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Hygrothermal Risk Assessment - Retrofit of External Wall by the Application of Interior Insulation

Simon Pallin, PhD [1]
Angela Sasic Kalagasidis, Associate Professor [2]

[1] Oak Ridge National Laboratory in Tennessee, U.S.A.
[2] Chalmers University of Technology, Sweden

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SUMMARY:

Inside insulation of external walls of timber-framed construction is an adequate retrofitting measure in cases where there is an interest of preserving the existing façade. According to certain recommendations, and for the purpose of minimizing the work efforts, the additional insulation is placed directly on an existing wall, leaving the existing vapour retarder in the area that is substantially colder than before the retrofitting and thus increasing the risk of mould growth in the wall. The hygrothermal conditions inside the retrofitted wall are investigated for various indoor and outdoor conditions, and with and without indoor air intrusion in the wall. According to the results, 32% of 500 simulated scenarios obtained an annual average of relative humidity larger than the critical value for mould growth at the most critical spot inside the wall. The corresponding ratio was 43% in the wall assembly with an assumed air intrusion. Suggestions for the improvements of the moisture performance of the wall are also suggested. The used methodology of risk assessment is fully presented in the paper; it is of a general character and can be used in other retrofitting studies.

1. Introduction

Hygrothermal design of building envelopes is associated with standards, procedures, data and tools that help engineers in finding solutions in accordance with performance goals and applicable regulations. These ordinances are consistent with a proven knowledge in this engineering field and they are essentially developed as means for minimizing failures in the design. Nevertheless, undesirable deviations between a predicted and actual performance of building envelopes do happen. One reason for this can be found in a lack of design practice to evaluate the performance of building envelopes under different operational scenarios. Another reason is the lack of expert knowledge in situations when a design contains details that are not covered by design references.

This paper applies a hygrothermal risk assessment approach for the evaluation of a building retrofit design for which there is a lack of design guidelines. The assessment approach is based on existing algorithms (Ljungquist 2005, Vose 2008, Sasic Kalagasidis and Rode 2011, Pallin 2013) and involves testing of a large number of operation scenarios. The risk assessment algorithm is designed for residential retrofitting but may also be used in the energy and moisture safety design of new building constructions.

2. Method

The risk assessment algorithm is based on a step-by-step approach and presented in FIG. 1. It is a set of guidelines on how to perceive conditions for possible variations and to systematically test, evaluate and document the effects of these deviations on the performance of a building envelope in question. The first step of the risk assessment is to define the **Scope**, which consists of *System Formulation*, *Targets and Concerns*, *Existing Conditions* and *Strategy Identification*. This section intends to describe the purpose of the retrofitting project, gather knowledge and experience from similar projects and to formulate the performance criteria of the risk assessment (such as energy efficiency, moisture durability, occupants' expected level of comfort, etc.). The purpose is also to describe valuable and available information of the building status, properties of technical equipment, occupants' comfort issues and other information needed for a suitable retrofit design. The final outcome of this section is to present the retrofitting strategies.

The section of **Qualitative Risk Analysis** (QlRA) in FIG. 1 consists of two analysis segments; the *Risks Identification*, which serves to identify possible unwanted events or consequences on the hygrothermal performance; and the definition of *Influential Parameters, Uncertainties and Correlations,* which purpose is to gather an in-depth understanding of the interaction between the influencing parameters and the performance criteria of the risk assessment. The QlRA is followed by a first evaluation of the analysis, in which the result of the first analysis is presented together with decisions on the necessity for further analyses. This step is referred to as a *Qualitative Risk Evaluation.*

The section of the **Quantitative Risk Analysis** (QRA) consists of defining *Method and Performance Indicators*; *Input Values and Probability Distributions;* determine the *Design and Run Simulation Model;* and making *Result, Sensitivity and Uncertainty Analyses* of the results. In *Method and Performance Indicators,* the type of simulation method for the analysis is determined and the availability of existing models is investigated. Performance indicators are defined to enable the result and sensitivity analyses of the risk assessment. The values of the input parameters must be established and their variability, uncertainty and correlations; to ensure realistic and reliable simulation results.

Once all the information needed is implemented into the model, the simulations can get started. The number of simulations depends on the prescribed convergence criteria for the simulations, the nature of the input parameter variability and uncertainty and also on the defined performance criteria. The simulation results enable a sensitivity and uncertainty analysis, which may be conducted for several reasons; to determine which of the input parameters require additional research in order to reduce the output uncertainty; which input parameters are insignificant and can be neglected in the risk assessment model; which of the varying parameters contribute the most and how are they correlated (Hamby 1994).

