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, external facades can often not be modified. Therefore, in heritage buildings interior insulation is often considered 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 as parameters such as temperature and precipitation will change over time. Hygrothermal models can provide relevant insights into the risk of deterioration associated with these damage phenomena. However, these 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 explains how these results can be translated into practice, providing building practitioners the most suitable insights and recommendations. The development of an interactive web tool to assess hygrothermal risks is demonstrated and its use and benefits are further elaborated.

Keywords: HAM-simulations, Interior retrofit, Deterioration risks, Masonry, Heritage, Decay

1) Introduction

It is beyond doubt that our historic building stock has great heritage value, nevertheless the building sector accounts for almost 40% of total energy consumption and 36% of CO2 emissions. (Blumberga et al., n.d.). The heritage buildings are unable to meet current energy reduction targets and are in need of undergoing an energy renovation through the installation of thermal insulation. This could potentially reduce the energy need for space heating by 9-43% (de Place Hansen and Wittchen, 2018). Considering that 30% of the European building stock was built before 1945, this represents a vast percentage of the current building stock, which underpins the need for safe solutions and designs to facilitate this retrofitting revolution.

Due to their often-protected facades, typically the only retrofitting solution for heritage buildings is to place insulation at the interior side of the wall in order to comply with energy renovation demands. As a result from such interior retrofit, the hygrothermal behaviour of a facade changes drastically as the wall drying ability decreases and the wall will be exposed to higher temperature fluctuations from the exterior climate (Zhou et al., 2017). The change in hygrothermal performance of the facade triggers different moisture related risks such as freeze-thaw damage, mould growth and wood decay. Because of the potential damage patterns, building practitioners often encounter reluctance to apply an interior retrofit solution (Vereecken et al., 2015).

Next to applying interior insulation, also climate change drastically affects the hygrothermal behaviour of a wall. Various studies have examined the impact of climate change for different regional climate models. The atlas of climate change (Sabbioni et al., 2010) illustrates the impact on European cultural heritage where different analyses, maps and management strategies can be found regarding different degradation phenomena. In the factorial study of Vandemeulebroucke et al. (2021), the impact of climate change on the hygrothermal behaviour of masonry walls was analysed for Brussels. The study concludes 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 (Vandemeulebroucke et al., 2021; Vandemeulebroucke, Kotova, et al., 2023).

Heat, Air and Moisture (abbrev. 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. Conducting a sensitivity analysis to gain insights from hygrothermal simulations has shown to provide a high potential, because it can indicate what factors influence the damage risks on masonry constructions (Calle and Van Den Bossche, 2021). Next to that, decision-making for interior insulation should be assisted by probabilistic risk assessment instead of the currently applied deterministic scenario analysis (Marincioni and Altamirano-Medina, 2018). A major assistance in this process can be the use of decision trees to derive practical guidelines from simulation results and help the translation process from theory to practice (Janssens et al., n.d.).

Existing methods

Different attempts have already been made to translate this academic knowledge related to hygrothermal risks to the building industry, each with their specific goals, achievements and pitfalls:

First, in 2010, the Isolin-tool was launched by the government of Wallonia, Belgium (Evrard et al., 2016). This excel tool requires to fill in every input parameter, and in turn provides the hygrothermal analysis of that specific wall set-up (which was derived from 7000 simulations performed in the software WUFI PRO 4.2). However, the tool is not accessible due to different reasons. First and foremost it is no longer operational or possible to get. Secondly, it is imperative to fill in every single variable such as the absorption coefficient of the brick, insulation type, interior climate, etc. (the tool does not work if an input is missing). Next to that, only two orientations are provided: North and South-West. The output of the tool includes the temperature and relative humidity, heat and moisture flux, and moisture release at the interior surface. Although relevant, this type of output is not very informative to steward decision making processes. Further, a traffic light advice (resulting in positive, risky or negative) is provided evaluated with the possible accumulation of water content inside the interior insulation. No other damage risks are discussed.

Secondly, an important report on interior insulation of facades (Steskens et al., 2012) supports decision-making using a traffic light system for risk assessment. A list of pass/fail (green/red) criteria is provided as a check-list for building professionals. However, in practice the majority of historical dwellings and facades fall within an additional orange zone, meaning

‘Applicability is unknown’. Moreover, the different criteria that lead to the green zone are in many cases not easily met or quantified.

Furthermore, the publication originating from the project Renofase (Renofase, 2015) entitled ‘A decision making tool for the energy efficient refurbishment of residential buildings’ elaborates on the previous project (Steskens et al., 2015). It adopts this pass/fail approach, although this methodology is not supported by any hygrothermal simulations and hence does not provide a finer granularity to steward building practitioners in the decision-making process.

Lastly, the project RIBuild (Blumberga et al., n.d.) focusses on interior insulation and provides a lot of useful information on typical damages, checklists, and different insulation systems. Furthermore, the RIBuild project launched the Insulation Calculation Tool (Moller et al., n.d.). That tool focusses on the evaluation of energy performance for different interior insulation systems for different places in Europe. Further, the tool provides the mould index behind the insulation layer and an algae index at the exterior to check the performance of the insulation system. Although the information provided is very interesting, the tool rather focusses on energy performance of different interior insulation systems on more general European scale than on future damage risk of the whole wall assembly. It lacks a clear prediction model to evaluate case-specific damage phenomena for a specific place and does not include the impact of climate change.

The goal of this research is just that: finding a way and methodology to predict damage risks customised for the knowledge that is available. This decision-framework will improve the decision-making for building practitioners and allows a more quantitative approach towards risk management for the current and future climate of Belgium.

2) Methodology

In the next part of the paper, the methodology will be explained. Firstly, the development of the hygrothermal model is explained. Secondly, the paper elaborates on the post-processing of the simulation data and which different performance criteria are applied to quantify the deterioration risk of the facade. Lastly, the practical usage of the post-processed data is explained focusing on translating the results to practice as comprehensible and case-specific as possible.

Simulation set-up

(a) HAM software and High Performance Computing (abbrev. HPC)

The study setup consisted of 48.348 HAM simulations performed in Delphin 6.1(Nicolai and Grunewald, 2003). To reduce computational costs, 1D simulations were adopted. The model construction consists out of 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 follows: first, all simulations were set up and run by an R script and simulation tool on the HPC. After a convergence check, the performance criteria were calculated by means of various R scripts run on HPC infrastructure.

(b) 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 parameter combination has been run, 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 [-]

(c) Material

Six different bricks were selected, based on the clustering approach of Vanderschelden et al. (Vanderschelden et al., 2022). In this way, each brick type is represented by a corresponding brick in the total dataset as shown in Figure 1. Three different wall thicknesses were chosen, i.e. 150 mm, 300 mm and 450 mm. As 1D simulations are used, the influence of mortar joints has not been taken into account. Three different interior insulation systems were modelled, a vapour open insulation system with a vapour control layer (VCL), no insulation 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. Please note that the insulation is assumed to be installed as designed, theoretically (ADT), meaning the systems are well installed following the state-of-the art and fully bonded with the existing masonry wall.

