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Annex 55
Reliability of Energy Efficient Building Retrofitting- Probability Assessment of Performance and Cost (RAP-RETRO)

Framework for probabilistic assessment of performance of retrofitted building envelopes

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 28 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates research and development in a number of areas related to energy. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)

Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings

Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)

Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation

Annex 57: Evaluation of Embodied Energy & Greenhouse Gas Emissions for Building Construction

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements

Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings

Annex 60: New Generation Computational Tools for Building & Community Energy Systems
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings
Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with

Exergy Principles
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behavior in Buildings
Annex 67: Energy Flexible Buildings
Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

Glossary

Framework – guidelines, flowcharts and similar step-by-step instructions for determining a course of action. None of the instruction forms are mandatory, i.e. they can be changed and adapted to specific tasks.

Performance – indicators of a building in use; in building physics applications, the following values are commonly indicated: airtightness, temperature and relative humidity indoors, ventilation flow rate, energy use for heating and cooling, daylight, etc.

Assessment of Performance – an act of comparing a building's performance with performance goals, which are expressed as specific, measurable, achievable or time-targeted values.

Probabilistic Assessment of Performance - a method to quantify for a population of buildings the number of circumstances when a single building fulfils design goals. When this numberis compared with the total number of buildings or circumstances enclosed in the analysis, the likelihood or the probability of failure can be found. .

Risk and **reliability** are two complementary terms. The risk is what is left over after all reliable cases are excluded.

In the continuation, the **Framework** for **Probabilistic Assessment** of **Performance** of retrofitted building envelopes will be called the framework.

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1 INTRODUCTION

A process of building envelope design, as any engineering design, is associated with standards, procedures, data and tools that help engineers in designing a building envelope in accordance with performance goals and applicable regulations. Being consistent with a proven knowledge in this engineering field, these processes help engineers to minimize the design failures. Nevertheless, targeted performances are not always met in practice. Higher energy demand for space conditioning, substandard indoor environmental quality and thermal environment, and degradation of wall surfaces are examples of failures that may be caused by regular or abnormal variability in outdoor conditions and material properties but also by inadequate design of building envelopes. Different use of the building compared to how it was intended, cost reductions in some phases of the project that lead to unproven changes of the design and deficient workmanship are some of the reasons for unsatisfactory performance of building envelopes. Other reasons can be found in the variety of designs. Although building regulations and design procedures do reflect the proven knowledge in this engineering area, they do not necessarily include up-to-date knowledge and definitely not all possible designs that may exist in reality. Building envelope performance may not be accurately predictable when a design contains details that are not covered by design references or where practical experience is lacking.

Uncertainty arises not only from design choices, but also the properties of the involved building products have stochastic variation, as does the data that characterize the outdoor climatic exposure or how occupants and operators use and maintain the building.

From a financial point of view, the cost of reparation of building envelopes is a large burden to a property owner, and also a reputational burden for designers and builders. From a sustainability point of view, substandard premises require more material, energy and human resources than necessary and may create conditions for health risks. In the end, it is a societal interest to acquire well-functioning and durable buildings.

Retrofitting of building envelopes is an area where a large number of new design cases can be expected as a result of unique combinations of old and new building materials and technologies. Many of these cases are not (yet) fully covered by design references or practical experiences. Retrofitting thus calls for ways to identify, limit or eliminate risk already in the design process. With the above in mind, this report presents a framework, which is a tool for perceiving, testing (by simulations or by experiments), evaluating and documenting possible variations in performance of building envelopes. The application of the framework is illustrated on selected examples of retrofitted building envelopes.

1.1 Basic engineering design approaches

There are two main ways to perform design of building envelopes: prescriptive and performance based design.

In the prescriptive design process, engineers rely on mandatory building codes which specify data, tools and methodology of design. These commonly include reference calculation procedures and standard data sets such as test meteorological years, material properties and indoor conditions. Desired performance of the building envelope is described by minimum or maximum values for its various parts which designers can choose among in agreement with the building owner. By balancing the unique qualities of the building in question with reference data, a technical solution for the building envelope can be specified.

The prescriptive design approach is a result of longer practice of building similar type of buildings, during which enough empirical knowledge is gained on how to include probable deviations of the building envelope performance into the design. It is easy to follow and it provides predictability of both time and costs required for the design. At the same time, it doesn´t encourage neither innovative nor risk thinking since testing of design alternatives is not required. The reference input data and design methods are produced with the purpose to exemplify how the building performs when constructed by immaculate workmanship and of damage-free materials, when it is inhabited by typical users and when all equipment functions properly. They should not be interpreted as working conditions for individual buildings, particularly not if the buildings are remarkably different from the reference sample, as this increases the risk of disagreement between the designed and actual performance of the building. Typically, such risks are not clearly communicated by the designers since the method itself does not support risk thinking.

Unlike the prescriptive design approach, in performance based design the engineers prescribe desired performances of the building envelope while having full freedom in choosing a design approach. They can use calculation procedures, tools and data according to own preferences because the design is evaluated through the measured performances when the building is put in use rather than through the applied design methodology. Performance based design seemingly asks for risk elimination thinking in the design as there is typically more than one way to go. By means of a reference building and computer simulations, a baseline performance is created for comparisons with alternative designs. Possible variations of the building performance can be communicated in the final design as percentage of agreement/disagreement with the reference performance. Where possible, the feedback from the measured building performance is provided to help engineers evaluate the design approach and gain design expertise. Annual energy use for air conditioning, average moisture excess in indoor air or airtightness of the building envelope are some examples of feedback that can be provided from the building in use.

Performance based design is very likely more time consuming than the prescribed one as it takes some efforts for design teams to produce reference buildings, collect input data and generate design alternatives. However, once familiar with the modelling methodology, design teams can identify adequate solutions out of various design strategies and present associated risks to the client. By gaining design experience, the performance based design will probably incorporate more and more prescriptive requirements to facilitate the design of similar buildings. Therefore, it can be seen as a precursor of the prescriptive design.

Probabilistic risk assessment has many similarities with the performance based design. It requires a reference case, sets of different design alternatives and data and evaluation criteria. Use of simulation tools is an essential part. As prescriptive design is fairly more practised than performance based design, it is very likely that the majority of engineers are not familiar with the methodology of the latter. The risk elimination thinking is usually found among experts, i.e. practitioners who are recognized by their extensive knowledge in a particular area, with which they are able to make correct judgements of novel designs without exact design procedures.

Performance based design is probably better suited for the design of retrofitted building envelopes than the prescribed design, at least until enough knowledge about various retrofitting techniques is gained.

1.2 Risk management and risk assessment

Risk thinking during a design process means anticipation of circumstances when a single design does not fulfil design goals. It also includes assessment methods with which it is possible to quantify the risk of failure of the design. These methods can be both mathematically accurate and also approximate. Accurate methods generally involves that relatively[1] exact results can be produced, while approximate ones are applied whenever there is neither information nor resources available for more exact analysis to be carried out.

Risk assessment is, together with measures for risk reductions, an essential part of a risk management process. Procedures for risk management differ between engineering disciplines, and also between the objects they are applied on within the same discipline. While some are regulated in standards, the others are developed freely by teams involved in the risk management process. Both risk assessment and risk reduction can be performed in steps and include iterative process (ref. *SS-EN1050:1996*).

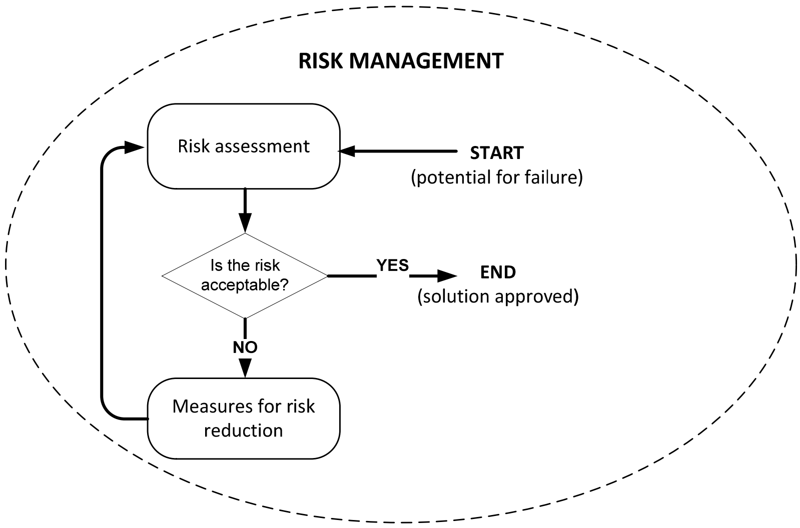


Figure 1 Illustration of sequential steps in handling of Risk Managements

A methodology for risk assessment is associated with frameworks, procedures, techniques and tools to manage the risks associated with a given engineering activity. It includes, in general, the following activities:

- Specifying and understanding a desired performance
- Anticipating conditions and measures that may lead to the spread in the performance

[1] Due to limited resources or information, the number of cases (buildings or circumstances) that is included in the risk assessment is very likely lower than the actual number of cases. Since the analyses are performed on samples of limited size, the calculated risk should be interpreted as 'relatively exact numbers'.

- Qualifying and quantifying the spread
- Evaluating the spread in terms of present acceptability and tolerance limits

Risk assessment can be both quantitative and also qualitative or approximate. The former generally involves that magnitudes of unwanted consequences can be produced, while the latter are applied whenever there is neither information nor resources available for more exact analysis to be carried out. The quantitative assessment can produce the following result 'the annual energy demand for heating of a building is exceeded by 10 kWh/m^2 and year'. For the same example, the qualitative assessment can possibly identify that 'the annual energy demand for heating of a building is exceeded by little or by much'.

Although quantitative assessment describes the risk in a more precise manner than the qualitative assessment, it should be understood that the accuracy of both methods depends largely on the accuracy of models and data used in the assessment, as well as on the skills of persons who are performing the assessment.

1.3 Probabilistic risk assessment

The main results of probabilistic risk assessments are probabilities or likelihoods, i.e. the numbers that show how many cases, out of all possible ones that do or do not meet the desired performance. For example, in addition to the result of the quantitative risk assessment saying that 'the annual energy demand for heating of a building is exceeded by 10 kWh/m2', mentioned in the previous section, the probabilistic risk assessment will reveal that '5 % of the buildings will fail the given criterion'.

These numbers may be obtained from field surveys, laboratory or numerical experiments. A large number of experiments are usually a necessary but not always a sufficient condition for obtaining representative results. Comprehensiveness and differences between the experiments, as well as the quality of the data used in the assessment are also important for the result. As indicated earlier, the limitations associated with the probabilistic risk assessment introduce uncertainty in the result of the assessment. For a more accurate description of the risks, the reliability of the estimate should be provided, i.e. 'with 90 % probability, 5 % of the buildings will fail the given criterion'.

A complete description of probabilistic assessment is an iterative process, usually beginning with the application of qualitative methods and progressing towards quantitative, if necessary and appropriate. If a quantitative analysis of building envelope performance is to be carried out, a numerical model of the building envelope must be established. When the model and the data are established, the calculations can begin to estimate the spread and identify the critical conditions and events. In the end, the results of numerical analyses should be compared with targets of the retrofit, also known as performance criteria, and an optimal retrofitting technique should be identified. The latter involves any technical or social[2] measure that decreases the number of failures from, for example 5% to 1 %.

[2] Associated with changes in human behaviour, i.e. how people use buildings

2 AIMS AND OBJECTIVES OF THE FRAMEWORK

The performance of a building envelope is crucial for determining how much energy is required for heating and cooling of the building, but also for achieving comfort levels and good indoor air quality. Renovation strategies for building envelopes differ between countries and climate zones, as summarized in Table 1. Whole building perspective is advised in numerous policy mechanisms, such as building performance certificates, as a method for reaching the goals with renovation. However, every-day practice is challenged by large variety of components, materials, building technologies as well as by high costs. Besides, the retrofit should satisfy other performance criteria than those directly related to the energy performance of the building or to economic interests. Moisture performance criteria can be easily overlooked in this complexity, particularly in areas where moisture safe design is not well established. Until sufficient knowledge is acquired about how to renovate building envelopes and to thereby achieve high reliability in performance, many retrofitting cases need to be regarded as unique design cases. The design engineers who are involved in retrofitting will need thus to act as experts. In view of that, the framework for risk assessment of performance of retrofitted building envelopes aims at providing instructions on how to analyse a complex retrofitting case and how to identify risks involved.

The framework includes step-by-step instructions on how to anticipate conditions that lead to adverse performance of the building envelope and to systematically test, evaluate and document these effects. Besides, it clarifies, via examples, the expert methods that can be used when designing a non-standard or a new case. However, none of the instructions are mandatory and can be revised during the process.

The probabilistic assessment of performance of building envelopes is a core activity of the framework. Since the calculated probabilities will serve as a basis in a decision making process, the scope, objectives and limitations of the assessment should be clearly presented in order to provide unambiguous results. Besides, the calculated probabilities may require another presentation than the language of mathematics in order to be understood by a larger public. Therefore, there are other activities associated with probabilistic risk assessment that are not directly covered by the framework. Details on preparation of data and tools for probabilistic assessment may be found in the reports of ST1 and ST2, while the presentation of the results is more discussed in ST4. This report includes a detailed description of the framework (Chapter 2), while Chapter 3 provides an overview of performance criteria for risk assessment of retrofitted building envelopes. A selection of retrofitted cases is included in Chapter 4 in order to illustrate the diversity and extent of the retrofit, and possibly to inspire individual studies. Finally, examples on probabilistic risk assessment are provided in the appendices.

Table 1 Building envelope technologies according to economy, climate and construction type (IEA, 2013)

Type of economy	Climate	Technology: New construction[3]	Technology: Retrofit[3]
Developed	**Hot climate**	• Architectural shading • Very low-SHGC windows (or dynamic shades/windows) • Reflective walls/roofs • Advanced roofs (integrated design/BIPV) • Optimised natural/mechanical ventilation.	• Exterior window shading and dynamic glass/shading • Reflective roofing materials and coatings • Reflective wall coatings • Window film with lower SHGC • New low-SHGC windows.
Developed	**Cold climate**	• Highly insulated windows • Passivhaus gain (architectural feature /dynamic glass/shades) • Passive house-equivalent performance based on LCC limitations.	• Highly insulated windows • Low-e storm or interior panels • Insulated shades and other insulating attachments (low-e films) • Exterior insulating wall systems • Interior high-performance insulation.
Developing	**Hot climate**	• Exterior shading and architectural features • Low-SHGC windows • Reflective roofs and wall coatings • Optimised natural/mechanical ventilation.	• Exterior shading • Reflective coatings (roof and wall) • Low-cost window films • Natural ventilation.
Developing	**Cold climate**	• Highly insulated windows (possibly double-glazed with low-e storm panel) • Passive heating gain (architectural feature) • Optimised low-cost insulation and air sealing.	• Low-e storm or interior panels • Insulated shades and other insulating attachments (low-e films) • Exterior insulating wall systems • Cavity insulation, lower-cost (e.g. expanded polystyrene) interior insulation.

[3] Insulation, air sealing and double-glazed low-e windows for all buildings. The IEA recommends a minimum performance for all new windows globally to meet the performance of double glaze low-e with low-conductive frames and climate-optimised SHGC. Air sealing is needed for any building that will have heating and cooling provided. Insulation is needed for all applications, renovation is more challenging but possible, especially for roofs in all climates. Notes: BIPV = building-integrated photovoltaic. Passivhaus, an advanced residential building programme that calls for very high levels of building envelope performance, has gained significant momentum in Europe and is active globally (see www.passiv.de/en/index.php).

2.1 Target users of the framework

It is anticipated that the framework will be of use in a design team who bears the responsibility that the design will meet the design targets when the building is put in use. In a simplified diagram of a building process shown below, this is indicated as a feedback about whether the targeted values are met or not. Whether this feedback exists or not, depends mainly on the adopted design approach.

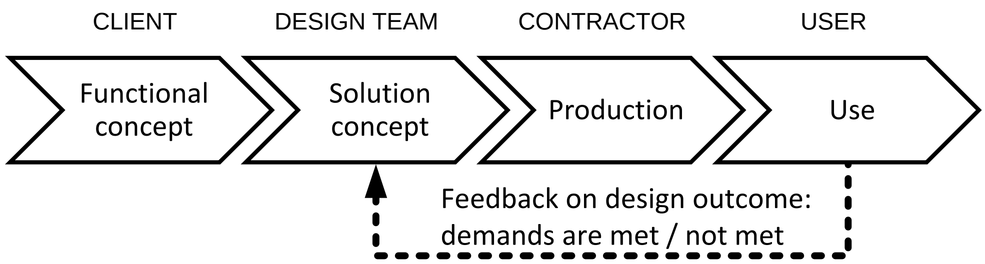


Figure 2 Illustration of how the framework will be used in the communication between stakeholders or actors and phases of a renovation project.

An example of a design method where the reliability of the moisture design is in focus can be found in the Swedish “Build Moisture” method (ByggaF method; Mjörnell et al. 2012). The purpose of the method is to help all actors involved in a construction project to work with moisture safety activities and to document them on a regular basis. The method includes routines, templates, checklists, references to literature and design examples. In the activity entitled ‘Dry building design’ (see Figure 3), the design engineers are recommended to perform a quantitative risk analysis in order to estimate the moisture safety of the design. Another methodology entitled ‘Calculate Moisture’ (ByggaR), which is under development, will provides step-by-step instructions on how to perform the quantitative assessment (Wallentén, 2012). The ByggaF method is now required by the Swedish Green building certification method in for higher certification grades.

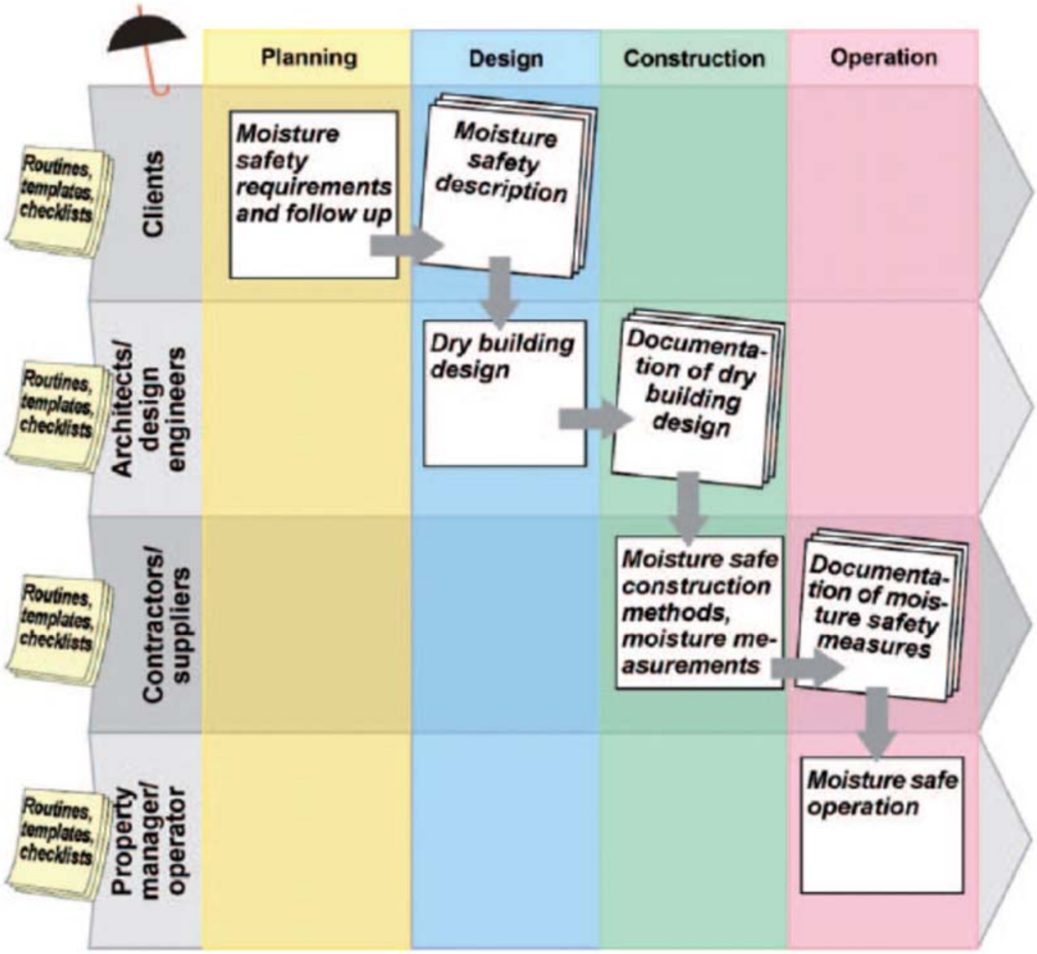


Figure 3 Conceptual outline of the ByggaF method (from Mjörnell et al. 2012).