However, a QRA is not necessarily required. The risk assessment can come to a halt depending on the outcome of the evaluation of the QlRA. If the proposed retrofitting measure, thus the studied object of the risk assessment, is considered as safe and reliable in the qualitative risk evaluation, a QRA is not needed. In addition, the risk assessment can come to a halt if crucial information is missing or if the credibility of the QlRA is low; as a result, the risk assessment is redirected back to the start of the QlRA; or if necessary, back to the section of the Scope. Such interrupting measures are also taken if the studied retrofit is considered to fail based on the defined targets and concerns.

A second evaluation determines whether the results obtained from the QRA is sufficient for risk tolerability decisions. If essential information is missing or if further analyses are required, the risk assessment is redirect back to the start of the QRA or, if necessary, redirected back to the QlRA.

In **Documentation**, the products of the risk analysis are presented in a *Risk Analysis Report* and *Options and Recommendations* for further analyses are presented together with suggestions on possible alternatives for improvement of the studying object. The documentation of the risk assessment serves as the foundation on which the decision makers should base their *Risk Tolerability Decisions*. While the above presented analysis is normally done by design engineer, this final step should be taken by a risk management team.

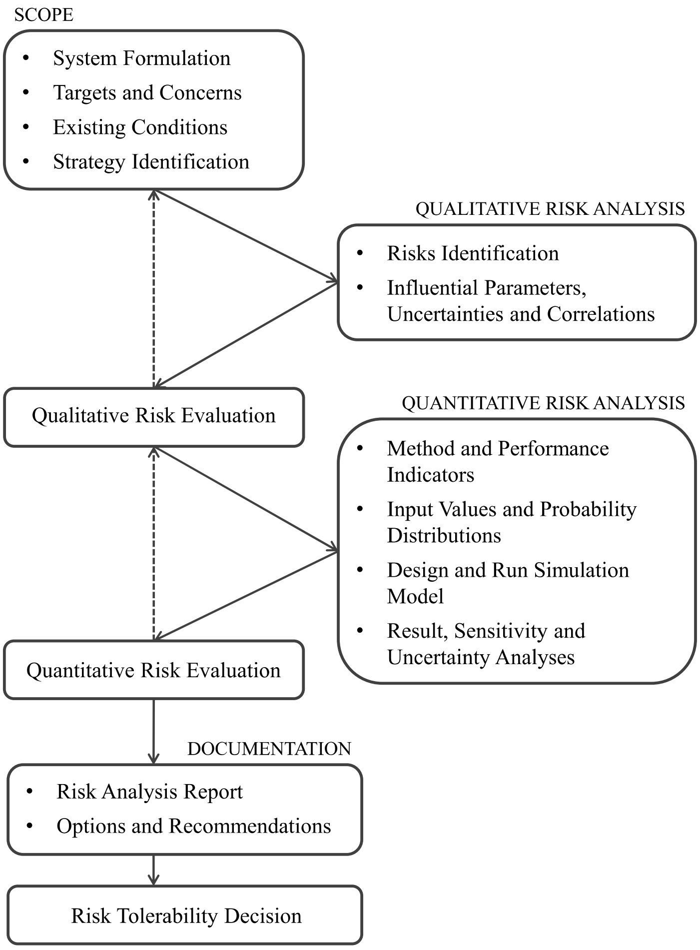

FIG. 1 A flowchart for hygrothermal risk assessment (adapted from Ljungquist 2005, Vose 2008, Sasic Kalagasidis and Rode 2011). *The dashed lines with arrows indicate possible redirections, based on the decisions made during the risk assessment procedure.*

3. Case study

A case study has been defined to evaluate the risk assessment algorithm presented in FIG. 1. The object of the case study is a recommended design of an exterior wall retrofit. The proposed retrofit involves addition of an insulation layer on the inside of the existing wall, thus not affecting the exterior cladding of the wall. Necessary conditions of the studied object are presumed to make the analysis credible and will be presented shortly. The procedure of analysing the hygrothermal performance of the wall after the retrofitting follows each step of the proposed risk assessment algorithm.