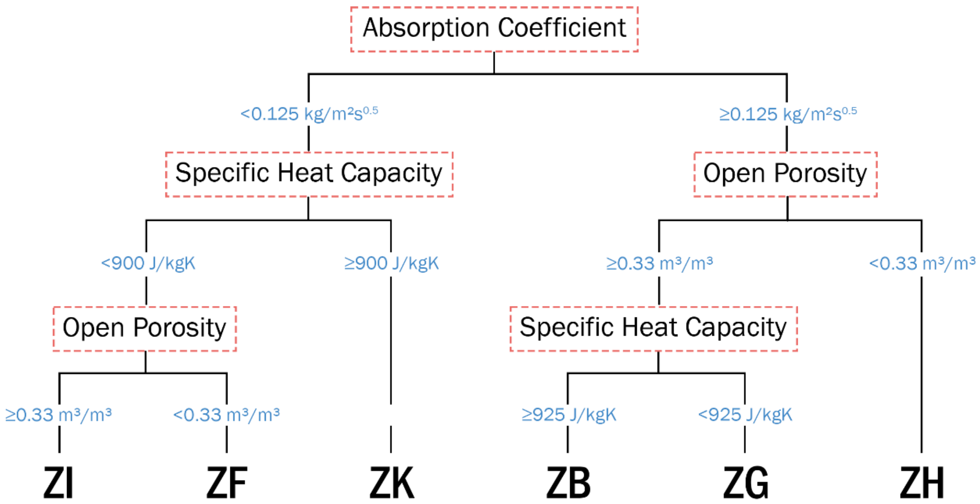

Figure 1. Selection of bricks from the Delphin material database based on clustering approach (Vanderschelden et al., 2022)

(d) Climate

The climate data were obtained from the ALARO-0 Regional Climate Model for the grid point of Brussels, Belgium (Giot et al., 2016 and Leissner et al., 2015). This consisted of two 30-year periods of historical data and climate projections, applied as described by Vandemeulebroucke et al., 2023. The historical climate data cover the period from 1972 until 2005 and the future climate data the period from 2066 until 2099. The climate projections are implemented to take into account climate change. 3 different RCPs were considered, namely RCP 2.6, RCP 4.5 and RCP 8.5. Respectively representing a low, medium and high emission scenario. Figure 2 shows the temperature [°C] and precipitation [l/m²h] of the different RCPs compared to the historical climate data over a 30 year period. It becomes clear that working with 30 year climate data is important to incorporate yearly differences and more extreme weather years.

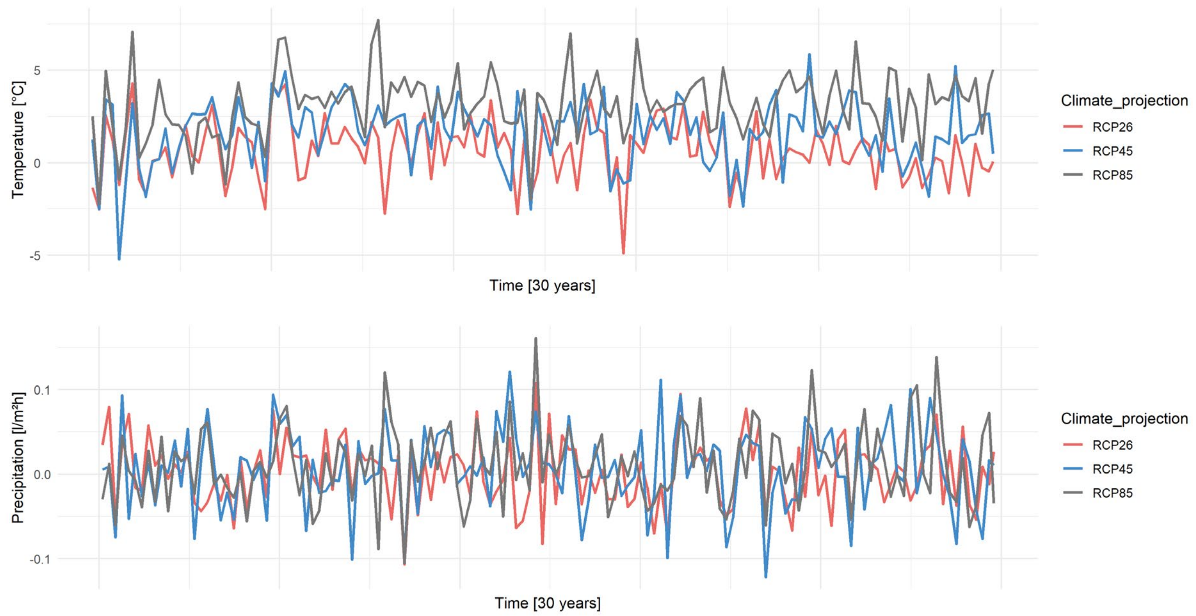

Figure 2. Temperature and precipitation for the different RCPs compared to the historical climate data plotted over a 30-year period based on average seasonal values

(e) Boundary conditions

Eight different orientations were simulated for each case: N, N-E, E, S-E, S, S-W, W and N-W. To represent different colours of the outer surface, three different shortwave absorption coefficients were used, 0.4, 0.6 and 0.8, respectively representing by a light- (0.4), mid-tone- (0.6) or dark-coloured (0.8) facade as provided by the German standard DIN 18599 (DIN V 18599- 2007). EN ISO 6946 (CEN. EN ISO 6946, 2017) was followed for the exterior boundary conditions regarding water vapour and heat transfer coefficients at the exterior surface. EN 15026 (CEN. EN 15026, 2007) 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 roof overhangs (rain exposure < 1) and runoff or malfunctioning gutters (rain exposure ≥1) (Calle, 2020). The reader can refer to the manual of the Delphin software (Nicolai and Grunewald, 2003) for more information about the set-up of a Delphin project.

Performance criteria

To predict the possible moisture-related deterioration of the wall assembly, this research looks at seven different decay mechanisms focused at the whole wall assembly, both the existing masonry wall as the possible insulation systems. To quantify these decay mechanisms different performance criteria were adopted. The importance of selecting the right performance criteria cannot be underestimated, as results will depend completely on which criteria apply. It is crucial for academia to continue reviewing and evaluating the existing methods. Please note that this study does not focus on the accuracy or evaluation of the performance criteria, instead existing criteria were obtained from literature. In the next section, the applied performance criteria will be explained.

(a) 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. The critical freeze-thaw cycle (abbrev. FTCcrit) method is applied based on research of Mensinga et al. (Mensinga et al., 2010). Whenever the ice mass density exceeds 25% of the open porosity, one FTCcrit is counted. The number of FTCcrit was calculated at a depth of 5mm from the exterior surface, which is considered to be the critical depth in relation to freeze-thaw action. Even though 25% is a rather conservative threshold, it allows to conduct comparative assessments if the applied material is not known in detail.

