Internal insulation – a preliminary assessment tool based on probabilistic simulations

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1. ABSTRACT

Historic buildings contribute heavily to the energy consumption of the European building stock, and internal insulation offers a possibility to improve energy performance and indoor thermal comfort, without compromising the buildings' architectural appearance. However, due to the complexity and many potential risks and uncertainties less experienced planners and building owners need a preliminary assessment tool and simple, practical guidance in a specific situation. This paper presents and discusses such a tool developed as part of RIBuild (www.ribuild.eu); the content, preconditions and limitations.

User input encompasses specific location and orientation of a building, and wall thickness and type, by using checkmarks and sliders. In each case, the tool delivers a list of solutions selected from a database of pre-calculated simulations made in the hygrothermal simulation tool DELPHIN with Quasi-Monte Carlo based repetitions of simulations; a probabilistic assessment. The user can prioritize solutions based on e.g. risk of mould growth or maximum thickness of insulation. The output describes the heat loss through 1 m² wall with and without internal insulation, as well as risk of mould growth behind the insulation and algae growth at the façade. An improvement of the reliability of the tool requires more simulations and the inclusion of other failure mechanisms than mould and algae growth.

2. INTRODUCTION

Internal insulation offers a possibility to improve energy performance and indoor thermal comfort of historic buildings, reducing their contribution to the energy consumption in buildings in Europe, without compromising their architectural appearance. However, internal insulation entails several risks as the original wall becomes colder and more humid. The RIBuild project (www.ribuild.eu) identified the need for a preliminary assessment tool and simple, practical guidance targeted at less experienced planners and building owners to overcome their restraint and to avoid mistakes when internal insulation of historic buildings is considered. The RIBuild website guides on how to determine if the building is suitable for internal insulation and it offers the Insulation Calculation Tool (ICT).

ICT is a web tool developed to be used by building owners or building professionals with limited knowledge on building physics, when they want to predict the implications of adding internal insulation to a solid wall made of brick or natural stone, by entering a few data on the building. Although energy savings are often the initiator for renovating a building, the development also focused on moisture related issues, e.g. mould and algae growth. The needed input data should be easy to find and not require laboratory tests. Before using the ICT, the user should have checked the building e.g. according to the guidelines at www.ribuild.eu and found it suitable for internal insulation. The ICT is a preliminary assessment tool; it cannot replace professional assessment by experts, but gives the owner an idea of whether it might be a good idea to proceed with plans of applying internal insulation.

Section 3 describes the main features of the ICT. The result of a test of the ICT is presented in Section 4. The ICT has some limitations, as at present combinations of relevant orientations, locations and insulation systems are few, and more failure modes would be relevant to include. This is discussed in Section 5. Finally, conclusions and suggestions for improving the tool are given in Section 6.

3. MATERIAL AND METHODS IN THE PRELIMINARY ASSESSMENT TOOL

The core of the ICT is a database consisting of 275,000 hygrothermal 1D simulation results based on DELPHIN [1] that provide a probabilistic assessment of the hygrothermal conditions at specific points in an internally insulated solid wall. Although important development has been achieved in RIBuild concerning the numerical efficiency of a probabilistic assessment approach [2], [3], real-time simulations that consider uncertainties, performed by a non-specialist, are still not realistic. Therefore, simulations have been performed beforehand, as a fast response has been a high priority. The ICT finds the simulations that come closest to a specific case described by an average U-value of the insulated wall, heat loss through 1 m² wall with and without a specific insulation system, and the internal surface temperature. Further, it assesses the risk of mould growth at the interface of insulation and existing wall, and the risk of algae growth at the external surface.

3.1 SIMULATIONS FOR A PROBABILISTIC ASSESSMENT

To reduce the number of simulations for a probabilistic approach, a Sobol sampling was chosen as the most effective Quasi-Monte Carlo method [2]. The probabilistic approach resulted in 16 uncertainty layers defining the wall configuration and the parameters that were to be varied in the simulations [4]. The RIBuild project showed that solid walls made of brick or natural stone by far are the most common external wall types in historic buildings [5]; in most cases they have an internal rendering and, in some cases, also an external rendering. As the internal rendering might be removed before applying internal insulation, four configurations of the existing wall were relevant to include: 1) Without any rendering, 2) Rendering on both sides, 3) Only external rendering, 4) Only internal rendering.