3 THE RAP-RETRO FRAMEWORK

There are no strict rules on how to construct a framework or how to present it. A great inspiration for the initial model of the framework has been found in the flowchart for probabilistic risk-based assessment of undesirable indoor events that was presented in Ljungquist (2005), which is also a developed version of the framework presented in the international standard IEC 60300-3-9:1995. Though the standard is primarily intended for risk analysis of technological systems, its generality makes it applicable in many engineering areas. For example, Ljungquist used the framework from Figure 4 to estimate the health risk due to the Indoor Environmental Quality resulting from the design and construction of a building. Since the subject of the cited research was related to the topics covered by building physics, it was believed that the same framework, with a few adjustments, could facilitate the probabilistic assessment of various issues in building physics design, such as energy performance, moisture durability, thermal comfort or IAQ. The flowchart of Ljungquist (Figure 4, left) was presented as a first proposal of the framework for probabilistic assessment and discussed with the Annex 55 participants. Based on the comments received, the revised version of the flowchart was proposed and adopted as the framework (Figure 4, right).

3.1 Steps and actions in the framework

The analysis starts with the definition of a Scope of the analysis, which is organized in several sub steps. In the System, a spatial scale of the analysis can be defined as a whole building, a zone in the building or a building envelope. In the perspective of the building physics design, the definition of a system describes indirectly a numerical model that will be used in the analysis, due to which certain assumptions need to be made. By stating that a building envelope model was used for the analysis, it would indicate that the environmental conditions on either side of the building envelope were assumed. If a whole building model was used for the same analysis, the indoor conditions would be calculated while the outdoor would be assumed. The calculated indoor conditions provide more realistic heat and moisture loads on the interior side of the building envelope, thereby increasing the credibility of the results.

In the next step termed Targets and Consequences the performance criteria of the analysis are presented along with the prediction of the consequences if these criteria are not fulfilled. Examples of performance criteria can be found in Section 5.3. Consequences of not meeting the target values are suitably described as increased costs of the project referring to costs of operation and maintenance of the building after the retrofit, of improved or degraded safety and well-being of the tenants, gained or lost reputation of the building owner and of the design team, etc. Due to this large variety of aspects included in the retrofit, it is advised to carefully reflect on the motives of choosing a retrofitting strategy, in the Existing conditions and information, and to consider alternative Retrofitting strategies. The latter will make room for relative ranking of the results. Finally, Limitations and assumptions of the assessment should be clearly declared to avoid erroneous generalization of the results of the assessment.

A qualitative performance assessment is enclosed in the Benefits and hazards and starts by considering the Influential parameters and uncertainties. Natural or abnormal variations of hygrothermal loads in indoor and outdoor environment, imperfections of structural dimensions, inconsistency of material specifications and other deviations in geometry and material properties are the parameters that may cause deviations of the specified performance goals. Note that the specification should be limited to the parameters that can be quantified; otherwise, we deal with the uncertainties. Qualitative analysis is basically a process in which this 'pool' of possible influential parameters is narrowed down through a consistent evaluation of their significance. The purpose of the qualitative analysis is to sort out conditions, operation scenarios where one or several influential parameters are involved, which lead to very high or very low risks of failure in fulfilling the performance goals. Qualitative analysis can be fully based on available knowledge in the field, which is usually provided in form of documents and recommendations that summarize the practical experiences. If these are not available, logical charts in form of fault trees and similar, could be used to perform the qualitative assessment. Simplified calculation analyses are also highly recommended at this stage for the purpose of quantifying reasonable limits of the scope of the retrofit measures. At the end, a First evaluation of the Result is presented and decisions on the necessity of further analyses are taken. For example, if the qualitative analysis identifies the scenarios with high or low risk of leading to the deviations of the specified performance goals, any further assessment of the exact value of these risks is not necessary and the assessment can be ended by reporting the results. However, the scenarios with 'some risks' can be considered for quantitative analyses.

If required, a Quantitative Probabilistic Assessment is performed. The quantitative assessment is characterized by the Method of analysis, which consists of a numerical model and a sampling technique. The first can range from a detailed to a simplified numerical model of the system, while the latter involves Monte Carlo and/or similar random and quasi-random sampling techniques. For the purpose of the analysis, the values of all influential parameters should be statistically processed into Probabilities with specified ranges and distributions. Note that gathering of the uncertainties and variations of the input parameters may require great effort. Results of multiple numerical simulations give the spread and the magnitude of Calculated performances.

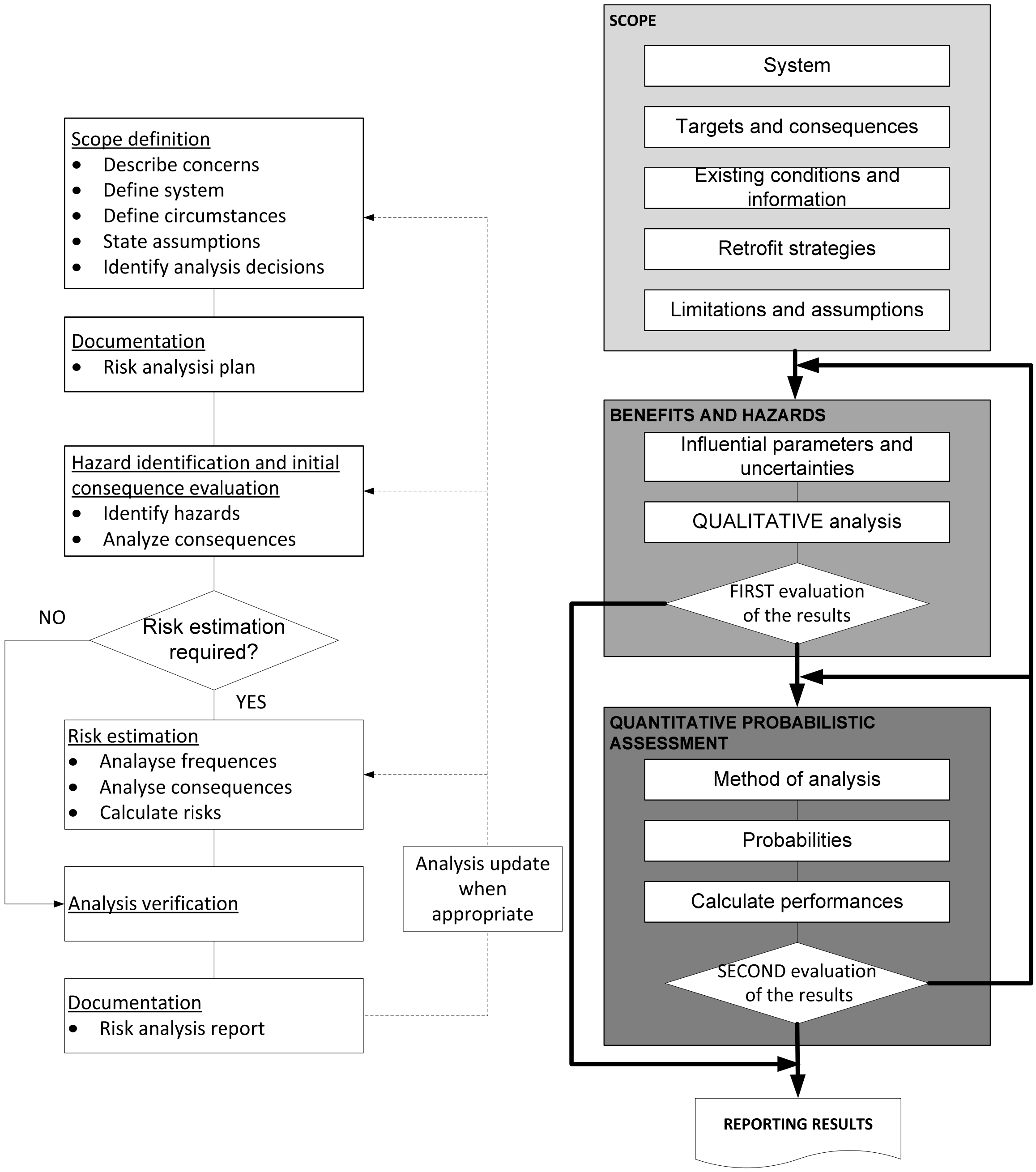


Figure 4 To the left: the model of the framework from Ljungquist (2005). To the right: the model of the framework proposed in the Annex.

Finally, the total result of the assessment is evaluated (Second evaluation of the results), the reliability is checked and all efforts are Reported. The risk of consequences is compared with the performance indicators and the predefined concerns. Discussions and recommendations on further analyses are made and suggestions are given on possible alternatives of redirecting. Ultimately, a decision is made on the acceptance of the risk. An example of how the steps in the framework can be organized in a report is given in section 5.4.

3.2 Presentation of results

Results of probabilistic risk assessments can be both complex and comprehensive. It is recommended to take into account the needs of future users when reporting the assessment. Three priority levels for the result presentation are identified, as shown in the graph below.

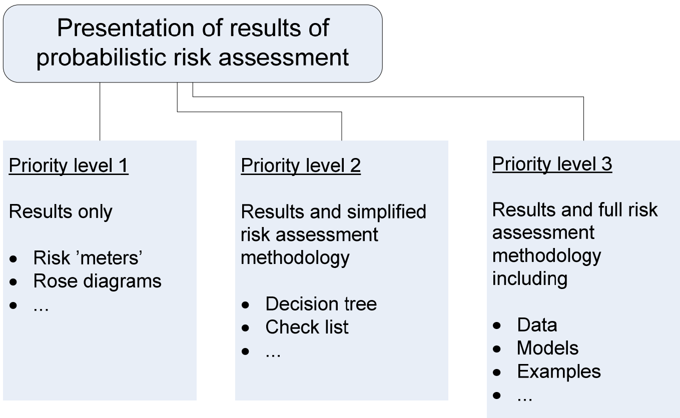


Figure 5 Various levels for the presentation of results of probabilistic risk assessments adopted as part of creating a framework for probabilistic assessment of renovation options

Results at the priority level 1 are for the users who are more interested in how to act rather than how the risk assessment is performed. Contractors, property owners and insurance companies may be interested in the results at this priority level. The results should allow a clear and simple insight into the most decisive parameters for the risk, as well as a conclusive choice of the course of action. For example, the risk “meter” in Figure 6 is used to describe the risk of mould growth on the roof underlay in a ventilated cold attic.

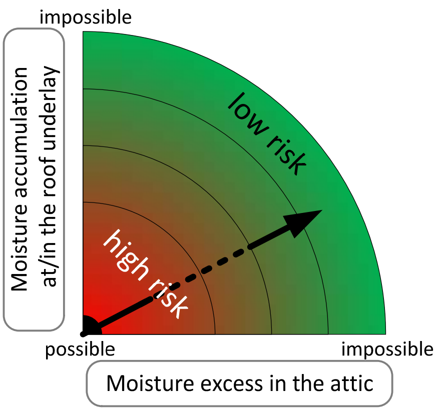
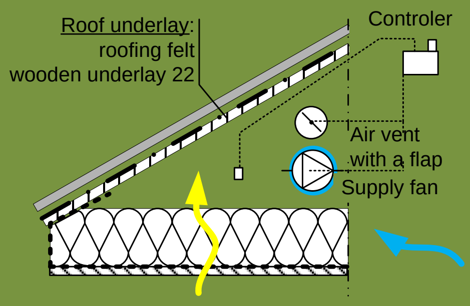
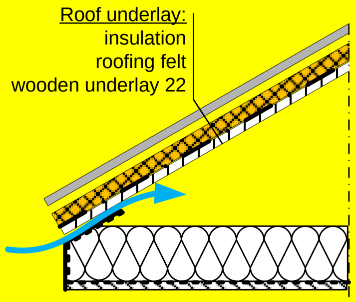
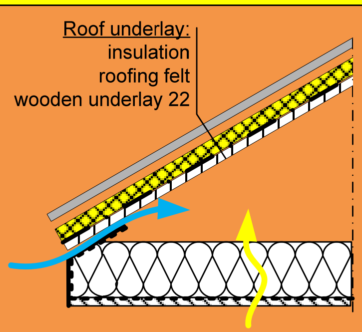


Figure 6 Risk ‘meter’ is used at the priority level 1 to correlate two main conditions for mould growth on the roof underlay in ventilated cold attics. The scale is rotatable and telescopic.

The mould growth risk depends on two conditions in the attic - a possibility for moisture accumulation in the roof underlay and a possibility for moisture excess in the attic. Both the conditions and the risk assessment are described in a qualitative way and a rotatable telescopic scale helps in finding the final risk. Another and more detailed presentation of the same results, still at the priority level 1, is shown on Figure 7. These are selected results of a comprehensive study of mould growth risks in ventilated cold attics by Hagentoft and Sasic Kalagasidis (2013), whose certain parts have been performed during the framework development (see Appendix 2). Further examples of results presentations at the priority level 1 can be found in Bednar and Hagentoft (2015).

	Cold attic construction	Requirements and sensitivity
Risk free	 Controlled mechanical ventilation	The airtightness of the attic should be 10 1/h @ 50Pa or better Ventilation should start directly after completeness of attic construction Requires alarm function for failure of mechanical devices Lowest total life cycle cost
Low risk	 Insulated roof, good air tightness of the attic floor	Requires durable solution for the airtightness of the attic floor. Works better at low moisture excess in the building (well ventilated housing - preferably exhaust only mechanical ventilation system). Sensitive to the building orientation. Some sensitivity to the local and future climate. Should be supplemented with dehumidifiers in the construction phase to eliminate built-in moisture.
Semi-high risk	 Insulated roof, some air leakage in the attic floor	Works better at low moisture excess in the building (well ventilated housing - preferably exhaust only mechanical ventilation system). Sensitive to the local and future climate. Should be supplemented with dehumidifiers in the construction phase to eliminate built-in moisture.

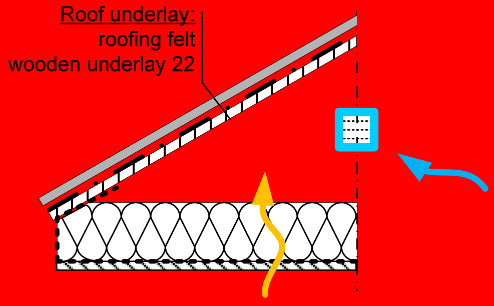
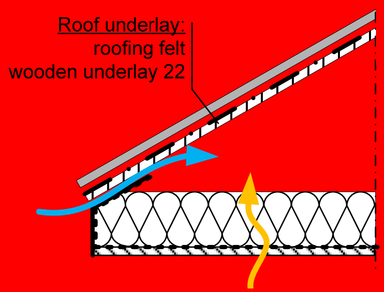
High risk	 Reduced ventilation – only through gable vents; air tight roof eaves.	Extra sensitive to the lack of air-tightness in the attic floor and high moisture excess in the home. Should be supplemented with dehumidifiers in the construction phase to eliminate built-in moisture. Sensitive to future climate.
High risk	 Traditional cold attic	Extra sensitive to the lack of air-tightness in the attic floor and high moisture excess in the home. Sensitive to future climate. The most expensive technical solution when lifecycle cost is assessed. Should be supplemented with dehumidifiers in the construction phase to eliminate built-in moisture.

Figure 7 Summarized risk levels of the various cold attics designs. Hagentoft and Sasic, (2014)

At the priority level 2, the user is interested in both the results and risk assessment process, but he/she prefers simplified presentation of the assessment. Design engineers and consulters in early stage of a design, and boards for standardization and regulations may be interested in these results. Fault trees, check lists and other means for describing cause-effect relationships in the risk assessment are appropriate at this level. An excerpt from a fault tree analysis is given in the next figure. It originates from the same study on the mould growth risks in ventilated cold attics, as the one shown in Figure 6. Unlike the risk meter, the fault tree shows possible order of events that lead to the conditions for the mould growth at the roof underlay. The whole fault tree can be found in Appendix 2.

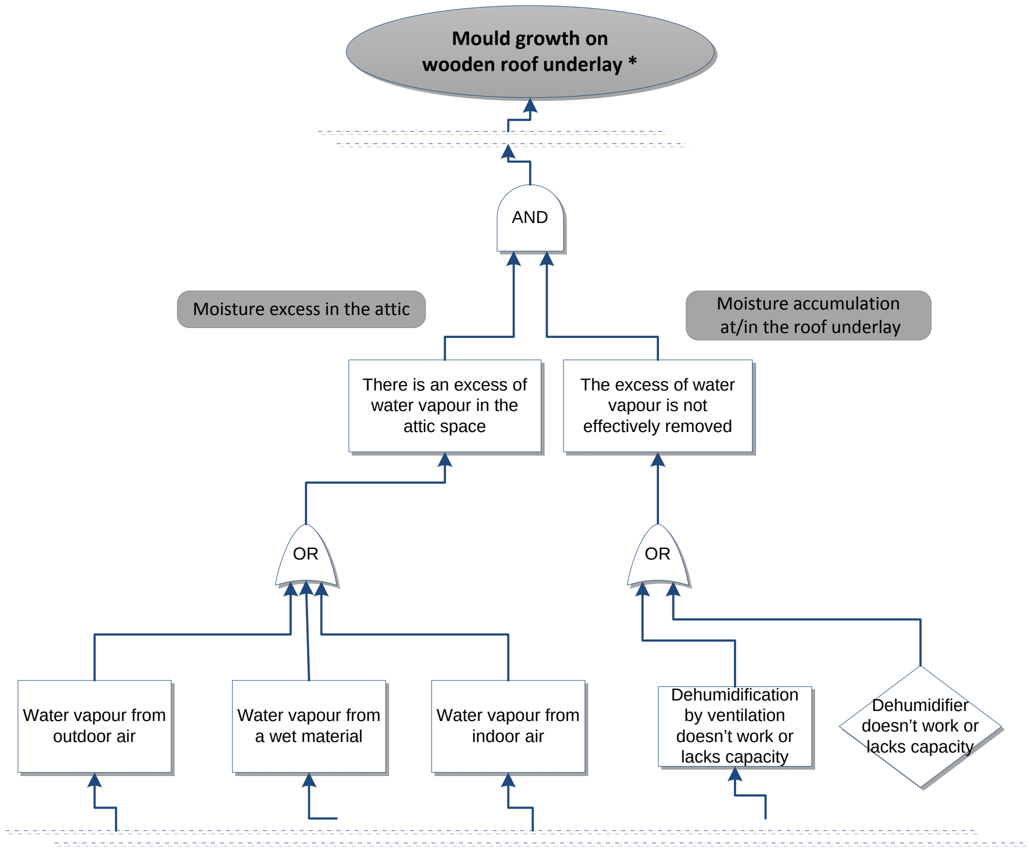


Figure 8 An excerpt from a fault tree analysis of events and conditions for mould growth risk on the roof underlay in ventilated cold attics. The full fault tree can be found in Appendix 2.

Finally, results at the priority level 3 provide deep insight into the probabilistic risk assessment, including examples, qualitative and quantitative models, input data and other information of relevance for the assessment. Such detailed presentation of the assessment is of interest for proving the credibility of the assessment or for training purposes. The solutions to common exercises that are appended to this report are all provided at the priority level 3.

4 EVALUATION OF THE FRAMEWORK

4.1 Methodology of evaluation

'Common exercises' have proven to be an efficient way of collecting responses from the participants in the Annex on questions related to calculation methodologies, problem solving issues, and similar. Hence, the evaluation of the framework was also organized through common exercises.

There were two main purposes with the common exercises. On one side, they should show how appropriate the proposed framework is as a tool for assessments of risks in building retrofitting. On the other side, the solutions obtained for the common exercises could be used in the future as examples on how to perform risk assessments.

For the purpose of obtaining the evaluations in a similar manner, the framework was prepared both as a flowchart and as a text template with section headings named and numbered after the steps in the flowchart, as shown in Table 1. The participants in the common exercises were asked to follow the individual steps and answer the supplementary questions and where it was found necessary, suggest modifications of the framework.