(b) Mould growth

Mould growth can occur at the interior building surface or behind the interior insulation under specific local environmental conditions. The mould growth can be defined by the mould index (M) and calculated using the VTT model (Viitanen et al., 2015). The mould index varies from 0 (spores not activated) to 6 (100% mould coverage). The mould index (abbrev. M) was calculated at the interior surface of the whole wall assembly and behind the interior retrofit, if present. 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 (Ojanen et al., 2011). Mould requires a surface to grow, therefore mould risk is only considered if the insulation is not fully bonded to the wall. A common threshold criterion is M=3 for interstitial layers (mould coverage between 10 and 30% where the mould is visually recognisable) and M=1 for a surface (initial stages of local growth). (Viitanen et al., 2015)

(c) Wood decay

Timber joists embedded in the masonry structure can be affected by wood rot which can eventually lead to structural failure. When a wall is internally insulated, the joist ends are exposed to a 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 joist end, the dose-response relationship of Brischke and Rapp was applied (Brischke and Rapp, 2008). As stated in EN 252 (CEN NBN EN 252, 2014), the mean wood decay rating (abbrev. WD) is classified as 0 (no attack), 1 (slight attack), 2 (moderate attack), 3 (severe attack) and 4 (failure). The possible wood decay was quantified at a depth of 100mm from the interior masonry surface which is the minimal structural support for timer joists embedded in a masonry wall. To limit the risk for wood decay the threshold value of 1 should not be superseded over a 30-year period, which is the minimal lifespan of wooden elements in building constructions. Because the study adopts 1D simulations, the timer joist itself was not modelled, therefore please note that the influence of the timber itself on the hygrothermal behaviour of the wall was not accounted for.

(d) 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 rain water ingress because of highly capillary active bricks. When moisture gets the chance to gather at a certain spot it can cause other damage such as mould growth or wood rot. The formation of droplets is accepted as long as they can dry out quickly and run-off is avoided. To quantify this risk, the hours of potential run-off were calculated (abbrev. *MA*) at the interior surface and behind the insulation layer, both for a criterium of 0.1 kg/m² (more conservative) and 0.2 kg/m² (ETAG 004, 2013).

(e) Salt efflorescence

Salt crystallisation is a prominent degradation risk triggered by phase transitions of the salt mixture 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. (Grossi et al., 2007). Two typical salts are represented, namely a non-hydrated and a hydrated salt. The first being halite, a common salt in monuments, and the second thenardite-mirabilite (abbrev. T-M), represents a more destructive salt. The crystallization-dissolution cycles are quantified at different places in the masonry wall: the exterior, 2mm, 5mm, 10mm, 30mm, 50mm and the interior. Grossi et al. advise to use daily values to count the cycles to take into account the buffering effect of the stone in the humidity transfer. Since the material moisture buffering effect is already included in hygrothermal modelling, the use of daily values can be questioned. Time is a highly important factor when looking at the formation of crystals in a porous medium, represented by the effective growth time (Godts et al., 2021). Therefore, the crystallisation-dissolution cycles were counted for three temporal resolutions: hourly values, 12 hourly values and daily values. Please note that the influence of the salt mixture itself on the hygrothermal behaviour of the wall assembly is not accounted for.

(f) Corrosion

Metallic reinforcements or steel components embedded in masonry can be affected by corrosion when exposed to a certain level of humidity (Straube and Schumacker C, 2006). The corrosion rate R [μm/year] (abbrev. Cor) is calculated using the combined hygrothermal and corrosion model of Zelinka et al. (Zelinka et al., 2011) at the interior side of masonry wall and at the joist ends. Note that the corrosion rate was calculated for galvanised steel, since only these corrosion parameters are provided in literature. 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/m^2] of 1 as stated by Marra et al. (Marra et al., 2015), the Faraday law was used to calculate the transition from corrosion rate to current density.

(g) 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 (Siegesmund and Snethlage, n.d.). 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. Furthermore, the species richness D (abbrev. Bio_richness) was calculated based on its negative correlation with temperature (Sabbioni et al., 2010).

Translation to practice

Although tools for hygrothermal modelling are commercially available, their use in practice remains limited. An explanation might be that an extensive knowledge to set up and post process the results is required. When HAM tools are applied in practice, a reduction in model quality is observed because the state-of-the-art is not always applied. This may be reflected in the choice of the wrong material files, the inaccessibility of appropriate climate data or the application of simple and very conservative post-process performance criteria. These insights were gained during workshops with building practitioners organised together with the UK Centre for Moisture in Buildings (UKCMB) group (https://ukcmb.org/).

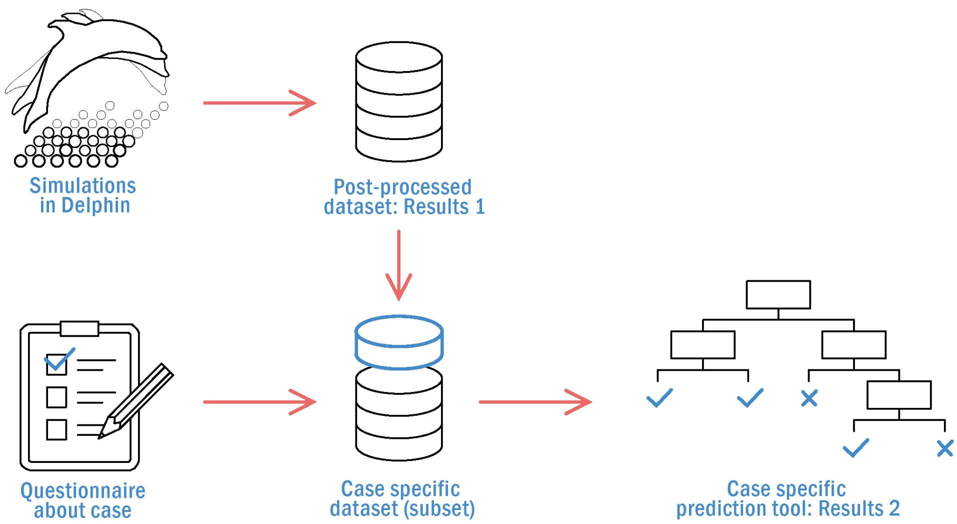

Figure 3. Flowchart of the applied methodology

To provide easy-to-read information for the building industry, the use of predictive models plotted as decision trees has proven to be a valuable method. Note that these models provide very accurate information on the complex interaction of all factors, as this is a non-linear prediction model. The higher a parameter appears in the tree, the more influence it has on the final result, for every 'step' all factors are reconsidered in the sensitivity analysis. In earlier research, 6 different prediction models were tested: Classification tree, Pruned tree, Bagging, Ada Boosting, Random Forest and Random Forest (ranger package). The Pruned tree resulted to be the most reliable option, however all models performed very good (Janssens et al., 2022).

