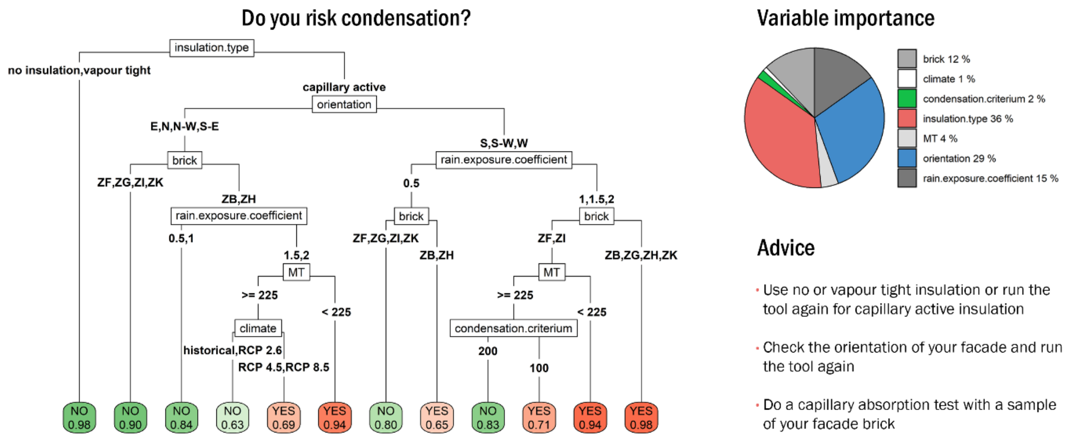

Figure 5. Example of the output of the webtool with the prediction model using a decision tree (with the probability under YES and NO), a pie chart for easy-to-read information and advice which is coupled to the most important variables.

4. Conclusions and discussion

HAM-tools are commercially available but rarely used in the building industry to study deterioration risks. Important reasons are the lack of reliability due to uncertainties on input parameters, and the required effort related to additional post-processing. Translating research into practical tools and guidelines is a challenge across the whole field of building renovation. In this research, 48,348 simulations were executed in Delphin 6.1 for different combinations of parameters. A dataset with seven different performance criteria was developed for each set of parameters, using the results of the HAM simulations. The analysis shows that it is of utmost importance to choose the parameters you simulate wisely, especially if they have a significant impact on the final result. The performance criteria should be further examined and the validation with reality tested.

Furthermore, climate change is also an important factor to consider. It is not straightforward how degradation risks will behave for different climate projections. Therefore, it is important to always apply different RCPs so that the final results will range somewhere intermediate.

By using decision trees, a framework for decision-making is developed based on the simulation results. To make these easily accessible, a web tool created in Shiny [26] is provided. To ensure that the results are as representative as possible for the user consulting the decision tool, a questionnaire is incorporated. Hence, a dynamic decision tool is developed that extracts information from the questionnaire to reduce the dataset. This tool provides valuable results, but in some cases it is still useful to run HAM simulations if the predicted damage risks require more detailed assessment. With all the great research already conducted, as discussed in the introduction, the tool can easily be linked to any of these projects to achieve the best overall quality and usage. The main goal of this research is to ensure its ease-of-use for everyone. Therefore, advice written in layman's terms can be linked to key variables to provide the user with case-specific knowledge. As such, practitioners in the construction industry do not always have to run HAM simulations themselves to predict moisture-related damage, but can create their own case-specific decision framework with advice within seconds.

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