Common exercises

There were two common exercises associated with the evaluation of the framework. In the first common exercise, the participants could freely choose a retrofit case, while it was pre-defined in the second common exercise. In regard to the first common exercise, three real building envelope retrofit cases were provided as inspiration: an old brick house from Køge, Denmark; multi-residential houses from Sigtuna, Sweden; and social houses from Porto, Portugal. Section 6 provides a short description of these buildings, including conditions before retrofitting and the goals of the retrofit.

The solutions obtained for the first common exercise can be grouped in regard to the spatial scale of the study. There are solutions focusing solely on the hygrothermal performance of the building envelope after the retrofitting, but some also include the comfort in a zone enclosed in a retrofitted building envelope. This is schematically described in Figure 9. There is a notable difference between the numerical tools used in these studies. Specifically, the indoor climate is prescribed as a random input to the studies focusing on building envelopes, while it appears as a probabilistic result in the studies focusing on ventilated zones in the building. Generally, the numerical tools involved in the latter are more complex.

Probabilistic risk assessment is a time consuming process, especially for non-trained staff. To facilitate the training of the participant, all information required in the Scope of the framework was provided in the second common exercise. Besides the retrofitting case, which was a ventilated cold attic, the numerical modelling tool and the variability of decisive input variables were provided. Thus, the study focused on the probabilistic assessment and on the presentation of the results, as illustrated in Figure 10.

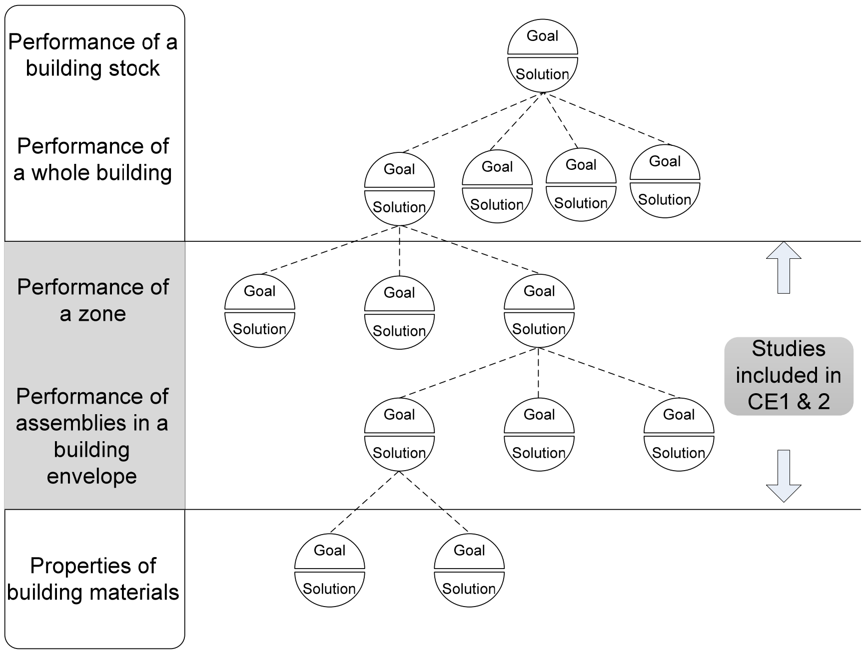


Figure 9 Spatial scale of the solutions obtained for Common Exercises 1 and 2

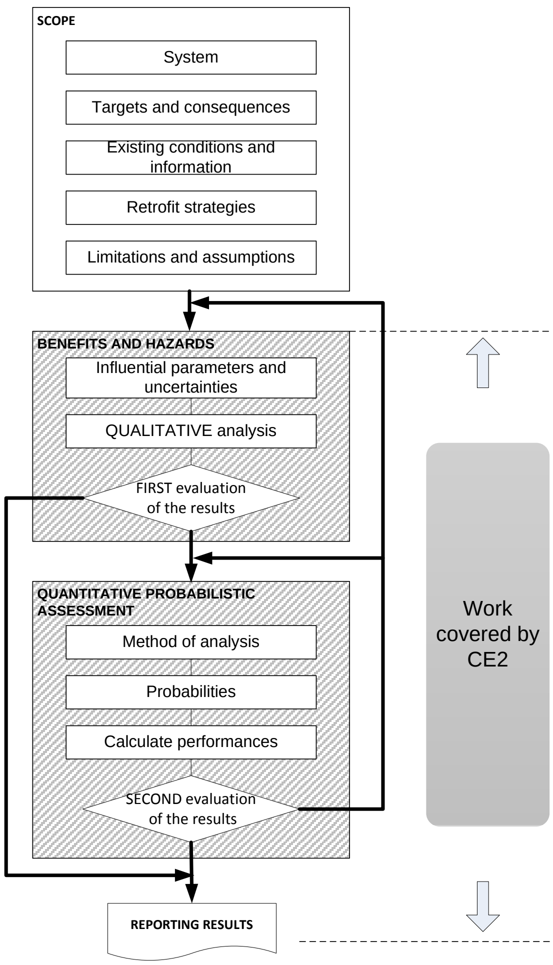


Figure 10 Steps in the framework to be executed in Common Exercise 2

Solutions available to CE1 and CE2

The following solutions have been obtained for Common Exercise 1

Chalmers, Sweden	Performance of a timber framed wall with additional insulation placed on inside of the wall
IVL, Sweden	Thermal comfort in an office after window retrofit
TU Wien, Austria	Performance of a massive brick wall with additional insulation placed on inside of the wall
TUT, Estonia	Performance of concrete walls with additional insulation placed on inside of the wall
DTU, Denmark	Hygrothermal conditions in cold attic spaces

Four detailed solutions have been provided for Common Exercise 2: Chalmers, Sweden, DTU, Denmark, SP, Sweden and ORNL, USA. The first two include the evaluation of the framework, while the last two focused mainly on the probabilistic risk assessment.

All listed solutions are provided in Appendices 1 and 2.

4.2 Suggested revisions

Based on the solutions for Common Exercises 1 and 2, which are provided in the appendices, it can be seen that the framework has been fairly followed. This has been interpreted as the framework is an appropriate tool for probabilistic risk assessment of retrofitted building envelopes. Also, several improvements of the initial framework have been identified, as presented hereafter.

Evaluation by Jakob Lindblom, IVL

If the results of a probabilistic risk assessment are contradictory with assumed targets of the retrofit, the assessment procedure should be revised from the start. This can be indicated by a return arrow embracing the scope section, as shown in Figure 11. Besides, a notice about keeping the data transparent for possible revisions of the evaluation process can be added. Furthermore, evaluation of intermediate results should also be advised throughout the framework. This would help in making earlier revisions of assumptions, input data and modelling strategy. Finally, a clear definition of the terminology used in the framework could facilitate a better interpretation of the framework.

Evaluation by Henrik Karlsson, SP

An early simple deterministic calculation can be recommended as a part of a qualitative assessment, in order to quantify reasonable limits of the scope of the retrofit measures. For example, by defining the insulation thickness on the attic floor as a stochastic variable in Common Exercise 2, and within a wide uniform span, a high degree of variability is introduced which doesn't exist in reality. Instead of defining a wide uniform spread of the insulation thickness, it is appealing (at least for the author) to study different populations of attic constructions. One population could be "highly insulated" retrofitted attics, another population is more "reasonable insulated" attics and so on. In each of the population the spread of the insulation thickness would then be small – it refers to the method of applying the actual insulation product (i.e. a few cm variations). Large amount of results of non-practical interests need to be correctly post-processed; otherwise, if not properly separated, they can mask the results of more practical interest.

Evaluation by Christopher Just Johnston, NIRAS A/S & DTU, and Lasse Juhl, DTU

The evaluation of the framework is done by answering few questions from the perspective of consulting engineers and building physicists.

'What is the purpose of working within the framework and what does it deliver?'

The motivation for using the framework would be for the purpose of obtaining quick and easy quality results. In order to do this, the framework would have to include elements of quality control and follow a structure that allows the user to naturally progress through the steps of the problem solving, without having to digress significantly from the plan laid out. Although the framework contains all these elements, its form could be improved. To illustrate what is meant by form (in opposition to content), there are three questions to answer:

‘Is it easy to use?’
‘Is it a timesaving tool?’
‘Can everybody use it?’
In response to the question ‘Is it easy to use?’, the answer is no mainly due to ambiguous wording, which gives the impression of overlap between steps and creates an uncertainty of how to answer the posed questions. To make the framework more accessible, step titles and explanatory notes should be written in a more direct language and in greater detail. An example of how the framework could be revised is shown in section 4.3, Figure 11.

‘Is it a timesaving tool?’. Where the short answer is yes, we do believe that the tool could benefit from another format that would facilitate efficient reporting. It could be split into two parts, a checklist and a reporting tool. The checklist alone will allow a fast overview of the analysis, while the reporting tool will lower post-analysis time. The questions in the checklist could be aligned to the reporting standards.

As for the final question ‘Can everybody use it?’, there are prerequisites that potential users need to meet before the framework can be fully utilised. Considering the aspect that there is still (and for some time to come) no computational program that can assess the influence of the stochastic variables on the hygrothermal conditions in a building design, it is necessary for a user to have considerable computational skills and good knowledge of building physics. Also, it should be mentioned that many of the computational programs, which can handle or can be programmed to handle the physics are expensive. Therefore, the framework could become an important tool for a significantly larger proportion of the building industry if the qualitative analysis section of the framework is expanded. This would, as an example, allow smaller businesses to do extensive parts of the preliminary work before handing the assignment over to more specialised groups and thereby reducing their costs. Also, if professionals can use the tool without having to go through quantitative analysis, the tool could fairly be expected to be used more often. This additional use and the inherent extra awareness could be hypothesised to have a positive impact on the quality of building designs.

Summary of the revisions

While some of the suggested improvements can be directly included in the initial framework, the NIRAS/DTU evaluation revealed a need for another framework which would be more oriented to practitioners. Therefore, two versions of the framework have been proposed: (i) ‘full version’, i.e. for users who are well acquainted with or are in a position to perform full probabilistic risk assessment, and, (ii) ‘simplified versions’ for users who have limited resources for making a full probabilistic assessment. The simplified version of the framework is focused mainly on qualitative assessment. It includes certain shortcuts that help moving quickly between the steps, and somewhat more detailed description of the tasks in a step.

All suggested improvements are found important and, therefore, adopted. The two versions of the framework, the full and the simplified one, are presented in Figure 11.

4.3 Revised versions of the framework

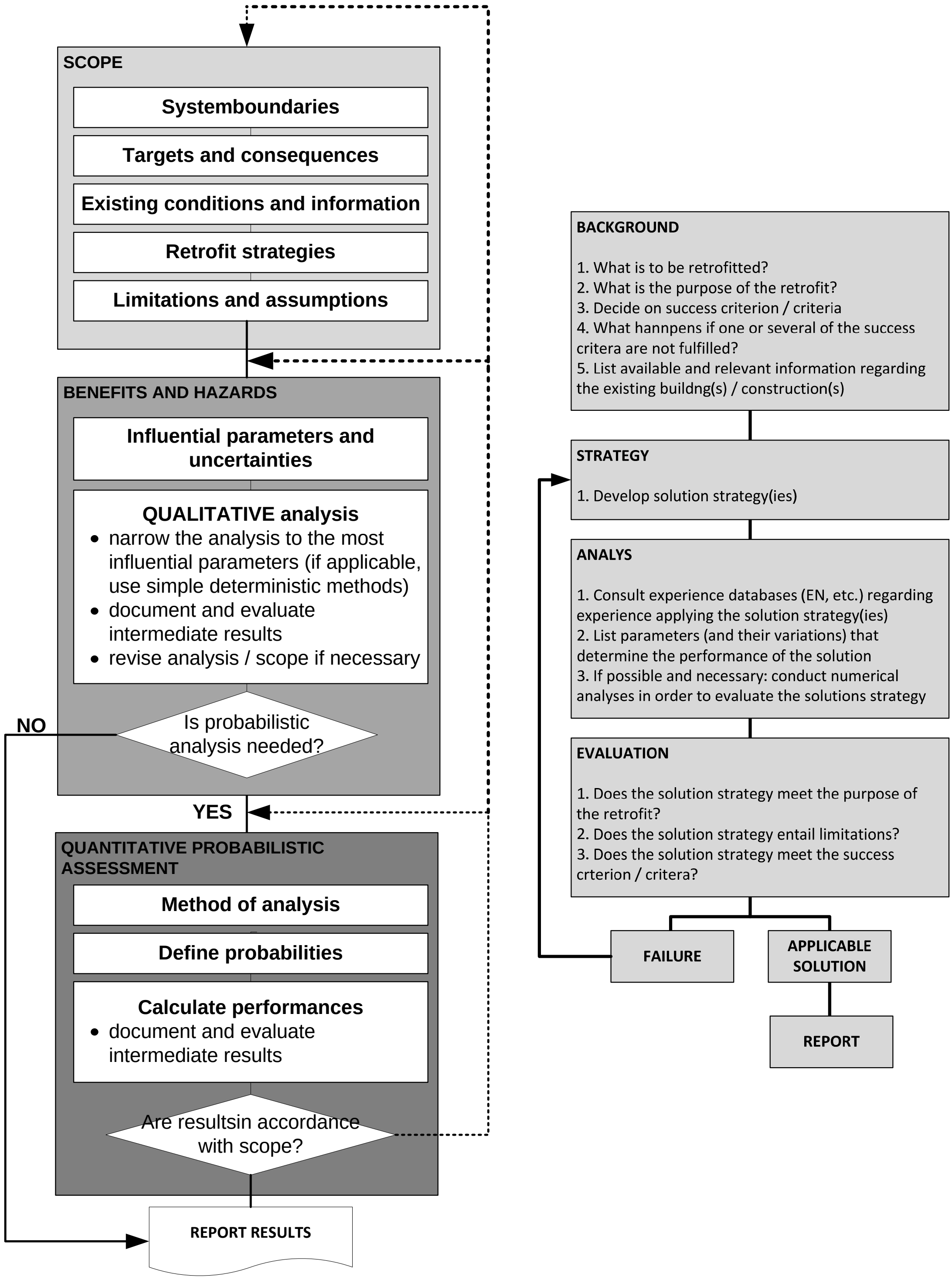


Figure 11 To the left: the full version of the framework is an updated version of the initial RAP-RETRO framework. To the right: the simplified version of the framework is adjusted to take account of limited time or resources for probabilistic risk assessments.

5 REQUIREMENTS FOR PROBABILISTIC RISK ASSESSMENT

5.1 Input data

Probabilistic risk assessment of performance of retrofitted building envelopes requires the same types of input data as any other building physics design. The data can be roughly grouped into indoor and outdoor conditions, which specify exposure and duration to various thermal and moisture loads, and construction details such as geometry, structural assembly and properties of building materials. Unlike a deterministic design where one set of data is provided for each input parameter, the probabilistic assessment needs variability of each data set which shows the spread and clustering of the data in the set. For example, a test or design reference year (TRY, DRY) of weather data is normally sufficient in deterministic building physics designs. In the probabilistic design, a set of several weather years is required in order to address both typical and extreme weather conditions. Natural variability of a climate system can be large and therefore 30-year periods of consecutive years are typically studied in meteorology to define the climate at a certain location (E. Kjellström et al. 2007) or the climate change impact on buildings (Nik 2012). Likewise, the variability of indoor conditions should reflect all possible living habits of tenants, appropriately translated into thermal and moisture loads on the building envelope (see examples below).

Data gathering and processing is challenging work. Existing data together with examples and guidelines on how to create new data sets are described in detail in Ramos and Grunewald (2015). Examples of how statistical input data can be generated are provided in Figure 12 and Figure 13.

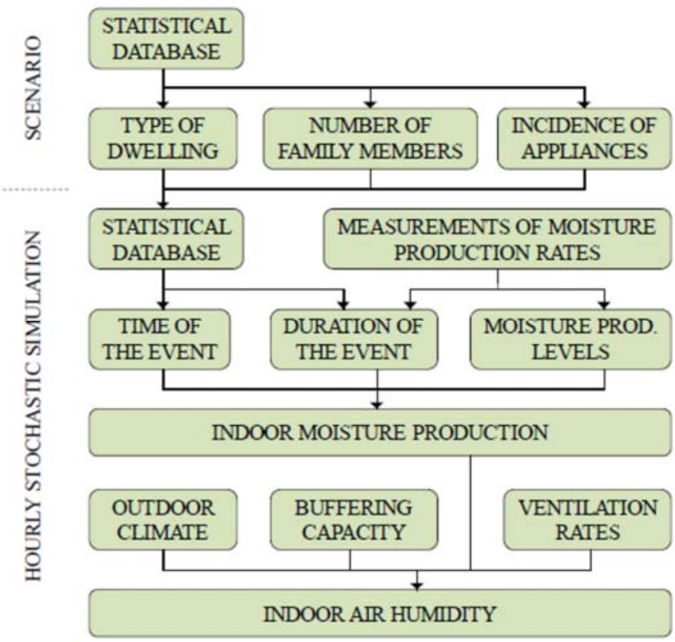


Figure 12 Simulation chart for the generation of statistical data on indoor moisture production in a dwelling. Statistical database at the top of the chart includes intensity of common indoor moisture sources in households together with expected variations of the moisture production (Pallin et al. 2011).

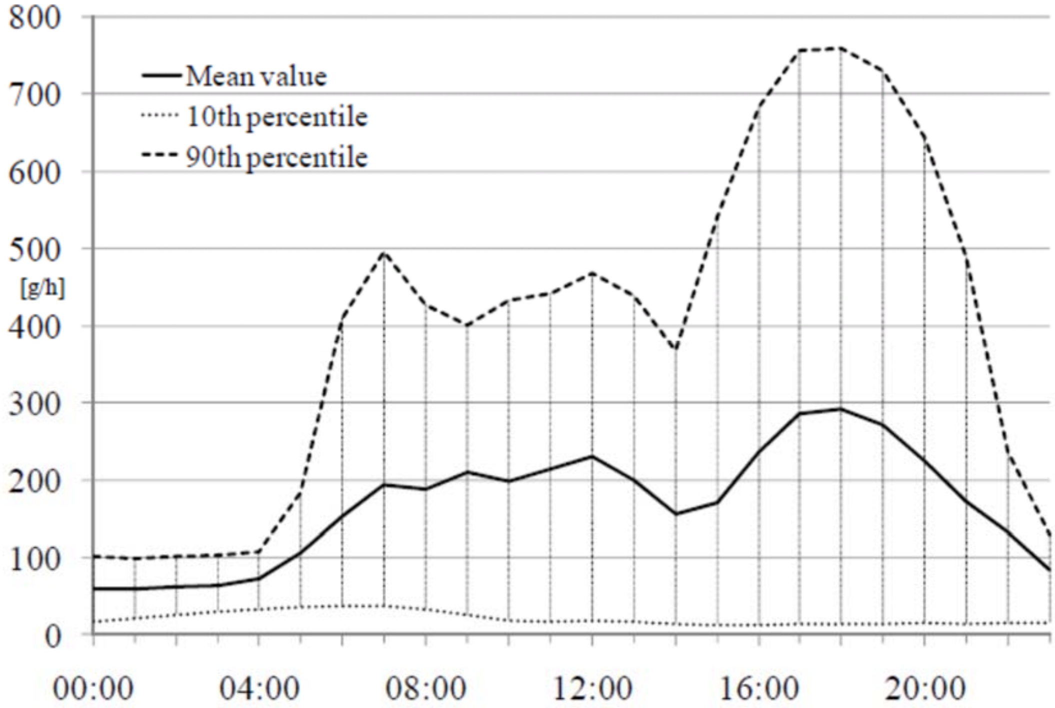


Figure 13 Hourly variations of the indoor moisture production based on simulations of 1000 Swedish households during one year. The simulations were performed according to the algorithm from Figure 12. The graph is presenting the mean value, 10th and 90th percentiles on an average yearly daily basis (Pallin et al. 2011).

5.2 Assessment tools

Qualitative and quantitative assessments are essential activities in probabilistic risk assessment. The qualitative assessment involves system thinking where efforts are made to decompose a system into separate parts in order to find how these parts are related to the risk addressed. System thinking should result in definition of a problem or situation, identification of key variables and performances, construction of casual loop diagrams, systems archetypes, key leverage points (sensitivity analysis), intervention strategies, etc. (Pietrzyk, 2012). Fault tree analysis (top down, deductive), event tree analyses (bottom up, inductive), check lists and similar tools for qualitative description of problems and consequences for a certain system are appropriate tools for qualitative risk assessment. An example of the fault tree analysis is shown in Figure 8 and more examples can be found in appended solutions to common exercises (see Appendix 1 and 2).