In Figure 3, a flowchart is depicted of the applied methodology in this research. It departs from the results of simulations performed in Delphin 6.1 that are subsequently post-processed using the performance criteria described in the previous subchapter. Utilizing the entire post-processed dataset for evaluating hygrothermal risks would yield valuable insights; nevertheless, employing it in a specific case may result in overly generalized advice. To overcome this problem and to provide a more case-specific decision framework, the data could be subdivided by a questionnaire that the user can fill in. The results of this questionnaire automatically divide the data resulting in a case specific subset. Lastly, to provide the user with an easy to use and case-specific decision frame, an interactive webtool was created in Shiny [26]. The webtool provides dynamic decision charts, a sensitivity analysis and advice.

To offer more comprehensive results for users to assess the potential damage risks, the tool incorporates not only decision trees based on dose-response method resulting in an index; e.g. the mould index or wood decay rating, but also threshold-based trees if thresholds are known; e.g. a mould index higher than 1 for surface mould is a clear risk. By presenting the output into a clear YES/NO statement considering risk rather than relying on the interpretation of indexes by the user, the tool aims to enhance user accessibility.

The integration of more advanced performance criteria, ensuring state-of-the-art simulations inputs, applying extensive climate data and the amount of parameter variations, ensures the tools adaptability to the diverse range of masonry facades.

3) Results

Firstly this section examines the overall insights gained from the simulation results by performing a sensitivity analysis. Subsequently, the paper focuses on how the results can be translated to the building industry by means of the creation of an interactive webtool. Finally, the benefits of using the webtool for hygrothermal risk assessment are shown.

Results 1: sensitivity analysis

First, it is essential to understand which parameters have a higher influence on the different performance criteria to gain insights to prevent or remedy (future) damage. Keep in mind that the correlation methods discussed below have the disadvantage of behaving monotonically, yet these methods are of great value for identifying significant input parameters. Note that these are not the same for all degradation phenomena; favourable conditions for one type of decay may be unfavourable for another.

Figure 4 (top), shows the Spearman rank correlation of the different variables in relation to the performance criteria. On the x-axis, the Rho-factor is depicted, a value between -1 and 1. 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. A lot of information can be derived from this correlation scheme. Regarding freeze-thaw damage it is clear that the rain exposure coefficient (RE) and the orientation were the two most important factors, as these dominate the exterior surface conditions. 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 in this study. The type of insulation system was highly significant when looking at mould behind the interior insulation, together with the RE and the orientation. Notable is that the type of salt, namely halite of thenardite-mirabilite, has a very high correlation with the number of salt cycles at the interior side of the masonry. The importance of the chosen temporal resolution decreases when going deeper into the masonry from the outside due to the damping effect of the brick material.

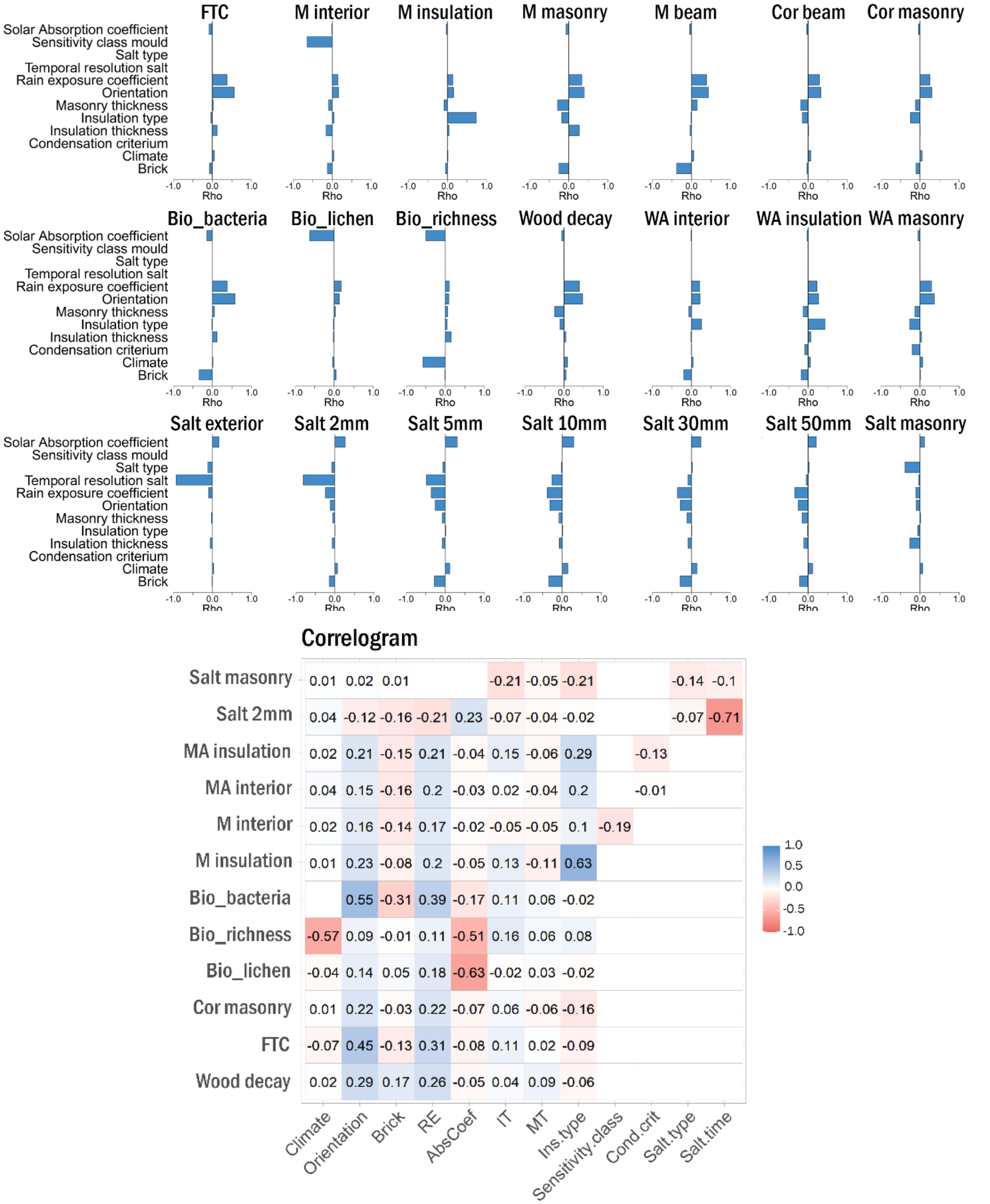

Figure 4. Top: Spearman rank correlation for every performance criterion. The abbreviation of the performance criterion is followed by the place in the wall assembly (with masonry as the inside of the existing wall). Bottom: Correlogram for the performance criteria and the variables

Figure 4 (bottom) also shows the correlogram of different performance criteria in a more numerical way: when blue, the correlation is positive and when red, negative. The brighter the colour, the higher the correlation. This graph makes it easier to visually assess the most influential parameters, such as the orientation, rain exposure and brick type. Very striking influential factors (with an absolute correlation higher than 0.5) are the climate and the shortwave absorption coefficient for the biological richness (Bio_richness), the shortwave absorption coefficient for the biological colonisation of lichen and fungi (Bio_lichen), the orientation and rain exposure for the biological colonisation of bacteria (Bio_bacteria), the type of insulation for the mould index behind the insulation layer, and the temporal resolution (Salt.time) for the number of crystallisation dissolution cycles at 2mm from the exterior surface.