3.1 Scope

Energy efficiency improvements are planned for an existing exterior wall. Due to the preserving interest of the exterior cladding, a supplement of insulation must be constructed on the inner side of the wall. The proposed design of the retrofitting measure is presented in FIG. 2, and consists of a new timber-framed wall, directly constructed onto the inner surface of the existing wall (also timber framed). The insulation material in the new construction is glass wool, which is mounted between the wooden studs. An additional gypsum board is mounted on the interior side of the new timber frame.

The intention of the retrofitting measure is to improve the thermal performance while maintaining a durable and moisture resistant wall assembly. However, the suggested solution is also motivated by minimum changes on the existing wall which, naturally, will minimize the costs from additional building material and optimize the construction time. Apparently, the conditions and functions of the existing building materials are considered acceptable. It is of great concern to create a design which enables a satisfying interaction between the existing and supplementary building materials. A possible unwanted consequence of interest for the risk assessment is the risk of mould.

The studied retrofitting measure is assumed to be constructed in Gothenburg, Sweden, which is considered as an oceanic climate. The retrofit is assumed to be constructed with satisfying workmanship. It is worth noting that the suggested retrofitting measure is not widely practiced.

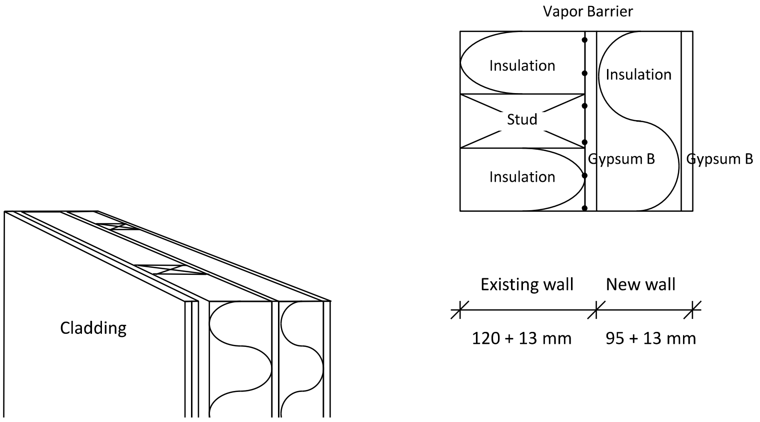

FIG. 2 An illustration of the design of the exterior wall retrofit, together with thicknesses of the applied materials, in both the new and existing wall assemblies.

3.2 Qualitative risk analysis

The major risks of concern in this risk assessment are mould growth, or other damages related to critical levels of moisture. The development of mould depends on the nutrients in the building material, the temperature, the relative humidity, φ, and the fluctuation and exposure time (Viitanen 2001, Johansson et al. 2005). Therefore, this case study aims at investigating the hygrothermal performance of the retrofitted wall and resistance to such moisture related damages.

A *Fault Tree Analysis* (FTA) can be a useful method to determine the mechanisms and influential parameters that will have an effect on the hygrothermal performance. FIG. 3 illustrates a FTA of the investigated retrofit and in concerns of the risk of mould in the wall assembly. FIG. 3 also includes a legend, describing the Boolean operators and the descending events of a FTA.

In concerns of FIG. 3; capillary suction, water leakages and built-in moisture (moisture damp) are assumed to be checked upon due to inspections of the wall prior the construction of the retrofit. Therefore, these mechanisms can be excluded from being decisive on the risk of mould. Neither is moisture infiltration by convection important, if the conditions and functions of the exisiting building materials are considered acceptable. However, two mechanisms probably possess a higher impact on the moisture performance. These are the indoor air exfiltration and the moisture transport by diffusion and shall be investigated further.

3.3 Qualitative Risk evaluation

The area around the existing studs, as seen in FIG. 2 and FIG. 4, will have a decreased temperature during the heating season in comparison with prior the retrofit. As a consequence, the existing gypsum board will have a lower moisture acceptance. Unfortunately, this critical position will commonly exist due to a shift in the placement of the existing and new studs, with the intention of avoiding thermal bridges.