The selected insulation systems were also based on investigations made in RIBuild [6]. Each of them is a complete system, i.e. with an intersection layer (glue mortar), an insulation material and a finishing layer. As an exception mineral wool was included as well, as this is common without being a complete system. For each system, simulations were based on standard thickness of the insulation material.

To avoid having unrealistic combinations of material parameters in each of the historic or insulation materials, the materials were treated as discrete parameters, i.e. for the probabilistic assessment different bricks were used, each with fixed material parameters. The different materials in each category (e.g. bricks) were chosen from the DELPHIN database included in [1], supplemented by a few historic materials, tested as a part of RIBuild and added to the DELPHIN database.

To cover Europe from North to South, weather data files were obtained from 152 weather stations. The data was future data developed in the project Climate for Culture (www.climateforculture.eu). Simulations were run for five years with a discrete starting year between 2020 and 2045. As indoor climate the two climate classes A and B were chosen based on EN 15026 [7]. The sources of the basic input data and the number of materials are listed in Table 1 .

Table 1: Basic input used for simulations and sources for these

Input	Variations	Source
Wall configuration: Solid wall (brick or natural stone) Plaster on either side is optional	52 brick types 33 natural stone types 11 plaster types	RIBuild investigations, www.ribuild.eu
Insulation systems: 11 different systems	Standard thickness given by the manufacturers	RIBuild investigations
Weather data	158 European weather stations	Climate for Culture
Indoor climate	Climate class A or B	EN 15026

Ten of the uncertainty layers were uniform parameters, i.e. could be any value within a range, many of these were coefficients describing the boundary conditions, e.g. heat or moisture transfer coefficients. Also, the orientation was a uniform parameter, between 0° and 360°, and the thickness of rendering and masonry were uniform parameters in the range of 1-2 cm and 10-90 cm, respectively.

3.2 USER INPUT

To filter out the relevant simulations, user inputs as simple as possible are needed. Only parameters that would be fairly easy to assess were chosen, described in Table 2. Based on this, the ICT delivers a list of possible solutions concerning internal insulation systems.

Table 2: User input to filter out the relevant simulations

Parameter	Type of input	Range
Location	Coordinates, address or click on map	-
Distance to weather station	Slider to maximize distance	10 km – 500 km
External plaster	Check box	Yes or No
Wall material	Check box	Brick or Natural stone
Internal plaster	Check box	Yes or No
Thickness of wall	Slider from both sides	100 mm – 900 mm
Orientation	Slider from both sides	0° – 360°

ICT includes two features to ensure that the most relevant solutions among those selected, based on the mandatory user inputs, will be on top of the list. Firstly, sliders can be used to prioritize the five parameters: U-value, heat loss, internal surface temperature, risk of mould growth, risk of algae growth. Secondly, the user can choose to restrict the thickness or type of internal insulation, within a range of 10 – 150 mm and between 11 insulation systems, respectively.

3.3 OUTPUT

The result of each of the performed simulations is a 5-year series of temperature, moisture content and relative humidity (hourly based) at five different points, illustrated in Figure 1. Points 1-4 were chosen as the most relevant places to investigate different failure modes. Point 5 was included as the internal surface temperature is important for the comfort close to the wall. The user does not see the 5-year series, these are used for the post processing, where failure modes are assessed together with the heat loss (per year), U-value, and minimum internal surface temperature.