Figure 5. (Left) 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 number of cycles on the exterior side.

When looking at calculating mould growth, a common approach is to use the sensitivity class '(very) sensitive' to account for the worst-case scenario. Looking at Figure 5. (Right), it is evident that this highly influences the outcome. It would be better to vary the class if the exact classification of the material is unclear. This way an over- or underestimation can be avoided (or at least quantified). Further, the sensitivity class determines whether a capillary active insulation material or a vapour open material performs better.

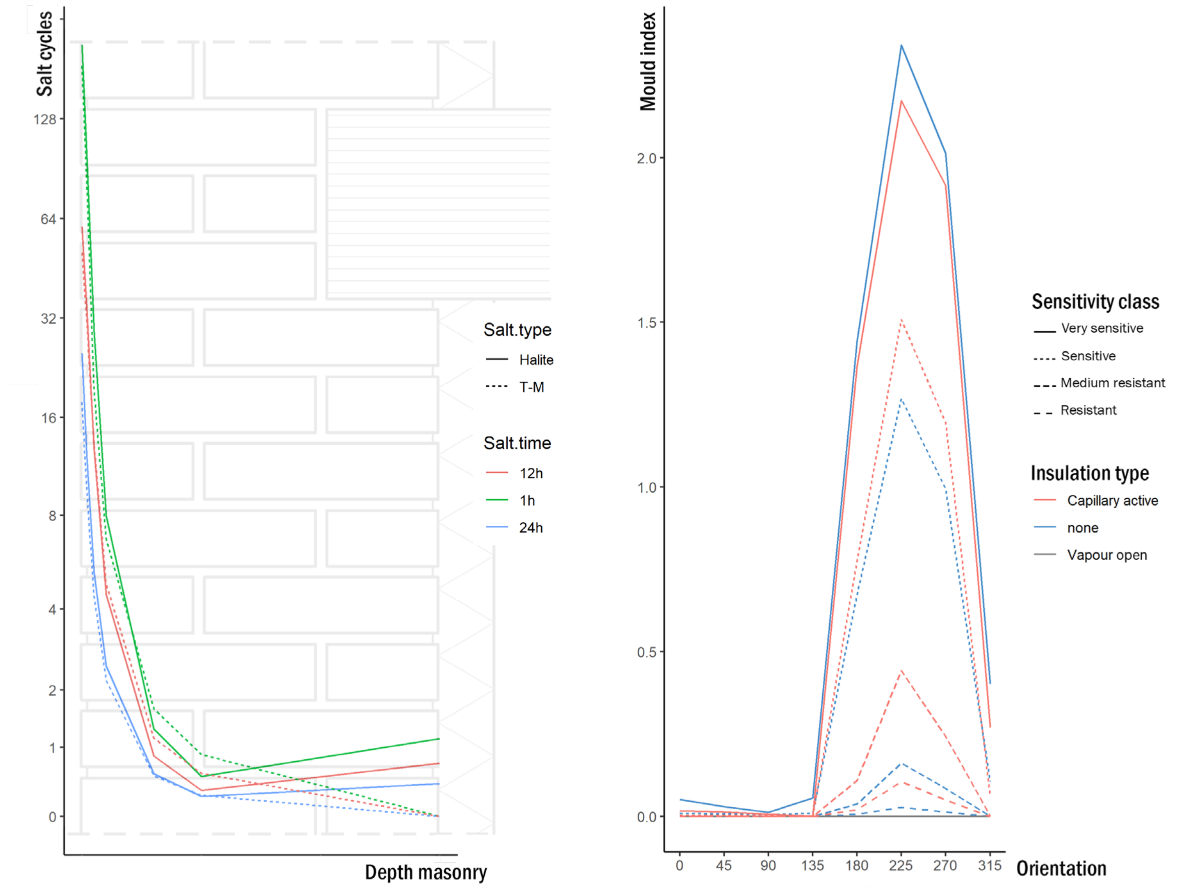

Figure 5. Left: the number of salt cycles throughout the depth of the masonry wall**.** Right: The mould index on the inside surface of the wall assembly as a function of wall orientation

Hygrothermal simulations have proven to be extremely useful in research on climate change and its impact on the built environment. In Figure 6 the impact of climate change on the risks and performance of the wall is reported in comparison with the historical climate. For RCP 2.6, in general, all degradation phenomena are expected to increase compared to the values derived for the historical climate. The general trend is that all damage risk will increase for future climate scenario's, except for freeze-thaw risk for RCP 4.5 and 8.5, and for biological decay for RCP 4.5. A big difference in between the different RCPs can be observed. This confirms the importance of using different climate projections. The biggest change can be seen in the mould index that will increase for all RCPs, however the largest increase is seen for the RCP 2.6 scenario. Note that these effects are also depending on the choice of performance criteria. Interestingly, the increase in damage risk is not necessarily the highest for the most extreme climate scenario (RCP 8.5).