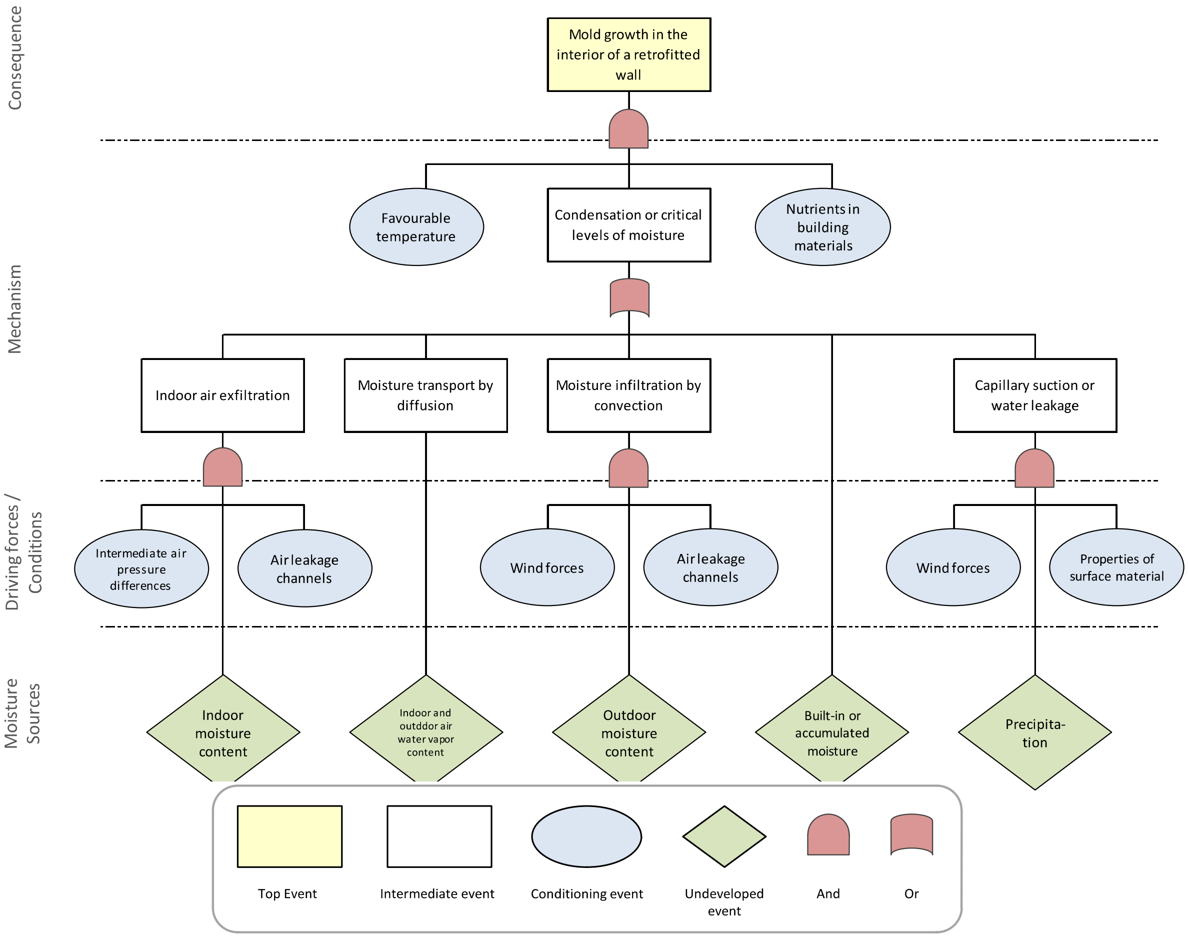

FIG. 3 A Fault Tree Analysis (FTA) depicts the most important mechanisms, driving potentials and sources of potential mould growth in the wall assembly. A legend illustrates the operators of the FTA.

A vapour retarder of the original wall remains in the same place, between the existing studs and the intermediate gypsum board, which is a substantially colder region than before the retrofitting. As a consequence, there will be moisture diffusion from the indoor environment during the cold periods and moisture accumulation in all materials on the inner side of the vapour retarder. All this will increase the risk of mould growth in the wall. An additional aspect that will affect the function and future performance of the retrofit is possible indoor air intrusion in the wall since the wall bearing is made of timber which will shrink, bend and crack depending on moisture content, temperature, quality of the material and the applied load (Breyer et al. 1998). A plausible scenario is that minor air gaps are created between the existing and new wall structures due to these structural movements.

In conclusion of the first risk evaluation, the studied retrofitting measure possesses a higher risk of mould growth in the wall assembly in comparison with prior the retrofit. However, the variability of the performance is difficult to estimate based on solely a QlRA. Therefore a QRA is recommended in order to evaluate influential parameters, likeliness of failure and possible actions of improvement.