Quantitative assessment involves a mathematical description of the system and computer simulations. All kinds of numerical design tools that give a fair representation of the system can be used for this purpose. It should be noted that the number of necessary simulations in probabilistic assessment can be rather high. Preferred simulation tools are thus those with possibilities for computerized reading of input data sets, where each set represents a possible working scenario, as well as with a short calculation time. Another preferable feature is a possibility for statistical processing of simulation results. The planning of numerical experiments and examples of simulation tools for probabilistic assessment are presented in Janssen et al. (2015).

During the RAP-RETRO project, a probabilistic simulation tool entitled ‘Simple Cold Attic’ has been developed for the assessment of mould growth risks in ventilated attics. As shown below, users can choose between deterministic and probabilistic simulations. The tool is available for free downloading (Nik, V. 2014) and can be used for both research and training purposes, i.e. for Common Exercise 2.

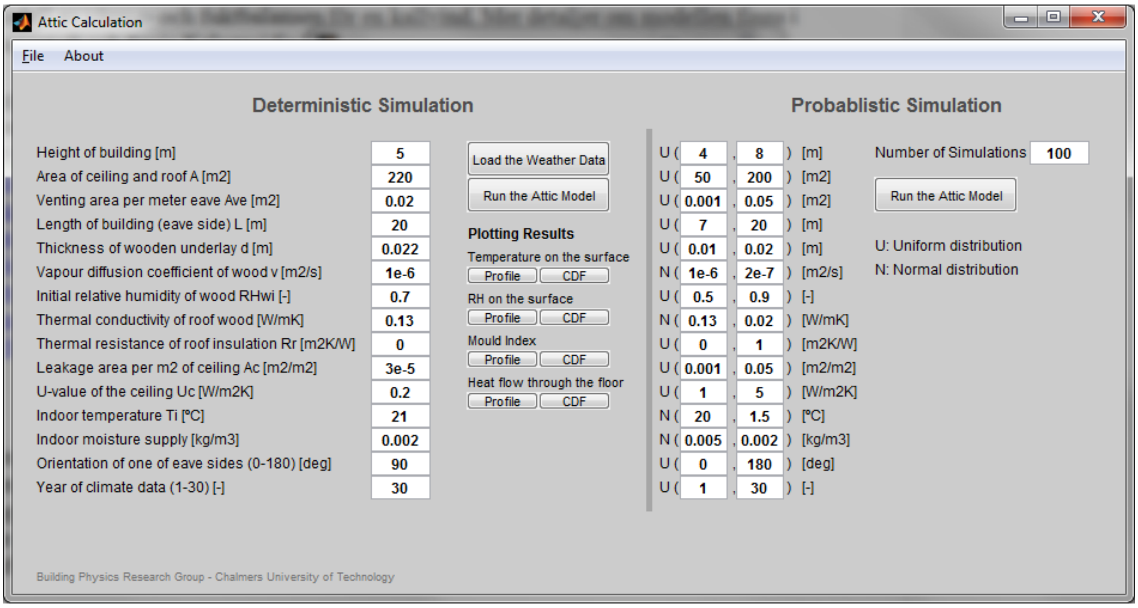


Figure 14 User interface of Simple Cold Attic developed within RAP-RETRO

5.3 Performance criteria

To successfully judge the quality of a design, thought must go into determining appropriate performance criteria. What criteria to choose will be dependent on the specifics of every single case; standards can be dictated by local building regulations, materials used in constructions can set a tolerance limit for exposure levels, or it can be a combination of standards and circumstances that lead to the choice of performance criteria.

A probabilistic assessment of a design yields a space of possible performance results with a most probable outcome and a measure of the uncertainty of the most probable outcome. This understanding of the design and the associated uncertainties must be compared to the chosen performance criteria in order to judge whether a design can be deemed adequately reliable for its purpose. That is, when comparing design results, e.g. from simulations, to performance criteria, a margin of safety should be incorporated. A safety margin could be equivalent to the calculated uncertainty but could, in difficult cases, also be subject to a weighing of risk to cost, which may be a choice a client could have an opinion upon.

It is often a simple and straightforward procedure to obtain performance criteria when they are set forth in building codes. However, in other cases it may be more difficult to identify performance criteria. That could for example be the case when a client broadly requires a “sustainable” solution, or with demands for a low maintenance building.

Performance criteria seem to fall in one of the following categories:

1. Absolute
2. Classifications
3. Relative
4. Probabilistic

Absolute criteria will for example be such that appear in a building code, and it is deemed to be unacceptable if they are not met.

These are absolute criteria that we know, and can relate to. They are simple and manageable – which is not without value for practical work.

Classifications allow the “user” to choose between two or more values from a list, typically in a rating system. For instance: I, II and III. This format can be useful when several levels of criteria fulfilment are acceptable; then it is up to the client to choose and specify the ambition level.

Relative criteria are those which **c**annot themselves be set by specific quantitative values, but they can be rated relatively when compared within a pool of performance results.

Relative criteria are possibly cumbersome. They can be hard to use e.g. for building permits or for a real risk assessment, but they can be used in a process where a solution space is sought and investigated, and can therefore still be decisive. Relative criteria cannot stand alone, but must be supported by absolute criteria.

Probabilistic criteria are such that indicate the risk of failure on a probabilistic scale. Still not many probabilistic criteria exist today, although there are few, e.g.:

- The well-known indices to rate thermal indoor climate: PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) (Fanger, 1970).
- The risk of mould growth as a result of relative humidity and temperature in the environment is reported for instance by Nevander et al. (1994).

Probabilistic criteria address the uncertainty that is associated with what is good, and what isn't. They make room for constructing in fields where knowledge is not absolute or where there are only few borders between different check areas. Probabilistically defined criteria make it difficult to address the issue of liability of fault.

In order to determine the appropriate performance criteria, it is helpful to identify the possible consequences of failure: If a material becomes too moist, will it swell? If frost sets in, will a moist material crack? If insulation is poorly fitted, can it cause local condensation? As choices for performance criteria, a designer can pick the possible failures found to be most likely, representative and/or critical. It can be good practice to choose more performance criteria than what appears necessary in order to avoid the consequences of misjudgement.

To help identify the correct performance criteria, a few ideas have been listed below. It is not an attempt to compile an exhaustive list. An exhaustive list would be nearly impossible to make, and future construction methods would soon diminish the value of such a list. Also, a comprehensive list might have the unfortunate side effect of appearing exhaustive and give a designer a false sense of security; every designer should attempt to identify possible critical points on his or her own.

General list of possible performance criteria

Performance criteria of interest in the IEA Annex 55 context could fall within the following subject areas:

- U-values for construction parts or construction as a whole
- Critical thermal bridges where temperatures drop below or close to indoor/outdoor dew-points
- Air changes that comply with building regulations or a client's wishes
- Reasonable and robust values for the relative humidity inside the building envelope
- Efficient vapour/moisture barriers in the building envelope
- Reasonable and robust values for the relative humidity in the construction materials
    - It is necessary to identify the critical points and surfaces
- Conditions for mould growth in construction parts and on surfaces
- Indoor environmental conditions
- Conditions for rot in construction parts
- Other location or situation-specific considerations (e.g. salt in maritime constructions, thawing of permafrost, etc.)

Similar and more criteria have been listed in conjunction with previous IEA projects, as well as in various predominantly national codes and guidelines. Examples can be taken from:

- IEA ECBCS Annex 24 - Heat, Air and Moisture Transfer in Insulated Envelope Parts
- IEA ECBCS Annex 32 - Integral Building Envelope Performance Assessment

- EN15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
- ASHRAE standards and ASHRAE handbooks

  In addition, criteria can be found in the vast number of national guidebooks and international research papers that exist, e.g.:

From Denmark:

- SBI-Guidebook 182 - Indoor environment handbook
- SBI-Guidebook 224 - Moisture in buildings
- SBI-Guidebook 204 - Investigation and evaluation of mould growth in buildings
- The Danish Building Regulations (BR10)

From Sweden:

- Moisture handbook (Nevander and Elmarsson B, 2006)

International research paper:

- Perceived indoor Air Quality (Fang et al., 1998)

Compound performance criteria such as mould growth models, which combine hygrothermal conditions at the surface of a material, type of the material and exposure time, are particularly suitable for risk assessments. Several mould growth models are available today and examples can be found below. However, these mould growth risk criteria could be too conservative for probabilistic risk assessment if they are applied solely as discrete limit states. For example, the target of a retrofit could be defined as all retrofitted constructions should have mould growth index less than 1. This means that all retrofitted constructions should be absolutely mould-free. In engineering disciplines where risk assessment is a part of engineering design, such structural engineering, a common practice is to define a probability of non-performance. A similar approach should be considered for hygrothermal risk assessments, where both a probability of non-performance and a variability of the limit state are defined (Thelandersson, 2012). A concept for such approach is illustrated in Figure 18. Another example of a performance criterion with included variability is predicted percentage of dissatisfied (Fanger, 1970), used for the assessment of thermal comfort in buildings.

Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10 % coverage, or, < 50 % coverage of mould (microscope)
4	Visual findings of mould on surface, 10 - 50 % coverage, or, >50 % coverage of mould (microscope)
5	Plenty of growth on surface, > 50 % coverage (visual)
6	Heavy and tight growth, coverage about 100 %

Figure 15 Mould growth rate description in the VTT Mould growth index (MGI) model (Ojanen et al., 2010)

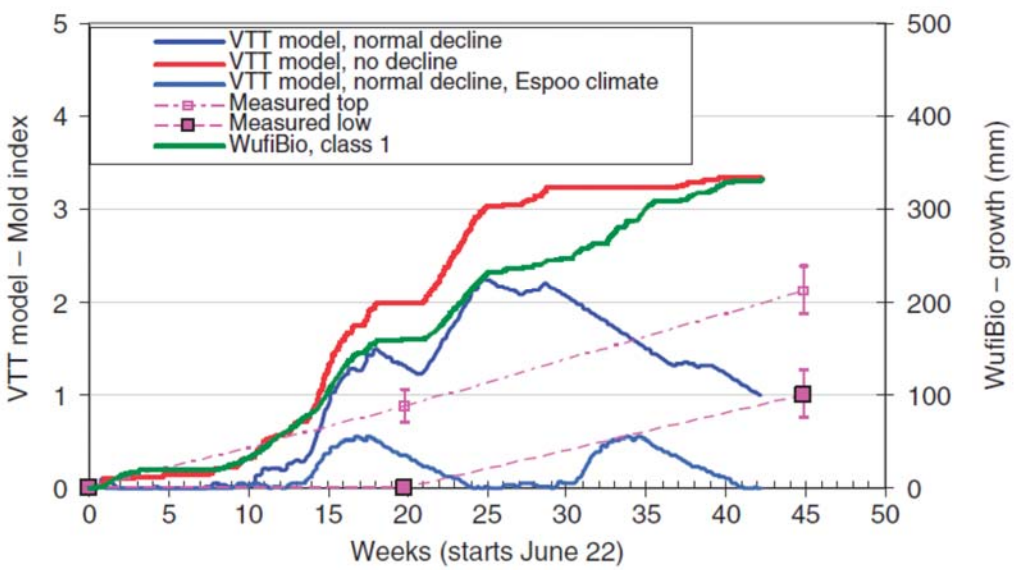


Figure 16 Comparison of measured mould index on the surface of pine sapwood with the VTT-MGI model and WufiBio (Viitanen et al., 2010)

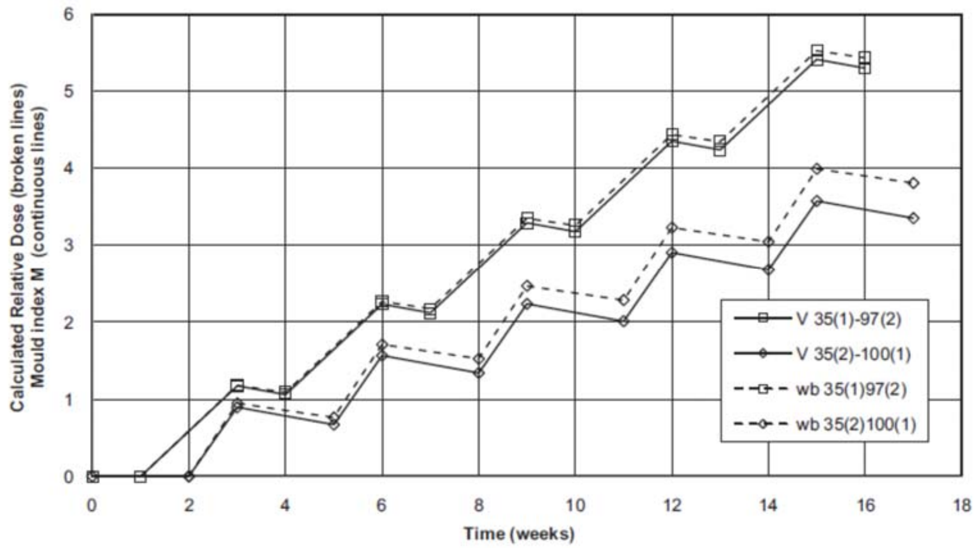


Figure 17 Comparison of Mould Dose Response (MDR) with VTT-MGI model (Isaksson et al. 2010).

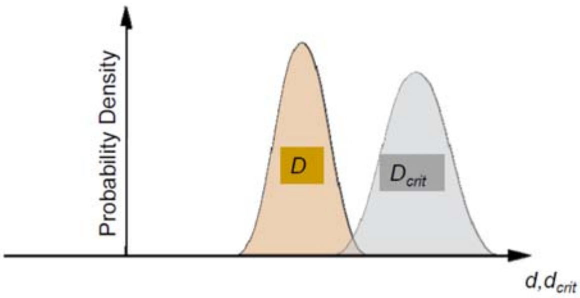


Figure 18 Probability of non-performance and a variability of the limit state defined for Mould Dose Response MDR (Thelandersson, 2012)

5.4 Plan for probabilistic assessment and documentation strategy

The RAP-RETRO Framework or similar guidelines, flowcharts and step-by-step instructions for organizing and documenting a probabilistic risk assessment are highly advised. An example of how the steps in the framework can be organized in a report is given below.

The RAP-RETRO Framework or similar guidelines, flowcharts and step-by-step instructions for organizing and documenting a probabilistic risk assessment are highly advised. An example of how the steps in the framework can be organized in a report is given below. Note that the flow chart includes conditional exits and returning loops, which are not visible in the list below.

1. SCOPE

1.1. System boundaries

Define the spatial scale of the project: whole building, zone, part of the building envelope, and/or building material

1.2. Targets (performance criteria) and consequences

Specify performance indicators and target values. Describe consequences if the targets are not fulfilled.

1.3. Existing conditions and information

Present facts and data about the current state of the building. Find out what motivates the choice of the selected retrofit strategy

1.4. Retrofit strategies

Present alternative retrofitting measure, if any, and specify how the ranking of the retrofit measures have been done

1.5. Limitations and assumptions

Declare what is assumed to be fulfilled and also what is not comprised by the analysis

2. IDENTIFICATION OF BENEFITS AND HAZARDS

2.1. Influential parameters and their uncertainties

Describe hygrothermal loads in indoor and outdoor environment that have been considered in the analysis. Explain normal and extreme values of these loads.

2.2. Performed QUALITATIVE probabilistic analysis

Present existing knowledge about the retrofit case. These could be recommendations, quality insurance systems and similar. Define the tools used for qualitative assessment: fault trees, simplified calculations, etc.

2.3. First evaluation of the results

Present pros and cons with the retrofitting based on the qualitative assessment. Group the results, if possible, in terms of areas with high, moderate and low risk. If the analysis has been stopped/continued at this step, explain why there is no/is need to go for a quantitative assessment.

3. QUANTITATIVE PROBABILISTIC ANALYSIS

3.1. Method of analysis

Describe numerical model, simulation scheme, number of necessary simulations and convergence criterion. List the influential parameters and group them, if possible, into discrete and stochastic.

3.2. Define probabilities

For each of the influential parameters define the mean and extreme values and their distributions. Define the values of discrete parameters

3.3. Calculated performances

Summarize in an appropriate way and describe the results of probabilistic simulations. It is essential that the results are correctly presented since they will be used in a decision making process.

3.4. Second evaluation of the results

Make some final comments about the reliability of the results and about the chosen method of analysis. Report all efforts, not just the final method that has shown appropriate. Make conclusions about the selected retrofit strategy.

4. REPORTING THE RESULTS

4.1. Results for priority level one

Charts, rose diagrams, tables - 'easy' information at hand

4.2. Results for priority level two

Flow charts and other methods for qualitative analyses

4.3. Results for priority level three

Detailed description of the assessment as shown in steps 1-4; see as possible examples the reports for ST3.

5.5 Examples of probabilistic assessment

Examples of probabilistic assessments could be valuable source of inspiration and training courses for inexperienced valuators or when assessing a certain construction for the first time. Appendices 1 and 2 provide a broad range of solved examples, which are done by practitioners and researchers with different levels of experience in probabilistic risk assessment. The solutions are presented in their original form for the purpose of illustrating different approaches in the assessment. Depending on the valuator, the approach may be different even when the same risk assessment procedure is followed (i.e. the RAP-RETRO framework). Even with different approaches, all risk assessments should lead to similar conclusions for a specific retrofit case. Examples can be found in Common Exercise 2 (Appendix 2), where all solutions indicate the same ranking of retrofitted strategies for cold attics. Otherwise, a source of divergence between the solutions should be found and the assessment should be revised accordingly.

6 EXAMPLES OF RETROFIT CASES

This section includes three examples of retrofit cases that differ both in methods and extent of the retrofit. These examples are provided as inspirations for self-standing studies on probabilistic assessment.

6.1 Social housing in Porto, Portugal

Bairro de Lordelo is a rental housing area in Porto with apartment buildings from the late 1970's. The area was a part of the retrofitting program of the municipality of Porto, which aimed at improving the life quality and comfort in the social housing in Porto. The type of tenure involved strict financial constraints in the project (12 500 euros per dwelling) and, therefore, the retrofit covered walls, roof and windows. The natural ventilation and intermittent heating have remained after the retrofitting. The mechanical cooling is not used.

The building envelope before retrofitting was composed of uninsulated cavity walls (brick veneer and concrete, U=1.4 W/(m^2·K)), uninsulated ceiling/attic floor (concrete) and single-glazed windows with wooden frames. Overheating in summer and mould growth on walls was present in most of the apartments before the renovation.

The contribution of this case study is to show the importance of the investment and the increase of the comfort for this situation, representative of different areas of the south of Europe. The houses were retrofitted in 2011 and the outcome of the retrofit has been measured since then (indoor climate in selected apartments).

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Façade

Roof and uninsulated attic floor (concrete)

Damaged brick venieer of the cavity wall. Inner wall is of concrete.

Mould on the wall in the kitchen.

Figure 19 Status of the houses before retrofitting. Photo Nuno Ramos and Vasco Freitas

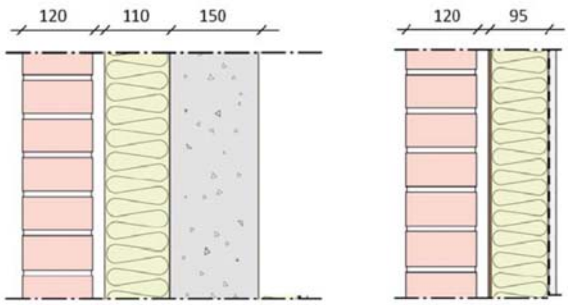
6.2 Neighbourhood Sigtuna, Sweden

Sigtuna is a neighbourhood in northern Stockholm with 50 multifamily two-storey buildings from early ‘70s. Each building has 12 to 14 apartments and the heated floor area of approximately 1100 square meters.