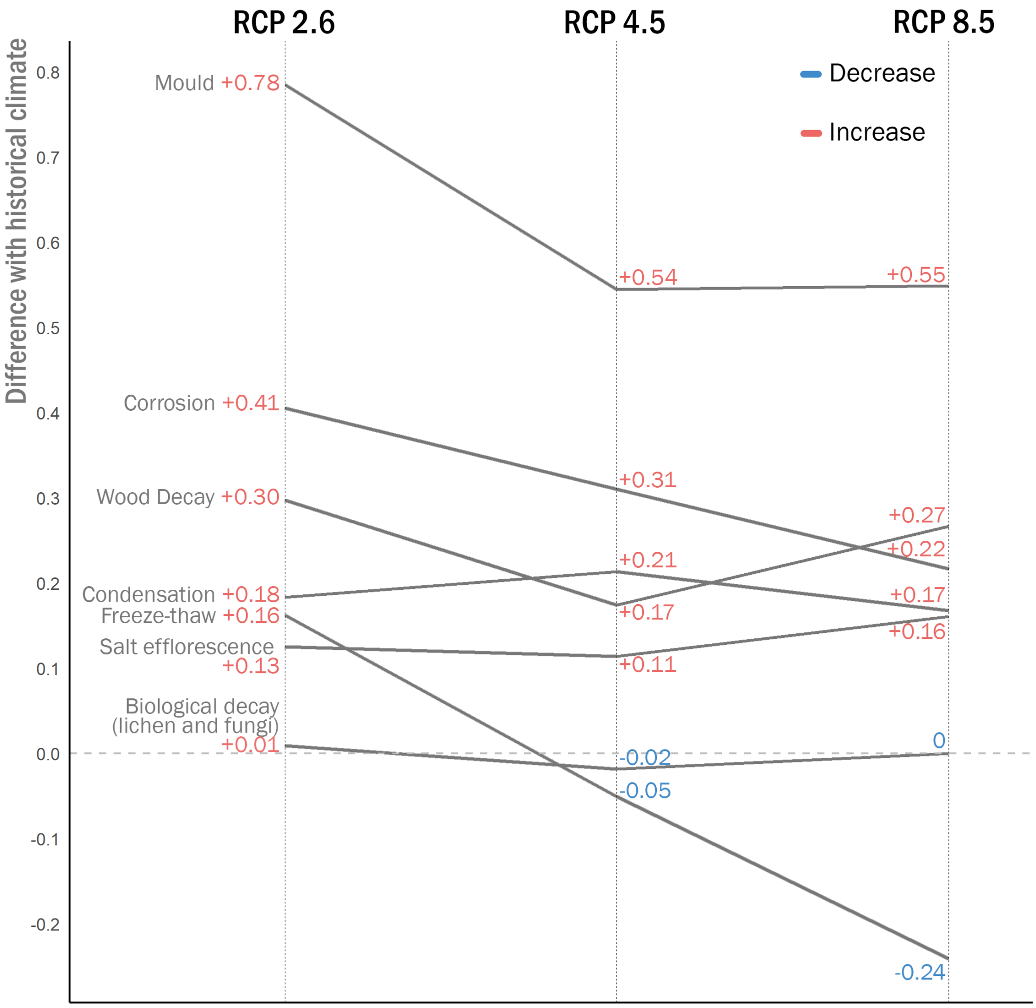

Figure 6. In- or decrease of the deterioration risk for the 3 RCPs in comparison with the historical climate. Next to the type of decay phenomenon, the in- or decrease is given [-].

As mentioned in the methodology, the use of decision trees as proven to be a valuable method to provide easy-to-read information. In Figure 7, such a decision tree is shown concerning the mould index on the interior surface. This illustrates the influence of orientation to be highest, followed by the insulation type and the sensitivity class of the surface material. Much information can be gained from a tree like this. For example, north-west to south-east facades have a low risk of mould growth, but this risk will increase in the future climates. Mould growth can be prevented by choosing a (medium) resistant sensitivity class material at the interior surface.

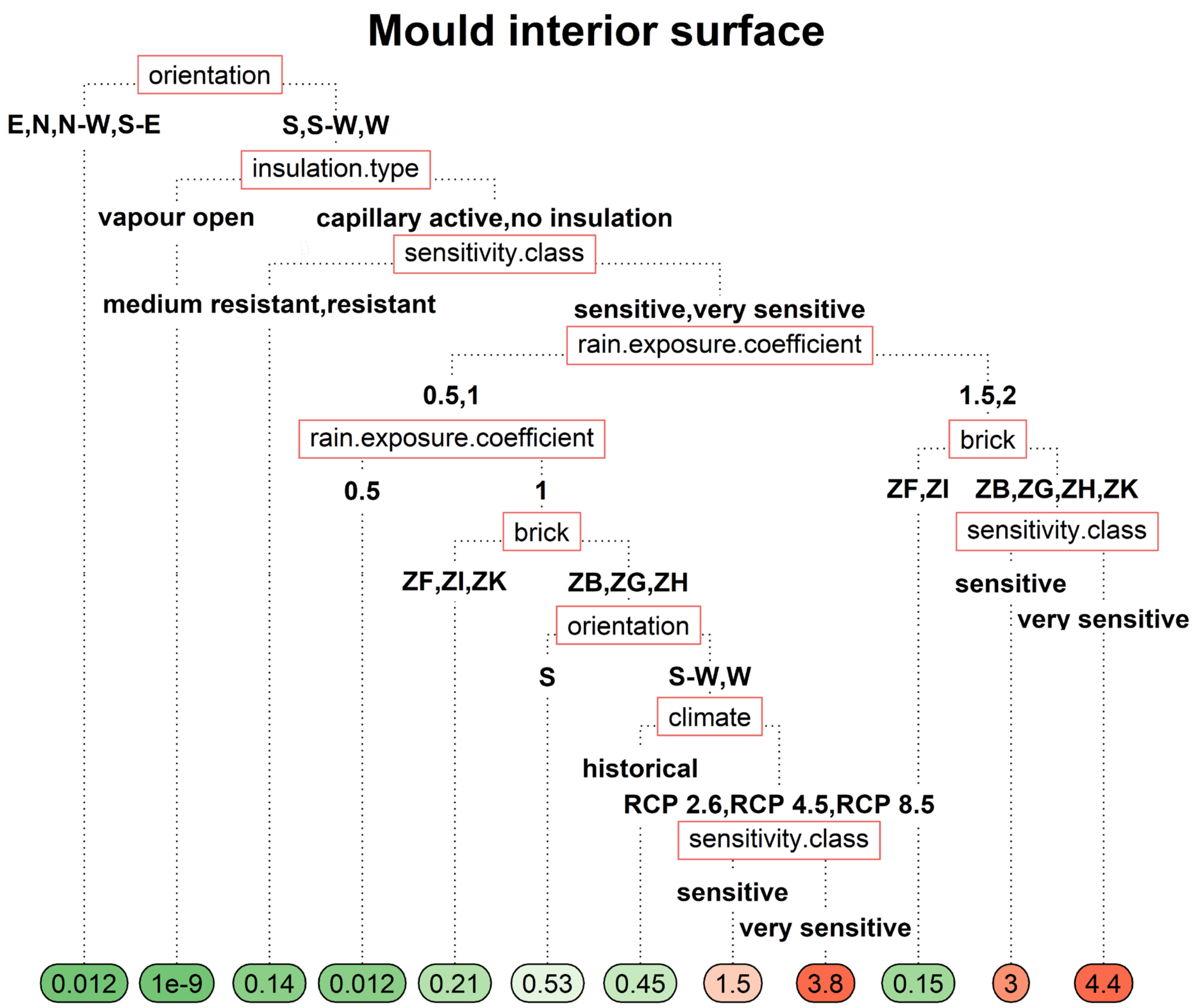

Figure 7. Example decision tree 'mould interior surface', results in mould index at the bottom

However, to assess the risk for a specific case, this decision tree could be devised more accurate. For instance, if the orientation of the facade is known, the first and seventh split is redundant, and a more precise prediction could be provided. Therefore, as pictured in Figure 3, the whole dataset is subset in a case specific dataset and a case specific prediction tool is developed.