3.4 Quantitative risk analysis

A model of the presented retrofit design in FIG. 2 was created in HAM-tools, which is a library of models developed in Simulink® and especially constructed to simulate heat and mass transport in building and building components (Sasic Kalagasidis 2004). The simulation model consists of a one-dimensional wall model and an air gap. The path of heat and mass transport through the wall, crossing the assumed critical position of the retrofit, can be seen in the left-hand illustration of FIG. 4.

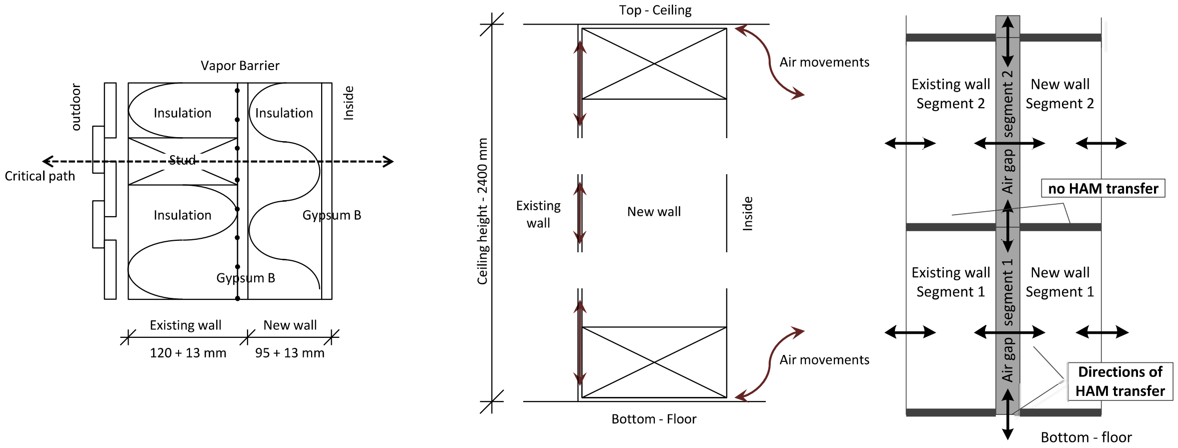

FIG. 4 The left-hand plan drawing illustrates the assumed critical path of the retrofitted wall. The middle picture illustrates a section drawing of the simulated wall, in which the two-headed arrows demonstrate possible positions and directions of air intrusion. The right-hand scheme illustrates numerical coupling between the wall elements and the air gaps.

An additional simulation model was made with an assumed 3 mm air gap between the new timber frame and the existing gypsum board, in accordance with the middle illustration of FIG. 4. The assumed width of the air gap is based on plausible deformations. The air movement inside the gap is driven by air pressure differences due to the variations in temperature along the air gap and in the inner environment. The air gap is discretized in five equally long segments, which are serially coupled along the wall height as shown in the right-hand picture in Figure 4. The temperature and moisture content of the air in each segment are found from the heat and mass balance between the air in the gap, adjacent wall elements as well as with the preceding and following air gaps. A well-mixed air is modelled in each segment. The resulting model of the wall is combination of one-dimensional wall segments and quasi two-dimensional air gaps.

The Monte Carlo method is applied for the sampling of the varying input parameters in the simulation model. The variability of three input parameters are implemented; the outdoor climate, the indoor moisture production and the ventilation rate. The weather data consists of 44 simulated years of the climate in Gothenburg, Sweden between 1960-2004 (Nik 2010). The applied ventilation rates are based on measurements made in 417 apartments in Sweden from 2008 to 2009 (Boverket 2009), while the variability of the indoor moisture production are based on simulations of 10 000 plausible scenarios of residential multi-family households (Pallin et al. 2011). Altogether, 500 consecutive years was simulated with hourly varying climate data, indoor moisture production rates area and with an annually constant ventilation rate.

As discussed, the area around the existing studs is assumed to be the most critical position of the wall in concerns of the risk of mould. FIG. 5 presents the probability distribution of the annual average of relative humidity in this critical position, both with and without an assumed air intrusion. Apparently, 32% of the simulated scenarios has an average above 80% relative humidity, which can be associated with a risk of mould (Hukka and Viitanen 1999). In the case of an assumed air intrusion, the corresponding number of the simulated scenarios with a critical average is 43%.

A sensitivity analysis was performed, using three different methods. The three analyses methods indicate that the ventilation rate has the highest influence on the annual average relative humidity in the intermediate gypsum board. Also the indoor moisture production proves to be influential, though slightly less. According the result of the sensitivity analysis in FIG. 6, the outdoor climate has the lowest influence. This means that the same risk may exist in other climates.