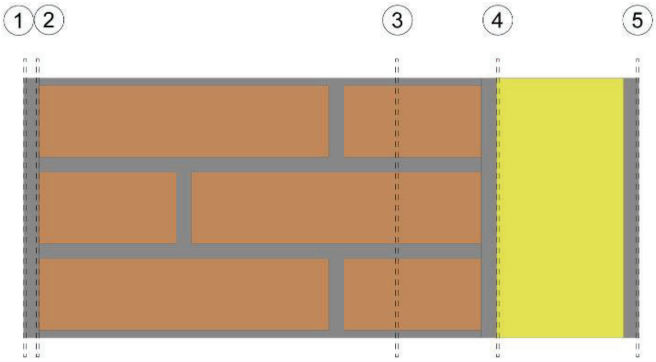

Figure 1. Cross-section of an internally insulated solid masonry wall indicating five locations relevant to four different failure modes and the internal surface temperature: 1) External surface; algae growth 2) 5 mm from the external surface; frost damage 3) 50 mm from the original internal surface; wood rot in wall plate 4) 0.5 mm from the interface between insulation and existing wall; mould growth 5) 0.5 mm from the internal surface; surface temperature

Originally it was planned to test for four different failure modes: Algae growth, frost damage, wood rot and mould growth. However, as the existing models for frost damage and wood rot were not fully developed to give realistic results, the ICT only tests for algae growth at the external surface (point 1) and for mould growth at the intersection between the existing wall and the insulation system (point 4). Minimum internal surface temperature and heat loss are shown as direct output in the ICT.

The risk of algae growth was determined using the method described in [8], giving an algae index between 0 and 1. For mould growth the VTT model [9] was used, depending on the material the scale goes from 0 to 6. For mould growth, the sensitivity class of the materials in the intersection has been set to 'Resistant', due to the initially high pH at the intersection caused by alkaline glue mortar, and the materials being inorganic. There are no general accepted threshold values for algae growth or mould growth; they may vary on a national scale or depend on the risk the specific user is prepared to take. Consequently, the ICT includes no threshold values, however, the results are coloured, indicating a high (red), medium (yellow) or low (green) number. The heat loss is given as a number (kWh/m²/year) and as a reduction compared to the uninsulated case. Furthermore, the calculated U-value and the minimum internal surface temperature is shown.

4. TEST OF THE PRELIMINARY ASSESSMENT TOOL

To compare the outcome of the ICT with the potential achievement of putting more effort into simulating a specific case, a test was made involving six case studies from RIBuild, containing in-situ measurements of temperature and relative humidity in the insulated walls. The cases represent brick and stone wall with and without external rendering, different systems for internal insulation, and different locations and orientations [10]. U-value, annual heat loss through 1 m^2 of external wall, Mould Index and minimum internal surface temperature were used as output parameters. Further, deterministic hygrothermal simulations in both WUFI and DELPHIN have been carried out using data on wall thickness etc. from the case studies. Post-processing tools were used, including WUFI Mould Index VTT [11] and the VTT Mould Model included in DELPHIN [1]. Figure 2 illustrates the procedure.

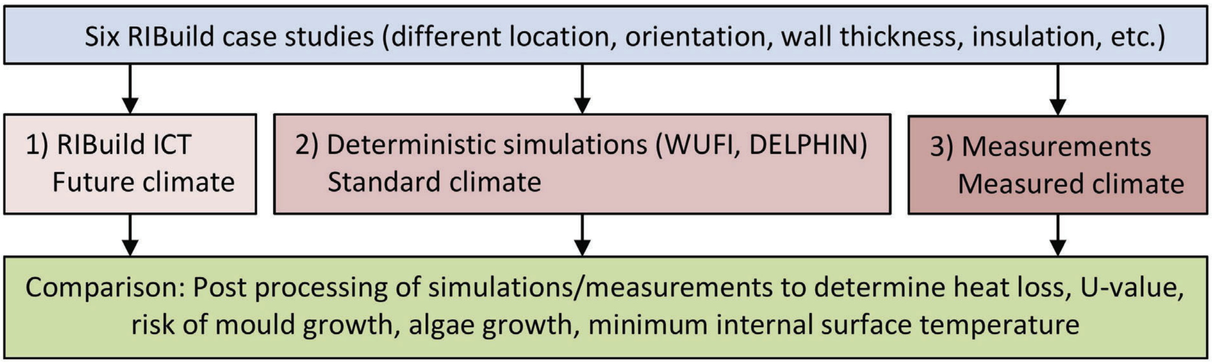

Figure 2. Procedure for testing RIBuild ICT by comparing outcome using 1) ICT, 2) deterministic simulations, and 3) measurements. Climates were chosen as close to the location as possible.