Appartment buildings in Sigtuna

Spatial paln of the area

The staus of the ventilated cold attic before the retrofitting



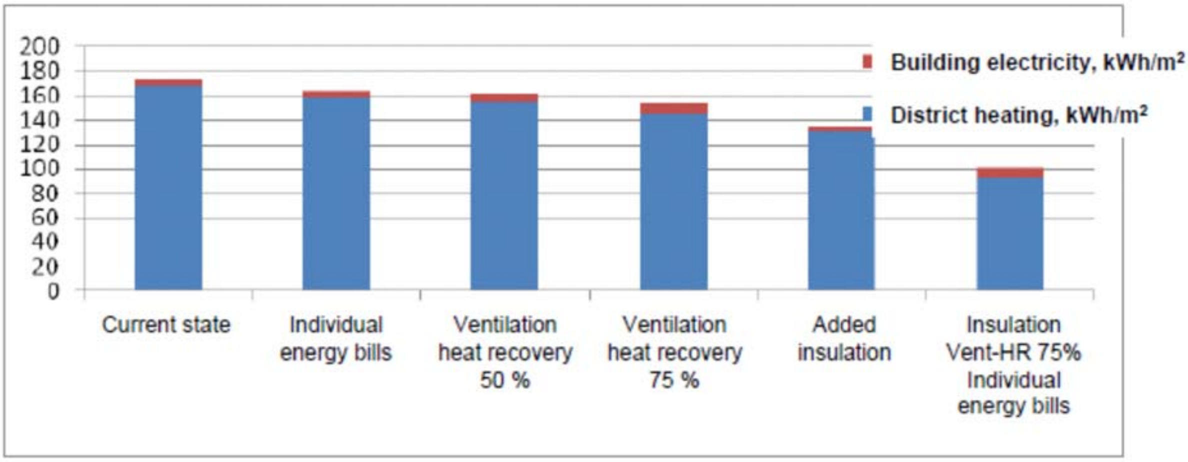
Construction of a load bearing (north and south) and curtain wall (east and west) before the retrofitting

Specific annual energy use in the buildings before renovation was approximately 170 kWh/m². The renovation of the buildings was planned in accordance with then the national goals for the reduction of total energy use per heated unit area in residential buildings, with target reductions of 20% by 2020 and 50% by 2050 compared with consumption in 1995. In addition, by 2020 the dependence on fossil fuels for the energy use in the built environment sector will be parted, while continuously increasing in the share of renewable energy. The limit set by the building regulation (reference year 2011) was 110 kWh/m² and year, or less. The goal for the buildings in Sigtuna was 89 kWh/m² and year. The owners demands were:

- to reduce the bought energy by 50 %
- to identify possible measures to reach a 50 % reduction

- another 40-years of use
- the retrofit should not cause higher rents

The diagram below shows results of a preliminary feasibility study. To achieve the desired goals, the renovation should include introduction of individual energy bills, mechanical ventilation with 75 % heat recovery and improved thermal insulation of the buildings.



Further details about the status of the building envelope before and after the retrofitting are summarized in the table below.

	Unit	*Before renovation*	*After renovation, estimated values*
Heated floor area	*m2*	*1 134*	*1 112*
Building envelope area		*1 865*	*n/a*
Window area		*108*	*n/a*
U-values	*W/m2K*		
Exterior wall, brick	W/m²K	*0.41*	*0.25*
Exterior wall, wood	W/m²K	*0.30*	*0.20*
Roof	W/m²K	*0.22*	*0.12*
Window	W/m²K	*2.8*	*1.2*
Ground floor slab	W/m²K	*0.33*	*0.27*
Doors	W/m²K	*1.77*	*1.77*
Thermal bridges	*W/K*	*73.4*	*n/a*
Ventilation flow rate	*m3/h*	*1 245*	*1 129*
Air leakage, @ 50 Pa	*l/m2s*	*1.2*	*0.65*
Domestic hot water	*kWh/year*	*50 370*	*36 135*
Household electricity	*kWh/year*	*28 007*	*n/a*
Building electricity	*kWh/year*	*8 148*	*n/a*

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6.3 Energy project Villa, *Køge, Denmark*

The Villa is an old typical Danish master builder house of 161 m² with a C5 classification for heating before the energy renovation. It has a full basement (not heated), a ground floor and a first floor, and is occupied by four persons – a family with two small children. C5 classification for heating is the poorest classification possible in Denmark. The monitored gross energy consumption of the Villa before renovation was 53,400 kWh per year (332 kWh/m²) at an indoor temperature of 20°C.

The original structures of the house were composed of 30 cm un-insulated cavity walls with steel ties. The windows were traditional, old windows with small wooden glazing bars, which, on the ground floor, were partly equipped with storm windows with ordinary glass. The space under the roof slope, the sloping walls and the collar-beam roof were insulated with old 50 mm insulation mats.

Front facade - south

Room heating was originally provided by old cast iron heaters with manually operated on/off valves. The room heating system was water-based, buoyancy driven, and two-stringed. The necessary ventilation, i.e. fresh air supply in the Villa was provided by means of manually opening and closing of windows combined with use of air shafts in external walls (i.e. natural ventilation). Besides this intended and controlled ventilation, an uncontrolled infiltration/ventilation of the building took place through various air leakages in the building envelope. Especially around the original window frames, the air leakage was significant, leading to cold draught near windows.

The measured temperature levels in the Villa before the renovation are characterised by:

Being generally low. The average room temperature in the villa before renovation is measured to 19.4 °C. Whereas standard temperature is minimum 20 °C. The measured minimum temperatures are down to 13-15 °C in several rooms for longer periods.

Varying considerably from room to room with average room temperatures varying from 17-22 °C.

Varying considerably over the day. This could be due to the fact that the existing cast iron radiators were provided with on/off valves only.

The air leakage of the building before energy renovation was measured to be19 air changes per hour at 50 Pa. In comparison, air-leakages in low-energy houses in DK with very tight building envelopes are measured to be 0.2-0.6 air changes per hour at 50 Pa.

The air change rate was measured to be 0.4 air changes per hour in the living rooms (i.e. living room, dining room, and bedrooms). In comparison a new built house in DK typically has an air change rate of 0.4-1.0 air changes.

The measured relative humidity in the villa before energy renovation generally varies from 40-60 % on average in most rooms. In the bedroom where the room temperature is generally kept very low - the average relative humidity is 65%. In the bathroom it is 70%.

The project was considered suitable for the purpose of Annex 55 because VILLA delivered before-and-after measurements of retrofitting effects and details on the retrofitting process and building structure. The same project subsequently used as the basic example on which the Common Exercises 1 and 2 in Subtask 2 were constructed.

The renovation of the villa was conducted from 2004 to 2005. The results of the renovation are summarized in a report (**2014, Rockwool).

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Appendix 1
Solutions to CE 1

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Austria: [TUV] Paul Wegerer and Thomas Bednar

Performance of a massive brick wall with additional insulation placed on inside of the wall

Denmark: [DTU] Christopher Just Johnston and Lasse Juhl

Hygrothermal conditions in cold attic spaces

Estonia: [TUT] Targo Kalamees, Simo Ilomets and Endrik Arumagi

Interior insulation of a concrete wall – thermal bridges

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Performance of a timber framed wall with additional insulation placed on inside of the wall

Sweden: [IVL] Jakob Lindblom

Thermal comfort in an office after window retrofit

Appendix 2
Solutions to CE 2

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Appendix 1 Solutions to CE 1

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B.

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Hygrothermal conditions in cold attic spaces

C.

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Risk of condensation and mould growth caused by thermal bridges

D.

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Thermal comfort in an office after window retrofit

E.

Sweden: [CTH] Simon Pallin

Performance of a timber framed wall with additional insulation placed on inside of the wall

Table of Contents

Short summary of the results

A. Performance of a massive brick wall with additional insulation placed on inside of the wall

The execution of an interior insulation system requires an intensive and detailed planning process. For that purpose a practical qualitative risk assessment tool in form of a questionnaire is presented. The tool guides designers and contractors through basic knockout criteria and important issues. The results of a quantitative probabilistic risk assessment of interior insulation show larger risks of mould growth than what is presented in currently valid Austrian standards ÖNORM B 8110-2 and EN ISO 13788. To decrease the risks, the thickness of interior insulation should be low and a ventilation system should be used to lower the average humidity level indoors.

B. Hygrothermal conditions in cold attic spaces

The analysis focused mainly on the evaluation of the framework by using ventilated cold attics as a study case. It was found that the framework could become an important tool for a significantly larger proportion of the building industry if the qualitative analysis section of the framework was expanded. A more practice oriented framework was suggested. More specific results for cold attics can be found in Appendix 2.

C. Risk of condensation and mould growth caused by thermal bridges

In cold climates, thermal bridges are important for moisture-safety because they may lead to failures in form of surface condensation and mould growth. The study evaluates criticality thermal bridges of an old concrete apartment building after retrofitting. Temperature factor at the internal surface was used as a a performance criterion to critically assess and to classify the thermal bridges. The results show that the probability of surface condensation at the thermal bridge, pre- and post-renovation, is 25% and 2%, respectively. The probability of mould growth is 21% before and 2% after the renovation. The design goal 0% for risk of failure with temperature factor 0.8 was not achieved.

D. Thermal comfort in an office after window retrofit

Building certification systems generally require a maximum value of PPD during a dimensioning situation. Such an approach does not provide information regarding how the result is spread over the year but within which boundaries. This case study aimed to assess the expected variability in thermal comfort performance for a future window retrofit case. The original target set was maximum 10 % PPD. A quantification of expected spread of results was calculated with different tools, but subsequent analysis shows that the result depends heavily on other parameters than the window performance. "Round three" suggests that the positive impact, from the window retrofit, on the thermal climate in this case result in approximately 5 % predicted better odds to meet the goal of maximum 10 % PPD in the building. Still this goal is not met during about 15 % of the time and this is to a large extent during non-challenging climate conditions and hence probably not majorly window related.

E. Performance of a timber framed wall with additional insulation placed on inside of the wall

The positions of former thermal bridges in the existing wall have an increased risk of critical intermediate moisture levels post retrofit. The future performance due to moisture safety of the recommended retrofit is not acceptable. The risks of moisture damages may be reduced if any of the following measures are performed: decrease the indoor moisture production, increase the indoor ventilation rate, assemble a vapour retarder between the supplementary insulation and the new Gypsum board or decrease the thickness of the supplementary insulation

Common exercise 1 - description and tasks

General information

The purpose of the framework is to provide information and methods for probabilistic assessment of hygrothermal performance of retrofitted buildings. Probabilistic assessment involves anticipating conditions and measures that lead to the spread in building performance as well as qualifying and quantifying the spread. If the spread is unacceptable in terms of present acceptability and tolerance limits, measures for reducing the spread should be considered.

A complete description of probabilistic assessment is an iterative process, usually beginning with the application of qualitative methods and progressing towards quantitative if necessary and appropriate. If a quantitative analysis of building performance is to be carried out, a probabilistic model of a building must be established. When the model and the data are established, the calculations can begin to estimate the spread and identify the critical conditions and events[1]. In the end, the results of numerical analyses should be compared with targets of the retrofit and an optimal retrofitting technique should be identified.

With this goal, the framework is seen as a methodology that encloses all these steps in a clear and efficient way in order to support decision-making process in building retrofitting projects.

Aim and scope of this and future common exercises within ST3

A first proposal of the framework for probabilistic assessment was presented and discussed at the Annex working meeting in Porto in April 2011. This framework was basically constructed out of the flowchart for risk assessment that was presented in Ljungquist (2005). The aim of this and future common exercises in Subtask 3 is to continue designing and evaluating the framework through case studies. If possible, the framework should facilitate the probabilistic assessment of various issues in building physics design, such as energy performance, moisture durability, thermal comfort or IAQ, and at different scales: whole building, building component or building material. However, the real challenge is to generate the results and methods that would upgrade available knowledge and information about uncertainties with building retrofitting.

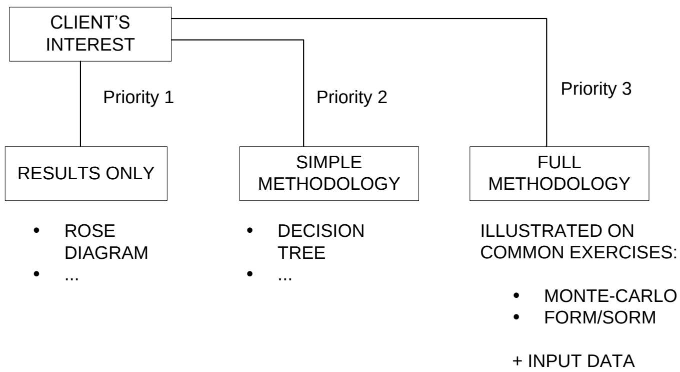
Design of framework is also an iterative process. Thus, if you are not able to complete the full analysis within the frame of Common exercise 1, we hope that your case will grow along with the Annex and that you will give us regular updates on the progress within the future exercises.

Specific tasks of CE1

A revised version of the framework is presented in tabular format on the next page. The numbered headings in the table present different steps in reliability assessment. The numbered system is introduced to facilitate future communication when designing the framework.

[1] This description is taken from K. Ljungquist. The difference is that she talks about risk assessment while I have used here probabilistic assessment.

- Choose a retrofitting case of your interest to which you would like to perform probabilistic assessments and try to organize the work by following the steps presented in the framework. If necessary, adapt and rearrange the steps according to the needs of your analysis. Keep however the numbering system in order to communicate the changes in the framework.
- Be specific when defining and describing the steps. If possible, use engineering rather than academic terms as your example might be used in the future to support a design process.
- Whenever using performance criteria and methods that are based on the expert knowledge (in your country or elsewhere), please provide a summary of those and a list with the corresponding references.
- When presenting the results of the probabilistic assessment, consider the needs of a future user. At the workshop in Copenhagen, three possible levels for result presentation were identified and shown in the graph below. The meeting also discussed and defined our 'clients' – engineers or academics. Report thus your results according to the priority level.



References

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The framework in a tabular form

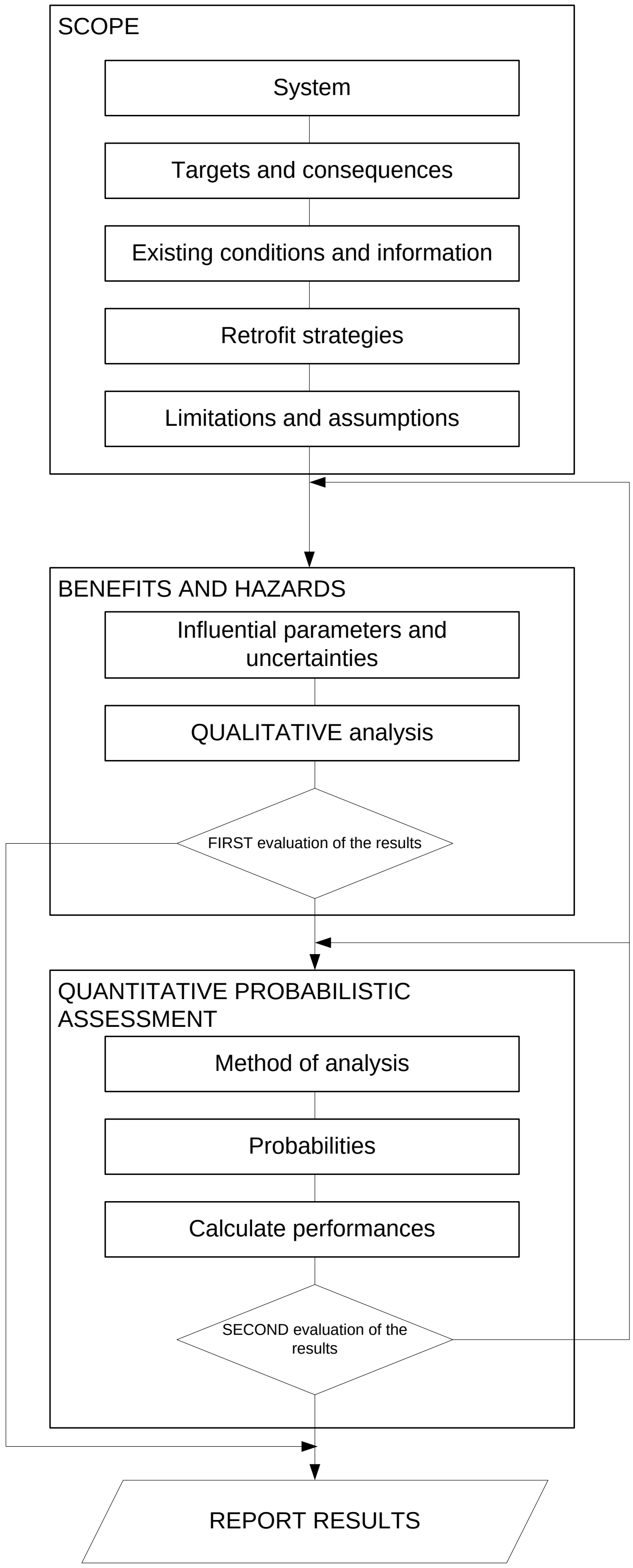
1. **SCOPE**
    1.1. System
    Spatial scale of the project: whole building, building part, building envelope, and/or building material
    1.2. Targets(performance criteria) and consequences
    Energy performance, moisture performance, IAQ, total cost of the project, and/or cost of operation
    What are the consequences if the targets are not fulfilled?
    1.3. Existing conditions and information
    Collect facts and data. What motivates the choice of retrofit strategy?
    1.4. Retrofit strategies
    Consider alternative retrofitting measures in order to make room for relative assessment ranking
    1.5. Limitations and assumptions
    Declare what is assumed to be fulfilled and also what is not comprised by the analysis

2. **IDENTIFICATION OF BENEFITS AND HAZARDS**
    2.1. Influential parameters and their uncertainties
    For example, intensity of HAM loads in indoor and outdoor environment
    2.2. Perform QUALITATIVE probabilistic analysis
    Explore the existing knowledge in form of recommendations, quality insurance systems and similar, or
    perform another form of qualitative analysis – fault trees and similar
    2.3. <u>First evaluation of the results</u>
    Pros and cons with the retrofitting. For example, areas identified where performance could be good or bad can be directly reported in step 4, while those 'in between' should go for further evaluation in step 3.

3. **QUANTITATIVE PROBABILISTIC ANALYSIS**
    3.1. Method of analysis
    3.2. Define probabilities
    3.3. Calculate performances
    3.4. <u>Second evaluation of the results</u>
    Check the reliability of the results, e.g. in the form of probability density functions (pdf's) of performance parameters, and the chosen method of analysis. Report all efforts, not just the final method that has shown appropriate.

4. **REPORTING THE RESULTS**
    1.1. Results for priority level one
    Charts, rose diagrams, tables - 'easy' information at hand
    1.2. Results for priority level two
    Flow charts and other methods for qualitative analyses
    1.3. Results for priority level three
    Detailed description of the assessment; could be the actual report you are writing for ST3.

The framework as a flow chart



A. Performance of a massive brick wall with additional insulation placed on inside of the wall

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A1 INTRODUCTION

Increasing energy consumption in buildings was leading to greater awareness of energy conservation and to rising energy efficiency. The highest potential for thermal optimization lies in renovating existing buildings. Due to the fact that many buildings are listed worthy of preservation renovating the historical façade with a thermal insulation system is obsolete. Therefore interior insulation is gaining tremendous importance and many research institutes, planers, executives and consulters are busily engaged with the process.

Hereafter the planning process of interior insulations and related questions are discussed. At the beginning the correlation of significant planning parameters are analysed. Subsequently the theoretical planning process is demonstrated by a case study. The approach is based on the specifications of the "Framework for Probabilistic Assessment" described in Subtask 3, Common Exercise 1 of the IEA Annex 55.

A2 SCOPE

A2.1 System

The planning and calculated proof of interior insulations working can be given on different levels of complexity:

- Building component with 1D layer structure
- Detail with multidimensional heat and moisture transport
- Detail with multidimensional heat and moisture transport inclusive airflows

As shown in [WEG13] the complexity of the simulation model has great impact on the results, especially the calculation of airflows through constructions with interior insulation. The following example focuses on the simplest case, the one-dimensional layered structure.

A2.2 Targets (performance criteria) and consequences

The central goals of thermally renovating an existing building using interior insulation is to increase the energy efficiency of the property and to enhance the thermal comfort. This is achieved by minimizing the heat losses and increasing the temperature on the inner wall surface. The effectiveness of a thermal retrofitting can be described by the maintenance of a certain U-value of an external wall structure. At the same time it must be ensured that the renovation does not cause any structural damage.