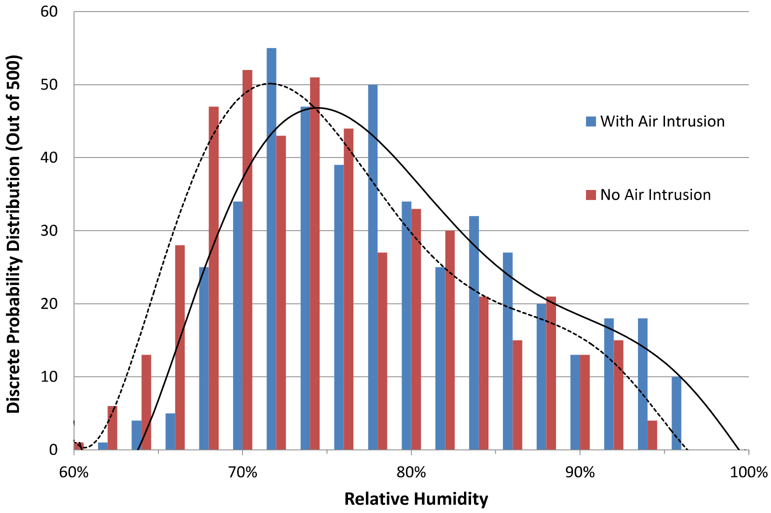

FIG. 5 Two discrete probability distributions illustrate the variability of the annual average of relative humidity in the assumed critical position (i.e. the intermediate gypsum board) post-retrofit. The disparity between the plots is whether an air intrusion is assumed or not. In addition, trend lines are added for both plots, hence representing two probability density functions.

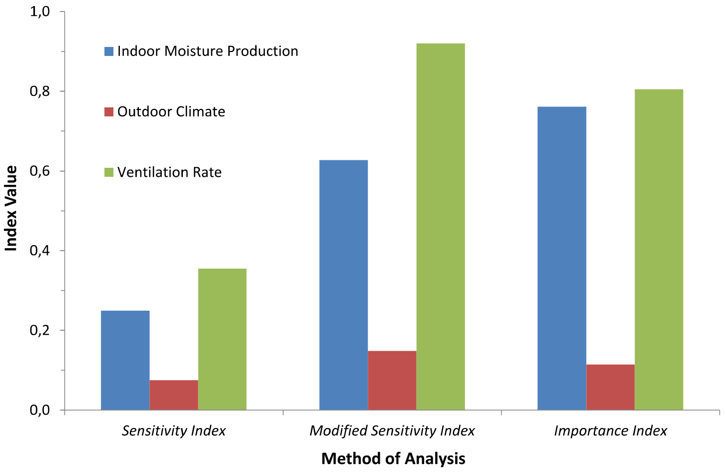

FIG. 6 present the results from the sensitivity analyses from three sensitivity analyses methods. The ventilation rate has the highest influence on the variability of the moisture content in the intermediate gypsum board close to the existing timber studs. The moisture production also has a high influence, though the outdoor climate has not. A high index value indicates a high influence.

4. Conclusion

The conclusion of this paper also serves as the *Risk evaluation, Options and Recommendations* of the case study, as seen in FIG. 1.

A recommended design for an external wall retrofit with interior additional insulation has been evaluated with a hygrothermal risk assessment procedure. The most decisive parameters in concerns of the moisture performance were identified; the outdoor climate, the indoor moisture production and the ventilation rate. Further, a critical position was identified in the wall assembly, which was assumed to have a higher risk of developing mould post-retrofit. Finally, the retrofit design was simulated using stochastic variations of the three most decisive parameters in a hygrothermal calculation tool.

According to the results, 32% of the simulated scenarios obtained an annual average of relative humidity larger than the critical value for mould growth. The corresponding ratio was 43% in the wall assembly with an assumed air intrusion of indoor air into to the wall assembly. The sensitivity analyses indicated that the air flow rate of the ventilation system has the highest influence on the moisture content in the intermediate gypsum board. The indoor moisture production is also influential, though the impact from the outdoor climate is low. This means that the same risk may exist in other climates.

However, the moisture performance of the studied retrofit can be improved if any of the following actions is taken; decrease the indoor moisture production or increase the ventilation rate; assemble a new vapour retarder behind the new gypsum board; ecrease the thickness of the additional insulation.

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