As the RIBuild ICT is based on previously performed simulations involving a probabilistic approach, ICT models do not necessarily match the case studies directly. Deviations are present both in relation to orientation, wall thickness, insulation thickness and thermal conductivity of the insulation material. Further, the ICT and the simulation tools used to support measurements in the case studies make use of different sets of climate data. All the deterministic simulations (WUFI, DELPHIN) were carried out for five years with local climate data from a location close to the case building in question.

Comparison of internal surface temperature simulated in ICT, WUFI and DELPHIN, shows in general good coherence. In most cases, the ICT appears to underestimate the heat loss when compared to simulation models and reported values from the case studies, which is surprising as is tends to overestimate the U-value.

The Mould Index is generated for the interface between internal insulation and the existing wall, as this is an area of risk, due to possible condensation. This parameter showed large differences between ICT, DELPHIN and WUFI. In some cases, WUFI and DELPHIN agreed, in other cases ICT and WUFI agreed. In general, the ICT generates no mould growth (Index of 0), except for one case 0.1, while DELPHIN in general gave a Mould Index around 2.

5. DISCUSSION

5.1 SIMPLIFICATIONS AND LIMITATIONS IN THE NUMBER OF SIMULATIONS

In regard to historic building materials, the user was given two options only; brick or natural stone. The different kind of brick (or natural stone) were handled as a parameter with a relatively high uncertainty, representing the many different kinds of bricks or stones in the pre-calculations. This choice was based on analyses made within RIBuild, showing that other factors such as location or orientation of the building were more important than the properties of the core material [12].

Aspects such as solar gains, ventilation losses, etc. are not included in the ICT, focusing on the external wall only. Irregularities such as thermal bridges and building details (e.g. around windows and beam ends), are also not accounted for as the simulations were made in 1D. However, such irregularities influence both heat loss and potential risk of moisture related damage and must therefore be assessed by professionals. 2D or 3D simulations would have prolonged the computing time enormously.

The database holds 275,000 simulations, however, in many cases the user will only find a few simulations to fit the specific case, as the wall thickness of the actual case might not be covered, and/or the orientation of the wall in the presented solutions, and the weather data that they are based on, might not be relevant for the case. Roughly 10 million simulations are needed to ensure that the user in most cases could find several simulations based on a relevant wall thickness and orientation, and weather data from a location close to the building. This would take years with the current rate that the simulations have been made with, despite queueing systems and powerful computers.

Using a meta-model with a machine learning algorithm, such as a neural network, would therefore be an obvious choice. Unfortunately, hygrothermal simulations sometimes fail, often rainfalls can have a fatal influence on the simulations, making them crash. This makes it difficult to introduce machine learning especially if the outcome is supposed to be time series of several parameters. Simpler things like heat loss might be possible. However, it is expected that the development of more advanced machine learning algorithms in time might solve the problem of time consuming calculations.

5.2 LIMITATIONS CONCERNING FAILURE MODES

Originally it was planned to include frost and wood rot as failure mechanisms. However, frost in masonry is a complex mechanism and no reliable model was found. Therefore, frost was omitted. Wood rot models exist, although, when applied to e.g. wall plates in old masonry, these models seem to overestimate the risk of wood rot [13]. According to the models most beam ends in historic buildings would have suffered from a fatal mass loss after a much shorter time (e.g. 10 years), than they already have existed (> 100 years). Consequently, wood rot was also omitted. Besides, the moisture and temperature threshold for mould growth based on the VTT model [9], is lower than what is expected for wood rot, and although wood rot is expected to occur at a slightly different place (point 3 in Figure 1) than mould growth (point 4) and there might be cases where mould may be acceptable but wood rot not, the mould growth threshold is most likely to be the decisive threshold.

The algae model was included although there is limited experience with it outside the lab. It might overestimate the risk of algae growth as the model will continue algae growth whenever the conditions are favourable, i.e. there is no decline. Consequently, if there are shorter periods favourable for algae growth at specific times of the year, the algae index will reach 1 given enough time.