Results 2: case specific prediction tool HAMalyser

The webtool, named HAMalyser (Janssens et al., 2023), is available online and has an open access (https://hamalyser.shinyapps.io/HAMalyser/). In the next paragraph, an example of the use of the webtool is discussed. The tool is online available, and additional features will be implemented in future updates.

A screenshot of the user interface of the tool is shown in Figure 8. In this case the user has a wooden joist end embedded in the wall and wants to place interior insulation, in doubt whether or not there is a risk for wood rot at the joist end in the current and future climate. First, on the left hand side the user provides the available information for the case. For instance, the facade has a south-west orientation, the aim is to place 15cm of interior insulation to meet energy requirements, and the thickness of the wall is 30cm. The user indicates to be interested in the dose-response results, e.g. wood decay rating, or in a YES/NO risk statement, e.g. risk for wood rot or no risk.

Figure 8. shows a screenshot of the webtool when the available information was filled in the questionnaire on the left hand side. On the right hand side, the decision tree is automatically generated and shown for this case. It can be inferred that the type of brick present in the wall and the exposure to rain have a large influence on the risk for wood rot. Furthermore, it can be stated that placing capillary active insulation is recommended for this case.

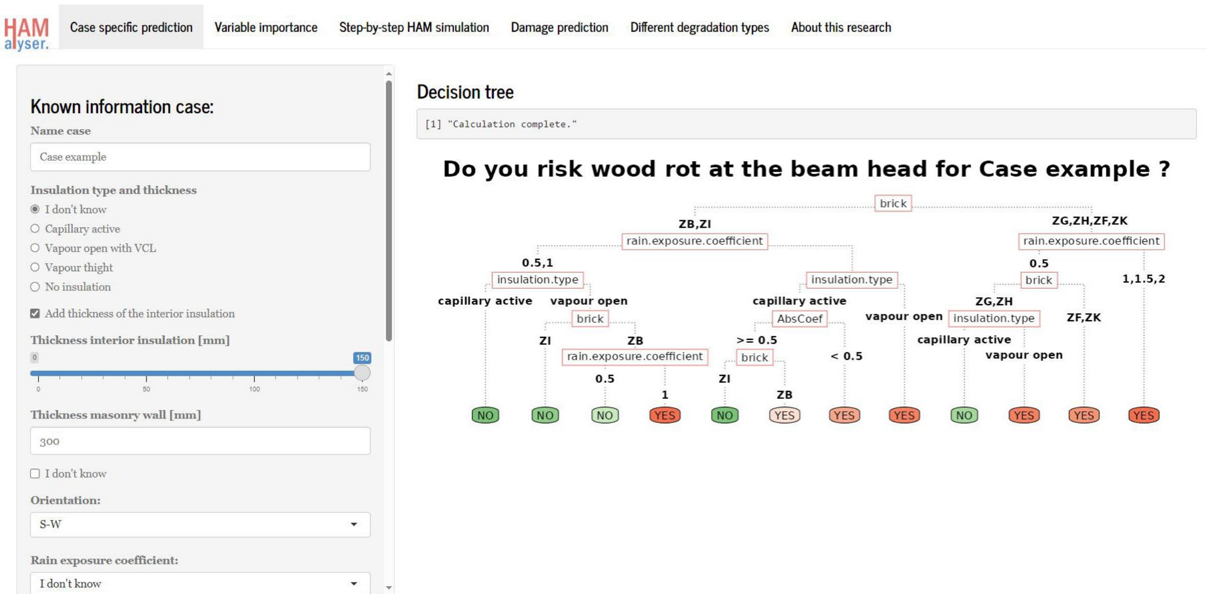

Figure 8. Example of the output of the webtool with the prediction model using a decision tree

To determine the most important parameters, graphs such as Figure. 7 and 8 contain the key data, 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 advice can be linked to the most influential parameters, aiming to provide the user information in layman's terms. Therefore, under the 'Variable importance' tab showed in Figure 9., a pie chart is generated which shows the remaining variables (i.e. the variables in the left pane that were not entered) that have a significant impact on (the uncertainty) of the end result.

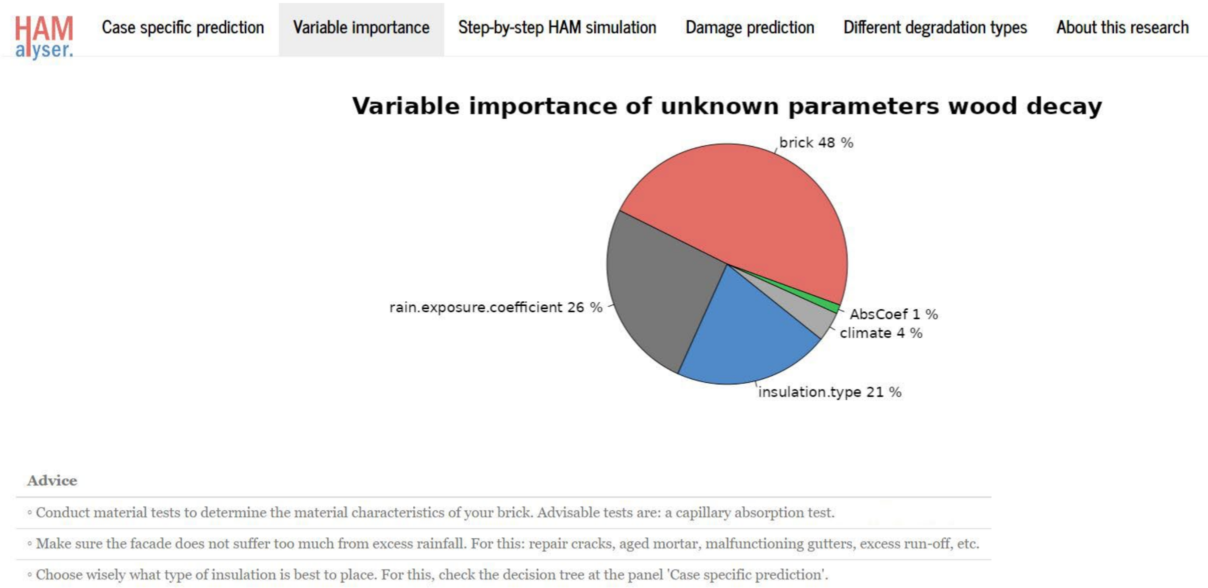

Figure 9. Variable importance tab for the example case: pie chart for the most important unknown parameters and associated advice.

Figure 9. shows an example of the 'variable importance' tab for the example case. It comes to front that the brick type, rain exposure coefficient and insulation type have the highest influence on whether or not wood rot is expected for the joist end. Therefore, to diminish the uncertainty of the advice or to diminish the decay risk the advice is offered to focus on characterizing the material by performing specific material tests. Furthermore, one should ensure that the facade does not suffer from excess rainfall, and for this case capillary active insulation materials provide the safest solution.