The consequence of adding interior insulation to an existing construction is that might incur a risk of condensation or high moisture contents near the interface between the original structure and the inside insulation. Furthermore, thermal bridges e.g. connections of interior and exterior walls or connections of ceilings with exterior walls may mean that the system with added insulation does not perform as effectively as anticipated, or as with exterior insulation. Besides moisture problems may also arise on the inside wall surface in areas close the thermal bridges.

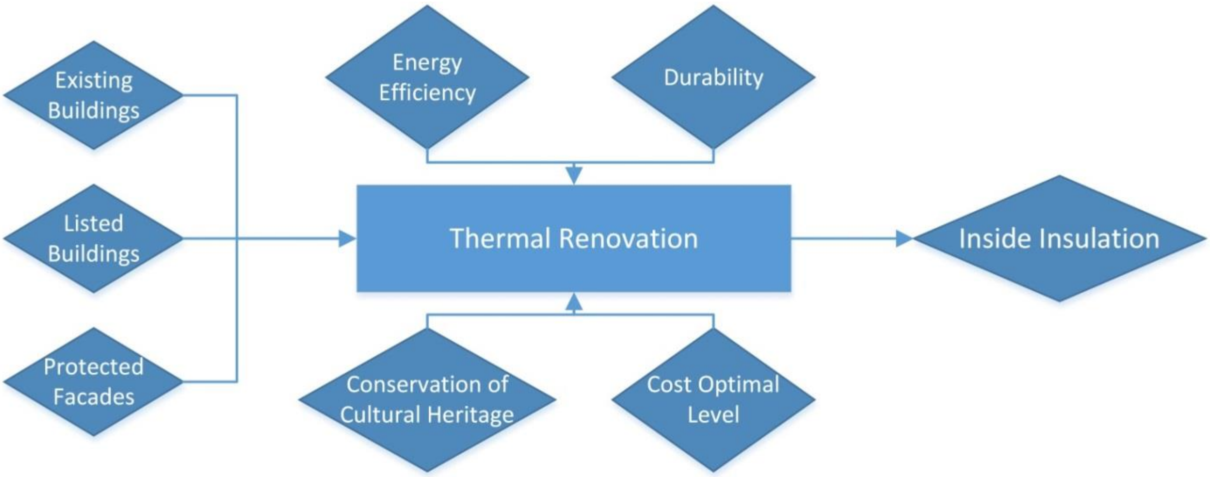

Figure 1: Targets and consequences of thermal renovation with interior insulation

If one considers a certain section of an internally insulated wall construction instead of taking an overall view of a building, more specific performance criteria are relevant. These criteria include for example the moisture behaviour of the materials and the permeability or the airtightness of a construction. The goal is to demonstrate the functionality of the interior insulated wall section. Moreover, it has to be proved that the construction shows a long-term damage-free condition. This verification is based on defining various influencing parameters as described in A3.1 and illustrated in Figure 2.

The combination of different influencing parameters leads to different scenarios that determine the functionality of a construction. Therefore the essential boundary conditions must be known during the planning process in order to prove the durability of the interior insulation. The negligence or disregard of certain conditions can cause significant harm to the interior insulation and the existing construction.

A2.3 Existing conditions and information

Interior insulation is mainly used when an external insulation is not possible. Because of architectural or historical protection reasons many buildings cannot be thermally renovated by using an external insulation. At half-timbered houses or brick facades the maintenance of the visible construction is more important than energy savings through insulation measures. In these cases the external walls are often insulated on the inside in order to achieve at least a slight increase in energy efficiency.

The specific retrofitting strategies become clear when one looks at the detailed design process and the complexity levels described in A2.1. In some cases – from the building physical point of view – an interior insulation does not lead to significant energy savings. Nevertheless the temperature of the internal outer wall surface can be increased even with low insulation thicknesses creating a more comfortable indoor environment.

A2.4 Retrofit strategies

If the possibilities of renovating a building thermally are already limited to applying an interior insulation the selection of alternatives is very small. It is, however, possible to raise the comfort with the help of special building services. Under-floor- and wall-heating-systems for example have a lower energy consumption and can be used to heat certain building components. This leads to an increase of comfort especially when the outer walls are tempered with a wall heating.

The installation of a ventilation system and tight windows can increase the energy efficiency of a building without insulation measures on the outside walls. These measures should be accompanied by other thermal rehabilitation works such as the insulation of the top floor or the basement ceiling.

A2.5 Limitations and assumptions

A basic calculation of an interior insulation can be performed with various assumptions. Especially material properties have to be estimated partially, because historical materials can have wide differences in their key parameters. External climatic conditions can be received by weather stations, thus providing very realistic input parameters for the calculation method. The internal climate conditions must be selected depending on the usage. The indoor climate is described in ÖNORM B 8110-2 or in the WTA data sheet 6-2-01.

A3 IDENTIFICATION OF BENEFITS AND HAZARDS

A3.1 Influential parameters and their uncertainties

The execution of an interior insulation system requires an intensive and detailed planning process. A lot of object-specific parameters must be investigated. The following figure shows the essential boundary conditions and divides them into four main groups, each with two sub-groups:

- outside boundary conditions
    - wall structure
    - external impact
- inside boundary conditions
    - surface of the inner wall
    - users and inhabitants
- verification
    - building physics requirement
    - thermal bridges
- quality assurance
    - detailed planning
    - execution

Figure 2: Influential parameters, split into four groups

The uncertainties of the individual parameters can be determined in several ways:

- Approximation of parameters (climate data of the location, moisture load of the interior climate etc.)
- Measurements of parameters in the laboratory (material data, flow resistance etc.)
- Measurements of parameters of existing properties or demonstration buildings (moisture content of the existing structure, climate conditions etc.)

In ongoing projects calculations of the construction are mainly based on assumptions about material parameters whereas measurements of individual parameters are only made in some specific cases. The efficiency of the internal insulation can be evaluated and limited by different variations of the parameters.

A3.2 Qualitative probabilistic analysis

As shown in [WEG10], the detailed planning process starts with a building survey. For this purpose a detailed assessment of certain issues concerning the renovation project is necessary. The questions must include all relevant influence parameters in order to make an object-specific statement. The following checklist shall help to identify the dangers and the relevant parameters within the given object.

The first part of the checklist deals with outside influences on the structure. Here the effects of weather and other constructive material-related features are revealed that – combined with internal insulation – may cause a problem.

Table 1: Questions for the survey based on the outside boundary conditions

Influences	Basic Questions	Y	N	T	L	Detailed Parameters
Outside Boundary Conditions	Are there any climate data of the location?					Which minimum temperature is to be expected in winter? In which climate region is the restoration object situated?
	Is there a driving rain?					Which driving rain group does exist? Which side is stressed the most? Is a functioning rain protection available?
	Is there a risk that the façade dries very slowly?					Can the facade dry fast enough after a driving rain event? Does the facade have parameters that facilitate the drying process? • coloring • surface roughness etc.
	Was the façade hydrophobized?					Are there any defects in the hydrophobing?
	Is there rising moisture?					Is it • constant humidity or • temporary humidity?
	Can the facade absorb moisture at a driving rain event?					How much moisture is absorbed? What happens to it? Can the consequences be estimated, or even seen?
	Is there solar irradiation to the facade?					May it come to reverse diffusion? Is the location of the building • freely and exposed or • in a built-in area?
	Is there existing damage on the facade due to effects of moisture?					Do the effects of moisture come • from the soil? • by driving rain? • by water damage?
	Are there areas on the facade where rainwater can easily penetrate into the construction?					Are • joints, • cracks, • vegetation recognizable?
	Is a hydrophobing planned during the interior insulation measure?					When is the hydrophobing planned in the construction process? Is a pressure impregnation intended?

Testing Option: Testing option available? (Y / N) | Limit: Limit available? (T / L)

The second part of the checklist deals with the boundary conditions on the inside of the wall construction and the user-specific conditions. Here the focus lies on existing damage due to moisture and constructive defects on the wall's surface.

Table 2: Questions for the survey based on parameters from the inside

Influences	Basic Questions	Y	N	T (Testing Option)	L (Limit)	Detailed Parameters
Inside Boundary Conditions	Can any damage to the inner wall surface be detected?					Is there • moist interior plaster, • mildew stains, • mold growth, • delamination of paint / wallpaper?
	Is the wall surface not plastered inside?					Is the wall former visible • partially or • in large areas?
	Are there hollow spaces on the inner surface?					Is the strength of the plaster sufficient for pasting with insulation panels? • plaster strength • adhesive pull strength to the ground
	Are there any impurities on the plaster surface?					
				Testing option available?	Limit available?	

Table 3: Questions for the survey based on parameters concerning the user behavior

Influences	Basic Questions	Y	N	Detailed Parameters
Users and Inhabitants	Is the use as a flat intended?			Which dedications do the individual rooms get? Where does high humidity of room air occur?
	Are there any user-specific facility requirements?			Which furniture adjoins the insulated construction? Are fitted wardrobes planned on an outside wall?
	Is the use as a function room intended?			What is the expected maximum moisture load? Are large gatherings of people regularly expected?
	Is a use with high moisture load intended?			Will the building be used as • greenhouse, • swimming pool or • unheated basement?
	Does a heating system exist or is one planned?			Is it a • conditioned or • unconditioned area?
	Is a ventilating system planned?			Which indoor climate is generated by the ventilation system? Does the ventilation system have an air humidification? How is the ventilation and air conditioning controlled?

The following sections of the questionnaire are dealing with constructive and component-dependent influences on an interior insulation. Usually there are no testing facilities in the sense of measurements given. Therefore, a correct assessment of the constructive inventory in the form of a detailed building survey is of great importance. Furthermore, a basic knowledge of the constructive and building physical correlations is required. When using empirical values this is especially important.

Table 4: Questions for the survey based on parameters concerning the construction

Influences	Basic Questions		Y	N	Detailed Parameters
Construction types	Which construction type is existent?	plastered brick masonry			Is there any moisture in the masonry and where does it come from? Are there any cracks in the plaster surface recognizable? Can any hollow layers be detected by tapping or palpation?
		exposed brick masonry			Does the brick material consist of • dense clinker, • medium density bricks and facing bricks, • absorbing facing bricks?
		natural stone façade			Does a brick lining or a solid stone wall exists?
		exposed framework construction			Is there a continuous material joint? How is the joint sealed? Is there any damage in joints? Does the infill consist of absorbent material? Does the infill material have a light or dark color?
		solid wood construction in a block design?			Are there any gaps that lead into the wood wall inwards and downwards? Are there any spots of rotted wood ?
	Is the inner wall surface even?				How can unevenness be localized?
	Is the façade material absorbent?				How much water can be absorbed by capillary action?
	Does the facade have a high proportion of joints?				How can the joint state be assessed? • Are the joints properly or renovated? • Is the jointing mortar partially broken or is • the jointing mortar partially loose or missing?
	Does the inner component plaster contain a blocking layer?				Is the blocking layer • on the surface or is it • • incorporated into the plaster?
	Does the plaster contain gypsum?				Are material incompatibilities possible?
	Will the interior insulation thickness be greater than 5 cm?				For insulation thicknesses greater than 5 cm a specialist planner is essential!

Table 5: Questions for the survey based on parameters concerning component connections

Influences	Basic Questions	Y	N	Detailed Parameters
Thermal Bridges	Is any damage to the component due to thermal bridges recognizable?			Which thermal bridges must be considered? Which thermal bridges must be calculated and verified?
	Does an inner wall connection exist?			Is the thermal conductivity of the inner wall better than that of the outer wall? Is it a flat separating wall?
	Does a solid ceiling connection exist?			Which ceiling construction is to be found? • arched solid ceiling • reinforced concrete slab ceiling • steel stone ceiling • ribbed reinforced concrete slab with hollow box • concrete beam ceiling Is a flow in case of a hollow box ceiling possible?
	Does a wooden ceiling connection exist?			Which ceiling structure is to be found? • wooden beam ceiling • Dippelbaumdecke
	Is there any damage in the ceiling beams bearing?			Which results does the investigation of the beam boxes show?
	Can the insulation be brought up to the ceiling beams?			Can the ceiling structure be opened? Is it possible to mount the insulation from the top to the ceiling beams?
	Do box-type windows exist?			Will they be renovated?
	Are insulation glass windows present or will they be installed?			Can a reveal insulation be mounted? May the depth of the window sill cause convective problems? Will the window recess be bricked up? Is a radiator under the window existing or intended?
	Does an outside corner to a non-insulated, freestanding fire wall exist?			Will the fire wall be insulated on the outside? Will the neighbouring property be covered with buildings?

By using the questionnaire the retrofitting object can be analyzed in detail. In this way problems which could be potentially overlooked in a rough planning process can be detected. The checklist gives further information on the objectives and design possibilities and provides clear knock-out criteria for certain variants.

The individual sections of the questionnaire can be assembled into a flow chart. In a further step a fault tree can be drawn by connecting individual questions from the checklist with the failure probability. The following example shows the failure probability of an internally insulated construction depending on rising moisture in the wall and a humidity level greater than 60%.

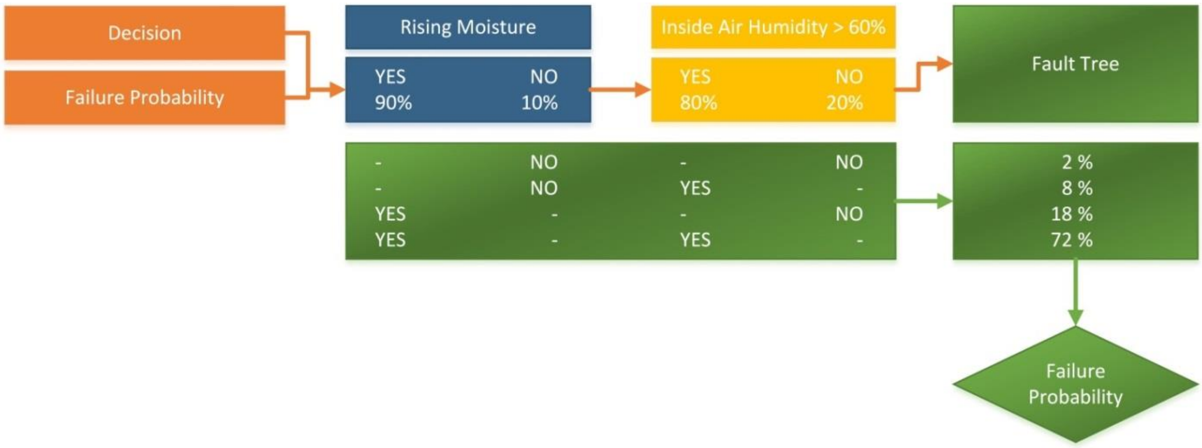

Figure 3: Fault tree taking two parameters into account

The graph clearly shows the large spread of the failure probability for the variations of the two parameters. Using the questionnaire one can assume more details of the planned construction to get an idea of the failure probability of the construction with interior insulation.

A3.3 First evaluation of the results

The results of the questionnaire provide a good basis for planning an interior insulation for a particular object. The answers from the checklist represent a deterministic approach in so far as limit values and yes/no-limits are set. In a further step, these findings can be converted into a probabilistic system by variations of the individual parameters or by an application of a probabilistic distribution function.

A major advantage of the proposed questionnaire is the good practical applicability for planners and contractors. Basic knockout criteria and important issues for planning an interior insulation are taken into account.

For the calculation and subsequently the verification of an interior insulation system this type of representation is limited. For a probabilistic proof all significant boundary conditions have to be provided with distribution functions. In this project this has not been done yet and remains a target for further work.

A4 Quantitative probabilistic analysis

A4.1 Method of analysis

In the following section two methods are being compared with each other. First a calculation based on the currently valid Austrian standards ÖNORM B 8110-2 and EN ISO 13788 is performed to create a risk assessment of the durability of an inside insulated construction. Then the results are compared with a probabilistic approach from Monte Carlo calculations and the requirements of A3.2. The aim is to analyze the risk of failure of an internally insulated construction with and without air conditioning.

The calculations in this project were made with the hygrothermal simulation tool HAM3D_VIE. The simulation program (developed at the Research Centre of Building Physics and Sound Protection, Institute of Building Construction and Technology, Vienna University of Technology) solves the equations for the coupled heat, air and moisture transport in porous building materials numerically considering given constraints. The equation systems mainly rest on the EN 15026 standard.

Three internally insulated structures with two different insulation thicknesses are compared. The evaluation is performed in terms of durability and energy efficiency of the construction in each case. The simulation is based on a 1D model.

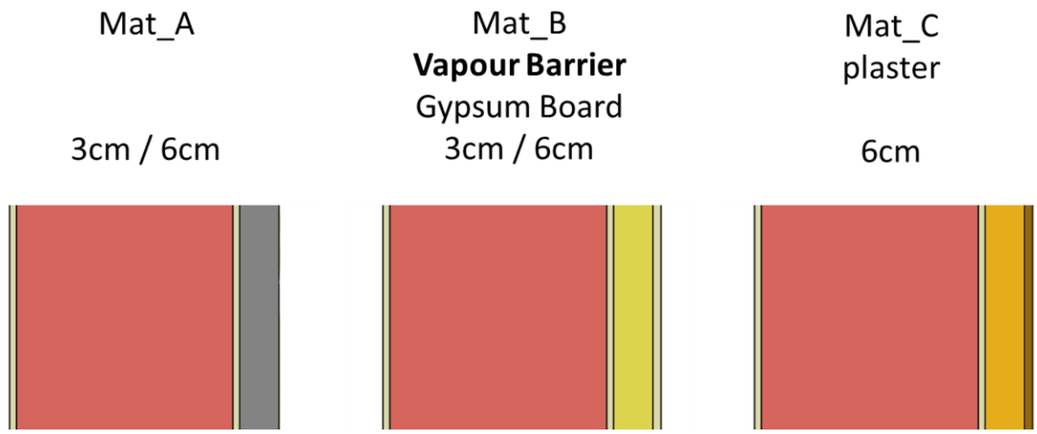

Figure 4: Examples of three inside insulated walls with different types of insulation material

In figure 4 the materials are defined as simplified material groups as, for instance:

Mat_A	plates of porous insulation material (e.g. calcium silicate with μ=4-6)
Mat_B	mineral wool with vapour barrier and gypsum board (e.g. mineral wool with foil as vapour retarder; $s_{d(foil)}$~100m)
Mat_C	plates of insulation material with plaster on the inside (e.g. woodfibre-board with plaster on the inside; $\mu_{(plaster)}$=15-20)

In the following these three groups of constructions are compared related to their durability and energy efficiency.

A4.2 Define probabilities

Probability distributions are not determined at this point of the project. Results on that section are still being processed. The main goal is to define probabilities for all essential parameters discussed in A3.1.

A4.3 Calculate performances

The qualitative evaluation of the three wall constructions according to ÖNORM B 8110-2 and EN ISO 13788 gives the following picture:

Table 6: Qualitative evaluation of the three constructions

	Durability	Energy
MatA 3cm	-	+
MatA 6cm	-	++
MatB 3cm VB	++	+
MatB 6cm VB	++	++
MatC 6cm	-	+

The current standardization characterizes tight structures with a vapour barrier to be very durable. This assumption is based on steady-state calculations using the Glaser method and assuming a tight structure without any leakages. In this case the highest energy efficiency is achieved by large insulation thicknesses and good insulating materials.

The analysis of the five wall structures using hygrothermal simulations and considering the findings from A3.2 provides similar results. Two scenarios can be distinguished: The indoor climate is varied for room humidity levels with and without air conditioning. It is assumed that the relative humidity does not exceed 40 % if a ventilation system is used. Without using a ventilation system the relative humidity is set to 60 %. The simulations with HAM3D_VIE show the following results:

Table 7: Results of hygrothermal simulations focusing on durability and energy efficiency

	Durability 40% relhum	Durability 60% relhum	Energy
MatA 3cm	++	-	+
MatA 6cm	++	-	++
MatB 3cm VB	++	++	+
MatB 6cm VB	++	++	++
MatC 6cm	++	++	+

It shows that airtight constructions (with vapour barrier) are very durable. In the calculations it is assumed that the airtight layer has no leakages. Under these circumstances the durability of the construction is independent from the indoor climate. Because of that a ventilation system has no effect on the results.

These assumptions, however, contradict reality, since in these simulations no probability distributions are adopted. A completely airtight construction is structurally not feasible. Therefore the real airtightness of the construction in combination with the actual relative humidity level must be taken into account in the form of a probability distribution. The relationship between climate and airtightness is described in [HAR12].