The mould growth model does not have this problem, as it can decline. However, the VTT model was developed for surfaces, not interfaces where the pH value is high, and without direct contact to interior air. As the high pH value may inhibit mould growth [14], the sensitivity class was changed. Simply changing the sensitivity class from 'Medium resistant' to 'Resistant' may be too simple a solution. The consequence has been that the mould index is very low in most cases. Further investigation on how pH can be integrated into e.g. the VTT model is needed.

When better failure models are available, an update of the tool is quite simple, as the failure models are post processors. The heavy work load are the simulations, the time series from these can be used for any failure mode, and by having outputs at point 2 and 3, frost and wood rot can also be included.

5.3 FEASIBILITY

Overall, RIBuild ICT appears to be a helpful tool, for a fast analysis of a given construction. It is based on a probabilistic approach, and the validity is therefore dependent on the number of simulations that have been run previously. The ICT generates probabilistic results within the given ranges of input, and can therefore include uncertainties on e.g. material parameters and climate. WUFI and DELPHIN operate deterministically, and do not address the uncertainties to the same extent. Further, parameters such as orientation, wall thickness and in some cases insulation thickness vary significantly in the ICT compared to the actual cases, which influences the results. With more simulations, the ICT will only improve. Furthermore, the ICT makes use of forecasted weather, while simulations in WUFI and DELPHIN are in generally based on historic climate data integrated in these tools. This is also expected to have an impact on results achieved.

RIBuild ICT does seem to overestimate the U-value in most cases, which may be explained by the use of a probabilistic approach, involving different types of brick and wall thicknesses, opposed to the case studies and the created WUFI and DELPHIN models. With an overestimation of the U-value, one would expect the ICT to overestimate the heat loss as well; surprisingly, in most cases the opposite can be seen. This may be due to different locations used for the Heating Degree Hours (HDH), used to generate the heat loss; for the manual processing, HDH has been chosen for the physically nearest location, while the ICT may interpolate between the locations included for climate determination. Furthermore, the ICT uses future climate, which might mean lower HDH.

The Mould Index yielded significant discrepancy between simulations, largely due to the variety in input parameters in the different programs, including the climate files. It is a general problem, not only in the ICT, that mould prediction models may not correspond to what is seen in reality [4]. Apparently, the models do not take into account that the pH behind insulation applied with a cement containing glue mortar inhibits mould growth [14]. That is why the sensitivity class in the intersection between wall and insulation was chosen to be ‘resistant’ in the ICT rather than ‘medium resistant’, although this may not be the right choice in all cases, depending on the pH level in the actual case. Correspondingly, a lower sensitivity class (higher resistance) than the default values were chosen for the post-processing tools when simulating in WUFI and DELPHIN (deterministic simulations). Mould index values based on the case studies show the effect of using a higher sensitivity (‘medium resistant’), as they in two cases are much higher (higher than 2) than the output of ICT (zero).

6. CONCLUSION AND PERSPECTIVES

The Insulation Calculation Tool (ICT) is based on a large number of pre-calculated simulations, using a probabilistic approach, and a few user input, using checkmarks and sliders. The user input filters the simulations and the results are shown as different solutions describing risk of mould and algae growth, minimum internal surface temperature, U-value and heat loss. This makes it accessible for people not necessarily having any pre-existing knowledge about internal insulation, but who are interested and able to investigate the building renovation options if the information available is not too technical.

Based on a comparison with deterministic simulations performed with WUFI and DELPHIN and with measurements from case studies, the overall impression is that the ICT, in its current state, gives valuable information to the user. Discrepancies are largely accounted for by missing simulations in RIBuild ICT, some of the results differ considerably and the algae growth may be overestimated. The user must be aware of the shortcomings of the tool at its current state, included in a disclaimer at the website. The ICT is meant as a help in the planning phase of a renovation possibly involving internal insulation and it should only be used as a preliminary assessment tool, giving an overview of possible solutions, of which analyses that are more detailed should be made by building professionals.

To improve the feasibility of the ICT, further development should be based on applying a meta-model with a machine-learning algorithm to the already performed simulations and through machine-learning fill in the gaps in the simulations. When reliable models for frost damage or wood rot are available it is possible to extend the ICT further, as this would only require simple post processing.

7. ACKNOWLEGDGEMENTS

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