Benefits use webtool

This section explores the advantages of using the webtool. We revisit the example described above where we analyse the risk of wood rot in a joist end for a south-west oriented facade of 30cm thickness and want to install 15cm interior insulation. Figure 10 shows the decision tree if a decision tree was generated with the whole dataset, without taking a subset with information known. From this tree, we can conclude that for a south-west orientation we expect a risk of wood rot regardless whether insulation is installed or not. This reflection can be backed by the correlation diagrams in Figure 4, which show that the type or presence of interior insulation has little influence on the risk of wood rot at the joist end. However, if the tree were generated based on the subset (with information known about the case: south-west orientation, 30cm masonry thickness and 15cm of interior insulation), as shown in Figure 8, we can state that it is most likely possible to place capillary active insulation without risking wood rot. This estimate is supported if we look at the most influential parameters of the subset in Figure 9, where the type of interior insulation is the third most important variable.

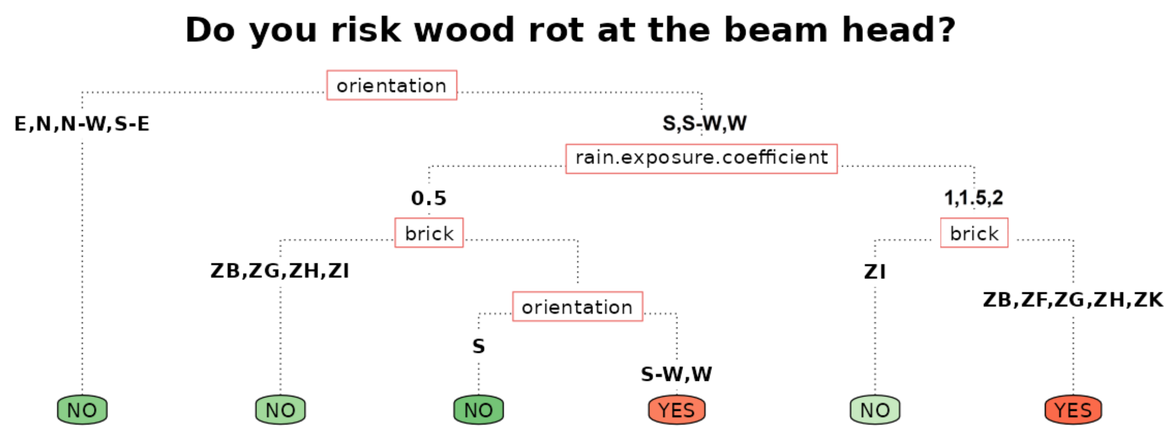

Figure 10. Decision tree 'wood decay' which shows there a risk or no risk is expected for the joist end (generated with the whole dataset).

Therefore, the web tool recommends providing more information on key parameters, in this example the type of brick, the rain exposure coefficient and the type of interior insulation. Obtaining more information on these parameters will drastically reduce the uncertainty of the prediction. Figure 11 shows the reduction in uncertainty for these different subsets, each of which has information on one additional parameter: subset 1 shows the initial subset (as shown in Figures 8 and 9) where the orientation, masonry thickness and interior insulation thickness are known. Subset 2 in addition contains information on the brick characteristics. It becomes clear that performing material tests really is beneficial in reducing the uncertainty of the risk assessment for this specific case. Subset 3 includes a fixed rain exposure coefficient (set at 0.5 in this example) in addition to the brick characteristics. Finally, subset 4 contains the type of interior insulation namely capillary active insulation. From the chart, the importance of knowing the most significant parameters becomes clear. As such, it is advisable to examine them or follow the advice to not have these parameters in the least favourable. This reduces the uncertainty of the risk assessment drastically.

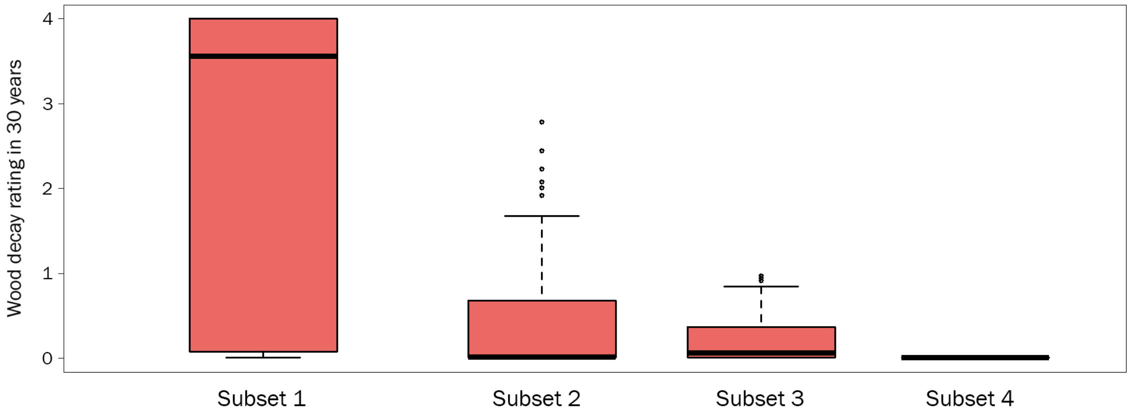

Figure 11. Boxplots wood decay rating in 30 years for different subsets.

4) Discussion and conclusions

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 parameter values in the simulation wisely, especially if these have a significant impact on the result. In future research the different 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 evolve for different climate projections. Therefore, it is important to always consider different RCPs to quantify the inherent uncertainty related to these climate conditions and that the final results will capture the range of possible future scenarios.

By using decision trees, a framework for decision-making is developed based on the simulation results. To make these easily accessible, a web tool named HAMalyser (https://hamalyser.shinyapps.io/HAMalyser/) is created in Shiny [26]. To ensure that the results are as specific as possible for the user consulting the decision tool for a case, a questionnaire is incorporated. Hence, a dynamic decision tool is developed that extracts information from the questionnaire to reduce the dataset and automatically generates decision trees that help the decision making progress regarding hygrothermal risk analysis. The trees focus on different degradation types and whether the facade is risking one of them. Next to that, advice is provided what unknown parameters are best examined to reduce the uncertainty as much as possible. 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. The integration of more advanced performance criteria in the already postprocessed simulation data further refines the tool's generalization of cases, ensuring its applicability and relevance to address the diverse masonry walls in the building stock.

Future research will include more variations of the input cases to prevent the subset being too small to extract valuable results. Next to that, instead of using a full factorial parameter variation a sampling scheme can be adopted to expand the application field while reducing the computational cost. Moreover, the performance criteria applied in the post-processing must be critically evaluated. The functionality and interpretation of the tool will be verified by performing workshops testing different user profiles.

The main concern of this webtool is to ensure it is 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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