The following chart shows the cumulative probability of the indoor relative humidity in January for constructions with high/low airtightness and dependence on the usage of the ventilation system.

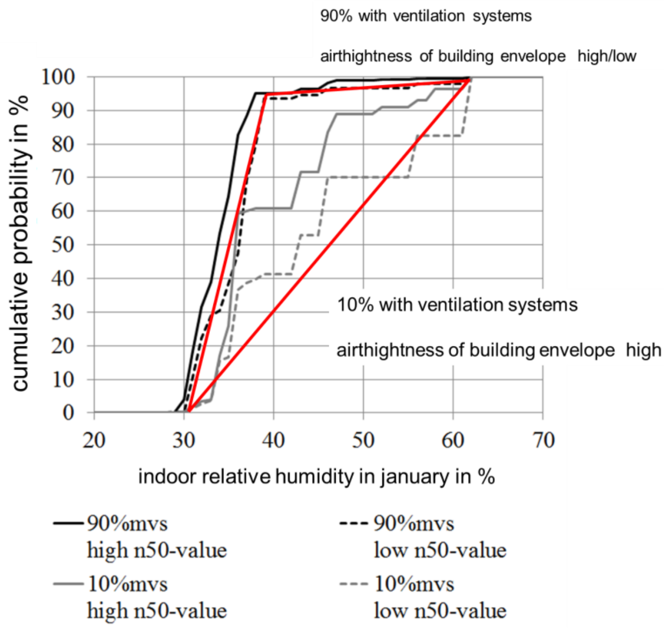

Figure 5: Cumulative probability of the indoor relative humidity for constructions with high/low airtightness

One can see the influence of the airtightness of the construction compared to the usage of the ventilation system. The red lines show the extreme combinations of these two parameters. It shows that airtight buildings with rarely usage of the ventilation system lead to higher indoor air humidity.

A4.4 Second evaluation of the results

By using the example of the airtightness of the five internally insulated constructions it can be shown that conventionally calculated variants cause a supposedly incorrect result. The inclusion of all possible leaks within the interior insulation combined with / without a ventilation system provides an example for a probabilistic proof of interior insulation systems.

The following two charts show the failure probability of the interior insulation with / without an indoor air ventilation system. The results are evaluated according to the mould growth.

Failure probability without ventilation system **Failure probability with ventilation system**

Assumption of 60 % indoor relative humidity **Assumption of 40 % indoor relative humidity**

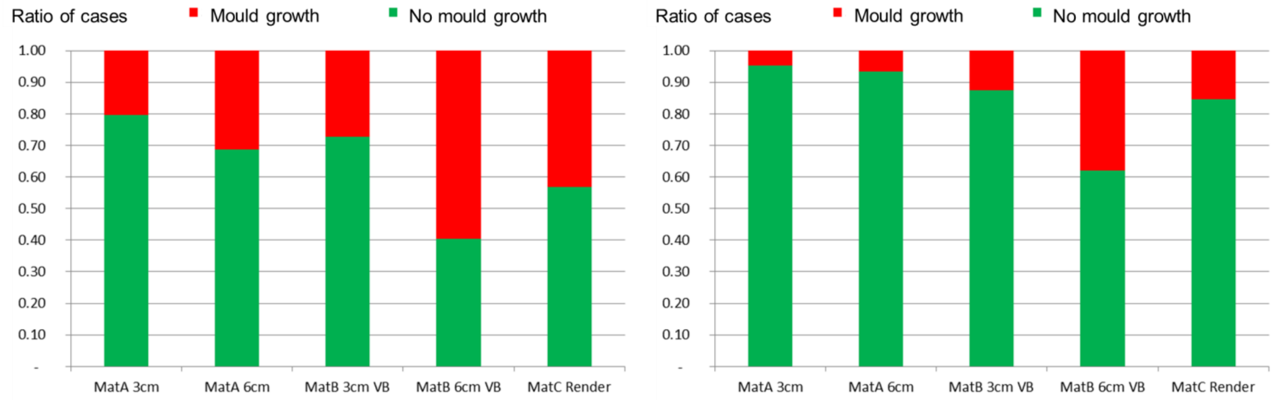

Figure 6: Failure probabilities with / without ventilation system

One can clearly see the difference between the results of the model with probability distributed indoor climate and the model discussed before. Therefore the risk of mould growth is lowest when the thickness of the insulation is low and a ventilation system is used. The results of the probabilistic assessment are shown in the following table:

Table 8: Results of probabilistic assessment

	Durability	Energy
MatA 3cm	+	+
MatA 6cm	O	++
MatB 3cm VB	-	+
MatB 6cm VB	--	++
MatC 6cm	-	+

A5 REPORTING THE RESULTS

On the example of planning an interior insulation qualitative and quantitative analysis have been performed. On the qualitative assessment benefits and hazards of interior insulation systems were being compared and the main influencing factors were registered. It became clear that moisture sources such as driving rain on the façade, rising moisture in masonry and high humidity levels of the interior climate are important factors influencing the functioning of an interior insulation system. By using a checklist for a documentation of the building all relevant boundary conditions for planning an interior insulation can be collected. The results demonstrate the possibilities of which insulating material could be used and which problems have to be considered in the calculations. In addition, limit values provide information on whether a certain construction can be provided with an interior insulation.

The quantitative probabilistic assessment was carried out by comparing calculation results in accordance with the actual Austrian standard to Monte Carlo calculations. The results of the qualitative analysis indicate that driving rain on an inside insulated façade has a significant influence on the durability of the construction. Therefore, all calculations were carried out assuming a water-repellent surface of the façade. These water-repellent properties can be achieved through hydrophobizing, which can have negative effects on the durability of the façade. When adopting a hydrophobizing for the calculation and proof of an interior insulation the water-absorption capacity of the façade must be inspected regularly to make sure that any damage to the construction – even after a long period of time – can be avoided. This is the only way to ensure that the simulation results reflect reality, even after several years of use.

Furthermore, the influence of the indoor climate was examined by simulations. On the basis of measured data from single-family houses the impact of the air's moisture content on the failure probability of the inside insulated construction was elaborated. It became clear that interior insulations bear a lower risk potential in apartments with a ventilation system due to the lower average humidity level while interior insulations are at greater risk in apartments without air conditioning. Moreover, this comparison shows what happens in the event of a failure of the ventilation system if the humidity level cannot be held on a permanently low level.

These findings were evaluated using five interior insulation systems with tree different insulating materials and insulation thicknesses. While the Austrian standard counts on an air-tight system with a vapour barrier Monte Carlo simulations show a different loss scenario. The results show that the risk potential is lower when a ventilation system is used. In addition, interior insulations of porous materials and smaller thicknesses can be described as more durable.

This leads to the conclusion that air tightness, air conditioning and moisture management are the main facts which have to be taken into account when planning an interior insulation.

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Standards

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DIN 4108-3: 2001-07: Wärmeschutz und Energie-Einsparung in Gebäuden Teil 3: Klimabedingter Feuchteschutz, Anforderungen, Berechnungsverfahren und Hinweise für Planung und Ausführung

DIN EN ISO 15927-3: 2009-08: Wärme- und feuchteschutztechnisches Verhalten von Gebäuden – Berechnung und Darstellung von Klimadaten – Teil 3: Berechnung des Schlagregenindexes für senkrechte Oberflächen aus stündlichen Wind- und Regendaten

B. Performance of ventilated attic constructions in Denmark

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B1 INTRODUCTION

The following text is written during work with Annex 55, Subtask 3, Common Exercise 1. The focus of the work is the suggested Framework, as it is shown in Figure 7. The work on the Framework is a simple test of its usefulness when applying it to a (hypothetical) design problem. The inspiration for the used design problem is an experiment on cold attics conducted at the Technical University of Denmark. The experiment tests what in Denmark is commonly accepted as good building practice when it comes to the construction of cold attic spaces. As a part of the experiment, a computational model was constructed to simulate the hygrothermal conditions in cold attic spaces under the eaves. Using results and experiences from the experiment allows the tester to focus entirely on the Framework.

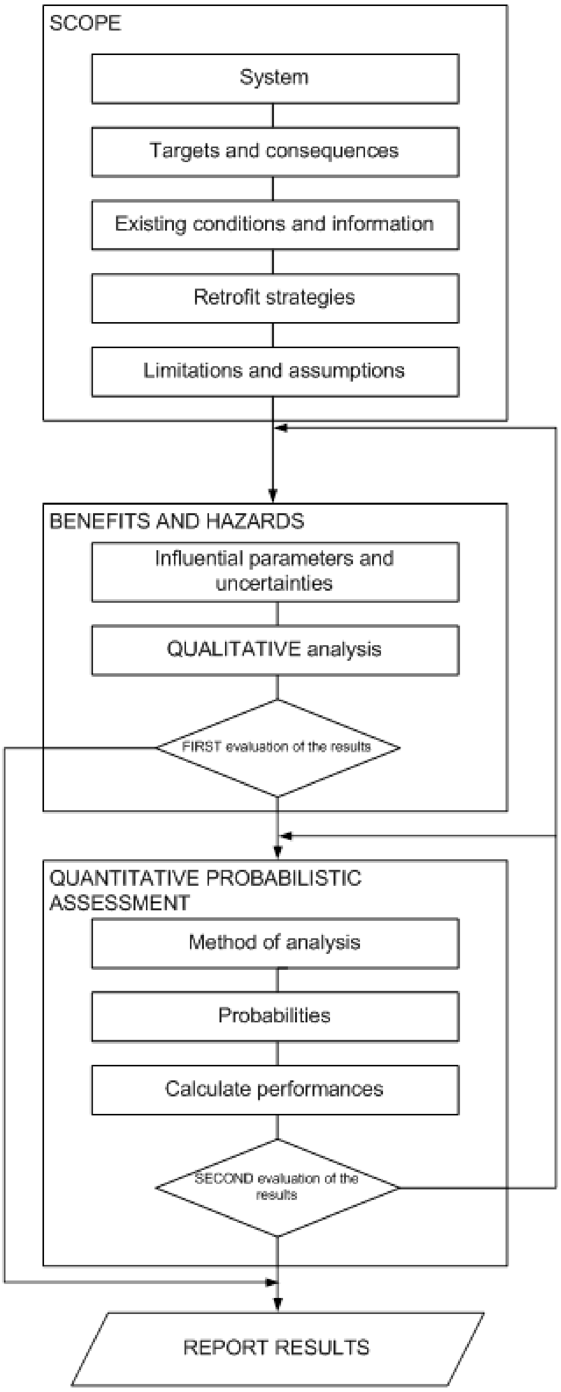

Figure 7: Framework for probabilistic assessment of performance of retrofitted buildings

B1.1 Working using the Framework

In this section the framework is tested and the test documented. The test is straight forward: The individual steps and supplementary questions are followed and answered. This way, it is sought to determine whether the process described by the Framework helps to facilitate the management of problem handling and if the Framework helps to disclose (necessary) information on pitfalls and other unforeseen difficulties. It is of special interest whether the Framework is deemed a timesaving tool and if it lends itself to easy use by the engineers and building physicists for whom the Framework is designed.

B2 SCOPE

B2.1 System

- Spatial scale of the project: whole building, building part, building envelope, and/or building material

The hygrothermal system of interest is the cold attic space under the roof slopes; insulated from the conditioned loft space by a vertical wall and from the below conditioned space by a horizontal ceiling, the room geometry is that of a right-angled triangle. The cold attic space is designed with a diffusion-open roofing underlay (membrane) underneath a corrugated fibre cement roof structure. The wall and ceiling separating the cold attic space under the eaves from the conditioned interior are heavily insulated and fitted with vapour barriers.

B2.2 Targets (performance criteria) and consequences

- Energy performance, moisture performance, IAQ, total cost of the project, and/or cost of operation
- What are the consequences if the targets are not fulfilled?

The retrofitting design of a roof structure is examined. The overall design will be considered a success if one or more of the suggested, minor variations to the base design of the cold attic space can be shown to be free from moisture related problems. Energy consumption and indoor temperature distribution are both assumed non-issues with the chosen base design. The hygrothermal environment, the cold attic designs and subsequent analysis are to be facilitated using a suitable hygrothermal, computational model. The model will be created to examine the expected worst case scenarios of the various designs.

In case that no viable variation of the base design can be found, a new design must be made. A new design will also entail an examination of the hygrothermal performance of the new design; as a consequence, more money will be spent on the design phase of the project.

B2.3 Existing conditions and information

- Collect facts and data. What motivates the choice of retrofit strategy?

The attic is to be used as a conditioned living space. The owners want vertical walls to separate the conditioned interior loft space from the unconditioned space under the eaves. The smaller volume created by the vertical walls is believed to be cheaper to maintain conditioned over the life span of the investment; for this reason, the technically more challenging solution of insulating the vertical walls – instead of the roof itself – is chosen. The exterior height of the wall will be approximately 1 m as will the depth of unconditioned attic space under the eaves (the roof has a 45° slope).

B2.4 Retrofit strategies

- Consider alternative retrofitting measures in order to make room for relative assessment ranking

An alternative to the insulated vertical walls is an insulated roof structure, leaving the unused space under the eaves conditioned. The design solution is simpler and cheaper to execute but leaves a larger volume to condition.

Another alternative could be to examine the effect of automatic, demand controlled ventilation of the unconditioned space under the eaves. The idea would be to only ventilate the unconditioned space with outdoor air in the periods where the outdoor absolute humidity was below the absolute humidity in the unconditioned space.

B2.5 Limitations and assumptions

- Declare what is assumed to be fulfilled and also what is not comprised by the analysis

Technical drawings are assumed to be accurate, technical specifications are assumed correct and craftsmanship is assumed to of good quality. The structure, in its entirety, is assumed to fulfil the requirements stated in the Danish Building Code. Also, as mentioned, energy consumption and indoor temperature distribution are both assumed non-issues.

The computational model will use numerical tools to approximate solutions to the governing differential equations but will not use a finite element method or similar. The computational model will assume that one point in a given environment (insulation layer, air space, etc.) is sufficient to describe the environment as a whole. As a result, temperature differences over an air volume and the variance in relative humidities will not be calculated. These undetermined variances are assumed to be non-issues.

B3 IDENTIFICATION OF BENEFITS AND HAZARDS

B3.1 Influential parameters and their uncertainties

- For example, intensity of HAM loads in indoor and outdoor environment

The single most worrying parameter is moisture. The structure is well insulated and the design allows for variations that include ventilation of the attic space under the eaves.

The moisture contribution to the cold attic space under the eaves from the conditioned interior is an unknown variable that is tied in with considerable uncertainties. The Danish Building Code stipulates that a structure at 50 Pa difference is allowed to leak no more than 1.5 L/s per square meter floor area. The structure is assumed to fulfil this requirement. Unfortunately, there is no way of saying where these leaks will be located exactly. However, it can be theorized that it is unlikely that the leaks will be uniformly distributed. Most leaks are likely to be found in joints - such as joints around windows and doors and the joining of wall and roof structures.

Knowing this makes it clear that it is likely that cold attic spaces under the eaves are subjected to larger influxes of conditioned interior air than the mentioned 1.5 L/s per square meter of cold attic space at an interior overpressure of 50 Pa. For this reason, it is important that the designed algorithm can accommodate variations in the variables describing the infiltration and that the attic designs are tested for infiltration loads higher than 1.5 $L/(s \cdot m^2)$.

B3.2 Perform QUALITATIVE probabilistic analysis

- Explore the existing knowledge in form of recommendations, quality insurance systems and similar, or perform another form of qualitative analysis – fault trees and similar

BYG-ERFA, a Danish organisation publishing informational sheets on processed and usually empirically derived constructional experiences and solutions, has published recommendations on how to design cold attic spaces under the eaves. BYG-ERFA states that an enclosed space under the eaves with a distance no greater than 1 meter from the outside of the roofing construction to the outside of the interior warm wall (bordering a warm/occupied space in the attic) does not need to be ventilated in order to avoid mould growth and wood rot related problems. However, it is known that this form for construction is associated with risk and multiple cases of mould growth and wood rot have been reported.

B3.3 First evaluation of the results

- Pros and cons with the retrofitting
- For example, areas identified where performance could be good or bad can be directly reported in step 4, while those 'in between' should go for further evaluation in step 3

The main distinguishing feature of the design is that it allows for vertical walls in the conditioned space. The design is technically not the simplest to construct and it is known to be associated with risks. A quantitative analysis is needed in order to determine the viability of the design.

B4 QUANTITATIVE PROBABILISTIC ANALYSIS

B4.1 Method of analysis

A computational model for quantitative analysis is designed specifically for the project. The model uses numerical tools to approximate solutions to the differential equations describing the included physical parameters and processes. The main focus is on airflow, temperature distribution and vapour pressure in the cold attic space under the eaves. The model uses information on weather conditions and indoor environment as input in order to calculate estimates of the hygrothermal conditions in the cold attic space under the eaves over time.

The computational model calculates heat and mass balances for the attic environment. It does not use a finite element method. The model assumes that one point in a given environment (insulation layer, air space, etc.) is sufficient to describe the environment as a whole. The program uses numerical methods and iterative processes to calculate the hygrothermal conditions in the attic space. As a result, the computational model needs considerable computational power and time to produce results. For this reason, extensive calculations on parameter variations, such as Monte Carlo simulations, are not performed. Instead eight different construction designs are examined using the model. Table 9 and Figure 8 show the variations in the designs.

The infiltration rate is set as 6 L/(s·m^2) at a pressure difference of 50 Pa. This is the equivalent of 4 m^2 floor area. The simulated cold attic under the eaves has a floor area of 1.5 m^2. This is assumed to be the worst case scenario in buildings that comply with the Danish Building Code. The pressure equalization valve is placed at the top of the attic room passing through the vapour open roofing underlay. The valve which opens for natural ventilation of the attic is placed at the bottom of the attic room passing through the vapour open roofing underlay.

Table 9: Variations in design of cold attic space under the eaves

Attic room #	Infiltration	Ventilation valve	Pressure equalization valve
1	-	-	-
2	-	-	+
3	-	+	+
4	100 %	-	-
5	100 %	-	+
6	100 %	+	+
7	40 %	-	+
8	40 %	+	+

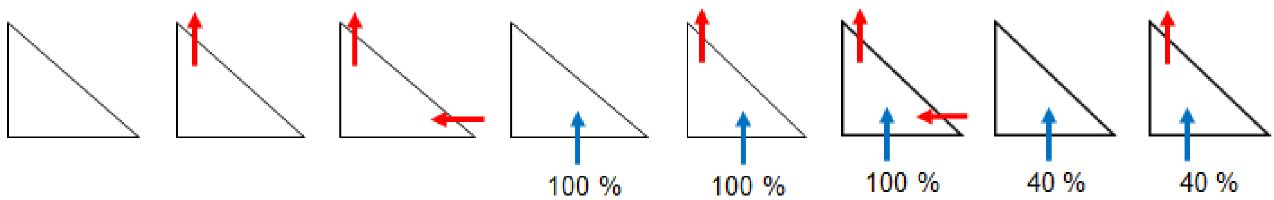

Figure 8: Variations in design of cold attic space under the eaves

B4.2 Define probabilities

Probability distributions are not determined as part of this project. For information on parameter variations, see the above section 'Method of Analysis'.

B4.3 Calculate performances

Calculated performances are reported in temperature (°C), relative humidity (RH) and in Peak Mould Growth Index (PMI). Using the Danish Reference Year (DRY) for exterior conditions and 20 °C and 60 % RH for interior conditions as input, all of the design variations have calculated PMIs of 6.

B4.4 Second evaluation of the results

- Check the reliability of the results, e.g. in the form of probability density functions (pdf's) of performance parameters, and the chosen method of analysis. Report all efforts, not just the final method that has shown appropriate.

Considering the calculated results and the uncertainties that are inherently associated with this particular (deterministic) analysis, none of the design variations have been found fit for construction. It is concluded that a new retrofitting strategy is needed. One of the strategies mentioned in the section 'Retrofit Strategies' could be taken into consideration.

The iterative process of testing a new design should be initiated. After the selection of a new strategy the process should be restarted from ‘F2: Benefits and hazards’, which is the first step of the qualitative analysis.

B5 REPORTING THE RESULTS

Reporting of the results of the test case is outside the scope of this test of the Framework.

C. Framework evaluation by risk assessment of thermal bridges

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Abstract

The probabilistic assessment of hygrothermal performance of the building envelope is used in Subtask-3 of Annex 55. Framework already proposed during the Annex is developed in order to guide an expert through the renovation process. Framework consists of four main parts – background, strategies, analysis, evaluation and it helps to map important parameters impacting the performance. It can also be used to evaluate the current state of art.

Our case study analysis uses the framework to evaluate the criticality of thermal bridges of an old concrete apartment building based on a renovation case study. We used the framework twice - first, it was used to assess the need for renovation at the current state of the art and secondly, to study the performance of the renovation scenario. The temperature factor $f_{Rsi,res}$ as a resistance from the surface temperature measurements with thermography and the $f_{Rsi,load}$ calculated based on the climate loads were used as the performance criteria for surface condensation and mould growth. Average and standard deviations of normally distributed temperature factors $f_{Rsi,res}$ and $f_{Rsi,load}$ was used to calculate the risk of failure before and after the renovation.

As a result, risk of surface condensation at pre- and post-renovation standing was 25% and 2%, respectively. Probability of mould growth was 21% before and 2% after the renovation. The design goal 0% for risk of failure was not achieved. Our conclusion is that the framework is a helpful tool and can be used by an expert or a designer in the future. It enables us to evaluate the need for renovation or the performance of a renovation scenario and, unlike the deterministic approach, also calculate the risk of failure.

C1 INTRODUCTION

In order to improve the energy performance of buildings, energy renovation of existing apartment buildings is essential. The need for renovation might derive from energy but also from other aspects, e.g. durability, indoor environment, aesthetics, building physics etc. Hence it is necessary to evaluate the current technical condition and need for renovation. Often, junctions rather than the performance of a regular plane building envelope appear crucial. Reliable methods are required to assess the performance of junctions, for example, from the aspect of thermal bridges.

Before the renovation of a building, it is essential to evaluate the technical condition of the buildings for safety, renovation needs and possible improvements of energy performance. Many older apartment buildings were constructed according to standard design requirements with similar architectural and constructional typology, including typical thermal bridges. We use a framework proposed in Subtask 3 of Annex 55 and test its benefit for a wider use by other researchers. As variability is representative of renovation as a whole, it must be considered also in terms of thermal bridges.

A thermal bridge is a part of the building envelope where the otherwise uniform thermal transmittance is locally significantly larger. In cold climate, thermal bridges are important also for moisture-safety because they may lead to failure:

- surface condensation: *f* (relative humidity: (water vapour pressure, saturation vapour pressure));
- mould growth: *f* (temperature, relative humidity, time, nutrient (surface material)).

Lower surface temperature on a thermal bridge leads to higher relative humidity (RH) on the surface. While surface condensation starts at the RH of 100%, the limit value for RH in respect of mould growth is from 75% to 95%, depending on temperature variations in time and the group of materials (Johansson et al. 2013, Hukka&Viitanen 1999). Analysis of the impact of thermal bridges in the building envelope helps stakeholders to make decisions about technical solutions and profitability of building envelope renovation.

Critical RH may therefore be written as shown in Eq. (1):

$$RH_{crit} = \begin{cases} 100\% & if\ t < 0^{o}C;\ condensation,\ short\ time \\ -0.00267 \cdot t^{3} + 0.160 \cdot t^{2} - 3.13 \cdot t + 100 & if\ 0^{o} < t < 20^{o}C;\ mould\ growth,\ long\ time \\ 80\% & if\ t > 20^{o}C;\ mould\ growth,\ long\ time \end{cases} \quad (1)$$

In our case study surface condensation appeared at the window glass/frame junction and mould growth was visually detected at the corners of a room (Figure 9).

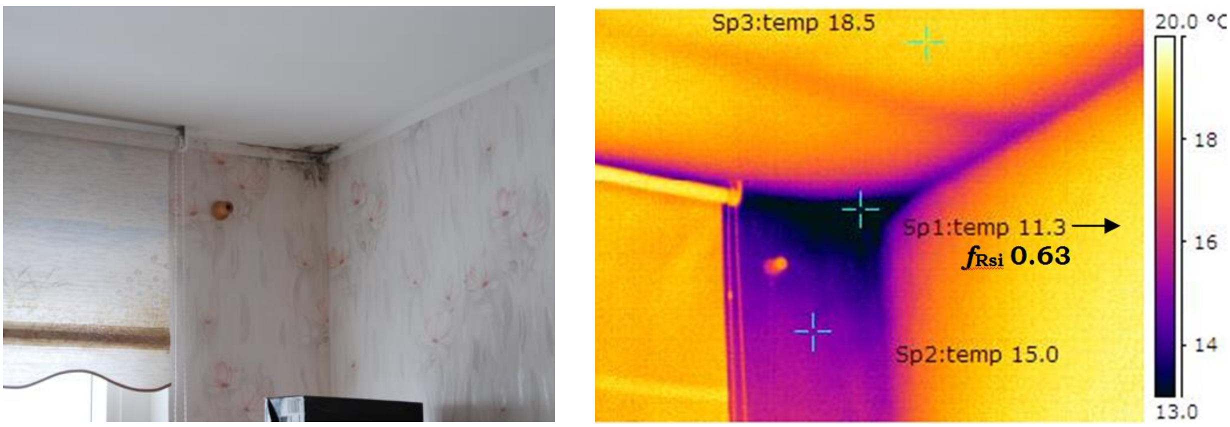


Figure 9. Visible mould growth at the corners of a building envelope might be caused by the thermal bridge.

Instead of the traditional deterministic approach, the probabilistic assessment of hygrothermal performance of the building envelope is used in Annex 55. As an advantage, the factors possibly influencing can be taken into account by using the variability of values according to distributions and more relevant ones can be detected from the results. Variability and uncertainty of the initial data (material properties, climate, workmanship, user behaviour etc) is typical of renovation.

The aim of this paper is to evaluate a framework for the probabilistic assessment of building envelope renovation. The framework developed provides a clear list of activities when planning a renovation project. The framework can be used for comprehensive renovation as well for handling a single aspect and for assessing the need for the renovation while designing a renovation project. It can also be used in order to evaluate the current state of art if a certain problem already exists. Our case study analysis uses the framework to evaluate the criticality of thermal bridges of an old concrete apartment building based on a renovation case study.

C2 METHODS

C2.1 Framework for probabilistic risk assessment

Application of the proposed framework (Figure 10) for building renovation is described in the Introduction. It consists of four main parts divided as levels – background, strategies, analysis and evaluation. To plan a renovation, all the levels from 1 to 4 should be covered. If the solution is evaluated to be acceptable (e.g. zero or very low level of risk), the framework will be run only once. In case the renovation scenario leads to failure, it is necessary to return to the renovation strategy (level 2) and rerun the framework until an applicable solution is achieved.

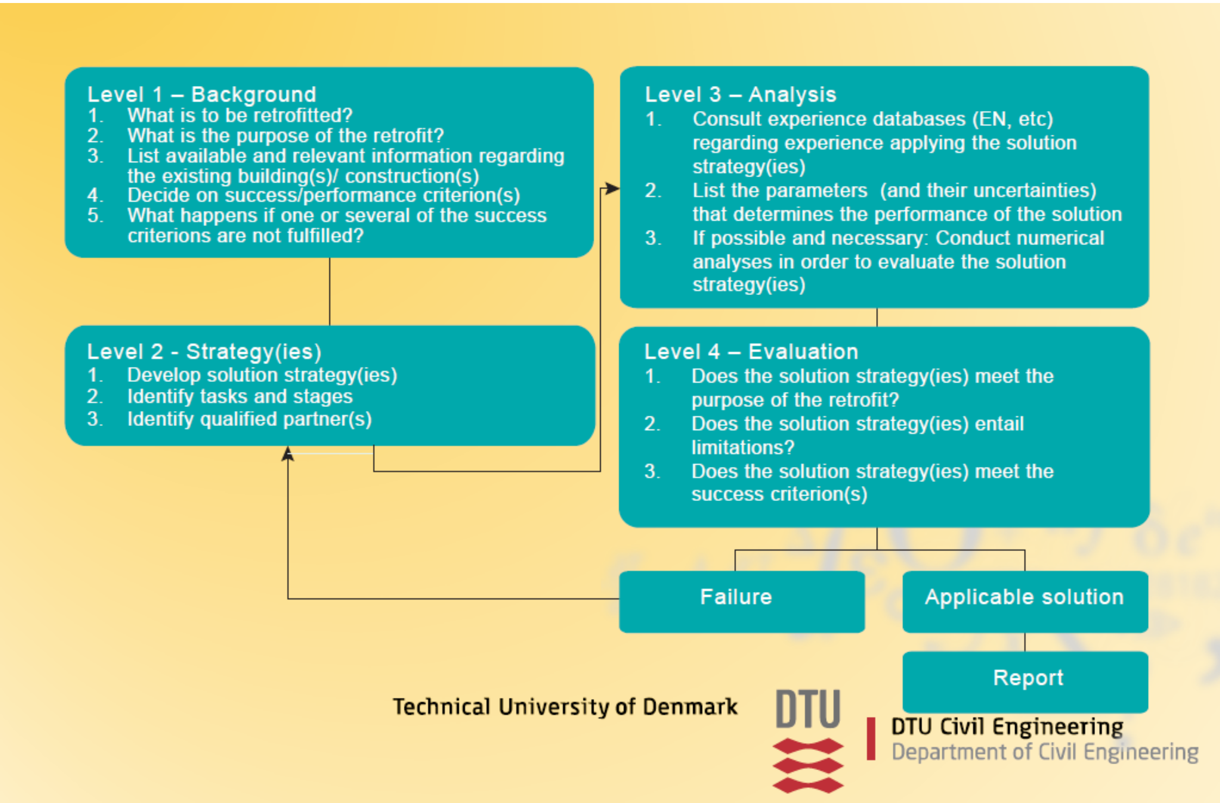


Figure 10. Framework proposed by (Rode 2013).

In this paper, the framework (Figure 10) was followed during a case study to evaluate the thermal bridges. The framework was run twice:

- To assess the risk of surface condensation and mould growth at the current state of the art
- To assess the performance of a renovation strategy.

At Level 1 a hypothesis can be set, e.g. mould growth derives from the thermal bridges (Figure 9). Within the framework, the probability of surface condensation or mould growth can be calculated. Differences exist between using the framework for the first or second time at Levels 2, 3 and 4. At round one (current state of the art) Level 2 (strategy) there is no renovation strategy yet. At Level 3.3, in addition to numerical analysis, measurements can be performed at round one. At round two, only numerical analysis is conducted.

C2.2 Evaluating the probability of critical thermal bridges

Temperature factor at the internal surface (f_{Rsi}, -) (Hens 1990, EN ISO 13788, EN ISO 10211) was used to assess the criticality and to classify the thermal bridges. The temperature factor at the internal surface shows the relation of the thermal resistance of the building envelope without the internal surface resistance R_{si}, (m^2·K)/W to the total thermal resistance of the building envelope R_T, (m^2·K)/W. The temperature factor is calculated as the difference between the internal surface temperature t_{si}, ºC and the external temperature t_e, ºC divided by the difference between the internal temperature t_i, ºC and the external temperature:

$$f_{Rsi} = \frac{t_{si} - t_e}{t_i - t_e} = \frac{R_T - R_{si}}{R_T} \qquad (2)$$

The limit value of the temperature factor depends on the indoor hygrothermal loads, the outdoor climate, the specific junction, hygrothermal criteria etc. In the cold climate of Estonia, the limit value of the temperature factor to reduce the risk of mould growth in dwellings with high indoor humidity loads is $f_{Rsi} \geq 0.8$ (Kalamees 2006). Figure 6 shows the factors impacting the temperature factor. The temperature factor can be calculated from:

- thermography measurements $f_{Rsi,res}$ representing the resistance of the thermal bridge;
- indoor and outdoor climate measurements $f_{Rsi,load}$ representing the load effect on the thermal bridge.

Failure (mould growth or surface condensation) occurs if $f_{Rsi,load} > f_{Rsi,res}$. The resulting probability of failure is the probability of low $f_{Rsi,res}$ values and high $f_{Rsi,load}$ values simultaneously (Figure 11).

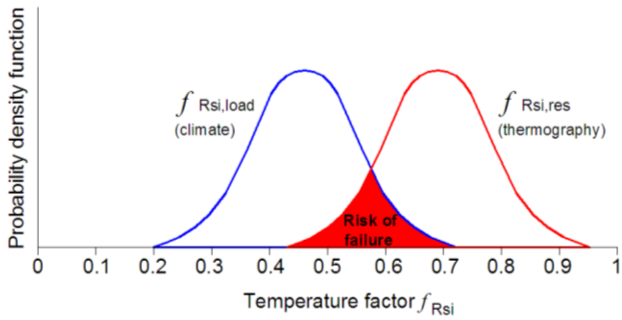


Figure 11. Probability density functions from the lowest values of $f_{Rsi,res}$ from each apartment (based on thermography measurements) and values of $f_{Rsi,load}$ from each apartment (based on climate measurements).

If the variations of all these parameters in Figure 14 are known, we can make detailed stochastic calculations. In this study only the main sphere of influence was taken into account:

- $f_{Rsi.res} = \dfrac{t_{si} - t_e}{t_i - t_e}$ is the result of the following parameters:
  - outdoor temperature t_e (in macro-, meso- and micro-scale) was measured during thermography measurements nearby the studied building;
  - indoor temperature t_i was measured during thermography measurements (depends strongly on the performance of heating systems);
  - interior surface temperature t_{si} measured by thermography is the result of the following parameters (in addition to indoor and outdoor temperatures):
  - interior and exterior surface resistance R_{si}, R_{se} (depends on convective and radiative heat transfer coefficients),
  - thermal resistance of building fabric (depends on the thermal conductivity λ and the thickness d of building materials).
- $f_{Rsi.load(mould,condensation)} = \dfrac{t_{si.crit(mould,condens)} - t_e}{t_i - t_e}$ is the result of the following parameters:
  - time: mould growth was calculated from monthly average (mould germination needs time) data and condensation was calculated from daily average (short time surface condensation is acceptable) data;
  - outdoor temperature t_e (in macro-, meso- and micro-scale) was taken from the nearest weather station;
  - indoor temperature t_i was measured by dataloggers in bedrooms over a one-year period (depends strongly on the performance and type of heating systems: source and price of energy, control system, and human habits);
  - critical interior surface temperature $t_{si.crit}$ was calculated by using indoor (=interior surface) water vapour content and critical RH_{crit} (Eq. 1);
  - indoor water vapour content depends on the outdoor water vapour content and moisture excess: $\nu_i = \nu_e + \Delta\nu = \nu_e + \dfrac{G}{q_\nu}$, g/m^3;
  - moisture excess is the function of air change and moisture production indoors:

- air change depends on infiltration (air leakage rate, pressure conditions, and window airing) and mechanical ventilation (air flow rate, heat recovery, price of energy, draft, noise, control system, and human habits);
- moisture production depends on the living style and housing equipment.

Based on indoor and outdoor climate measurements, the critical temperature factor $f_{Rsi,load}$ was calculated to avoid the mould growth and surface condensation. To avoid the mould growth the average monthly climate was used. With the maximum acceptable RH_{crit} (Hukka and Viitanen 1999) at the thermal bridge`s surface, the maximum acceptable absolute humidity was calculated, wherefrom the minimum acceptable surface temperature was calculated. Using this minimum acceptable surface temperature, outdoor temperature, and indoor temperature, the minimum temperature factor was calculated according to Eq. (2). The calculation procedure employed for selecting the critical temperature factor to avoid surface condensation was the same, only the average daily climate values and the maximum acceptable RH at the thermal envelope`s surface RH_{si} 100 % was used.

Probabilistic approach with normal distribution curves of temperature factors based on climate data measurement $f_{Rsi,load}$ and critical temperature factors $f_{Rsi,res}$ based on thermography were used. This was done in order to evaluate the risk of condensation and mould growth in four apartments of one concrete element apartment building before and after the renovation as a case study. Risk of mould growth and surface condensation for each building type was calculated according to Eq. (3):

$$P\left(f_{Rsi.load} > f_{Rsi.res}\right) \approx f\left(\mu_{f_{Rsi.load}} - \mu_{f_{Rsi.res}}; \sqrt{\sigma_{f_{Rsi.load}}{}^2 + \sigma_{f_{Rsi.res}}{}^2}\right) \quad (3)$$

where: P is the probability of an event, μ is an average and σ is a standard deviation. All the parameters were assumed to be normally distributed. Probability of an event can be easily calculated with MS Excel by inserting Eq. (4):

$$= NORMDIST\left(0, \mu_{f_{Rsi.res}} - \mu_{f_{Rsi.load}}, sqrt\left(\sigma_{f_{Rsi.load}} \cdot \sigma_{f_{Rsi.load}} + \sigma_{f_{Rsi.res}} \cdot \sigma_{f_{Rsi.res}}\right), true\right)$$

C2.3 Case study building

External walls of the concrete element building (Figure 12) built in 1966 are composed of two layers of reinforced concrete (50 mm inner, load-bearing layer and 50 mm outer core) and 150 mm thick fibrolite insulation layer in-between. Different elements are welded and concreted together in-situ. Thermal transmittance U of solid walls varies around 0.8 W/(m²·K) and of concrete panel roofs 0.7 W/(m²·K). The building has an unheated cellar and the inserted ceiling separating the heated space has no significant thermal resistance. The five-storey building has four staircases and 60 apartments. Before the renovation, the building had an old natural passive stack ventilation and a one-pipe water battery heating system based on district heating.

Figure 12. External view of the case study building before the renovation (left) and junction of external walls at inserted ceiling of a cellar as a regular photo (middle) and a thermal image (right).

C2.4 Measurements and calculations

To determine typical thermal bridges and their distribution, measurements with infrared image camera FLIR ThermaCam E320 (thermal sensitivity of 0.1 °C, measurement range from -20 °C to +500 °C) were conducted in four apartments (including bottom and top floors) according to the standard EN 13187 during the winter while the temperature difference between the in- and outdoor air was at least 20 K. Thermography and climate measurements can be used only at round one, since the renovation strategy at round two is based only on the numerical analysis.

Indoor humidity load was determined based on indoor climate measurements with small data loggers for temperature and RH (HOBO U12-013) at one-hour intervals over a one-year period. Long-term outdoor climate was measured near the building or obtained from the nearest weather station.

Temperature factor and linear thermal transmittance of 2D thermal for different junctions were calculated with finite element heat transfer software Therm 6.3. Average internal surface resistance f_{Rsi}=0.13 (m^2·K)/W was used to calculate the linear thermal transmittance and f_{Rsi}=0.25 (m^2·K)/W for the temperature factor.

C3 RESULTS

Results have been presented for both rounds:

- ROUND ONE - current state of the art
- ROUND TWO – assessment of a renovation strategy.

Background for both rounds is the same.

C3.1 Level 1 – Background and initial information

What is to be renovated

In our case study building, visual surface condensation and mould growth were detected at the corner of the building envelope.

Purpose of the renovation

The purpose of the renovation was to minimise the risk of surface condensation and mould since it has negative impact on the indoor air quality - mould spores worsen the human health. Another purpose is to avoid damages of a surface finish and improve aesthetics of a room. Other general aspects are the decrease of heat loss and the durability of the building envelope. The risk of surface condensation or mould should be evaluated notwithstanding if the problems had already appeared or not.

Relevant information about the building and structures

At round one, the framework is applied to confirm or falsify the hypothesis (based on relevant information about building structures) – mould growth (as the need for renovation) originates from critical thermal bridges.

Thermal bridges have been profoundly studied experimentally (including thermography) and analytically by many authors. In Estonia, a large scale analysis of three building types based on field measurements of thermography and climate refers also to possible surface condensation and mould growth (Ilomets et al. 2011, Ilomets and Kalamees 2013, Ilomets et al. 2014).

Current technical condition of a building has to be assessed in detail. Original design drawings (Figure 13), previous renovation documentation and maintenance information must be collected. The operator and a selected group of inhabitants should be interviewed and non-destructive measurements of a building and indoor climate should be performed if possible. Furthermore, relevant literature has to be reviewed.

Performance criteria

Temperature factor f_{Rsi} on the internal surface of the building envelope is used as the performance criterion. Risk of condensation/ mould due to thermal bridges was calculated from the intersection of $f_{Rsi,load}$ and $f_{Rsi,res}$ distributions (**Error! Reference source not found.**).

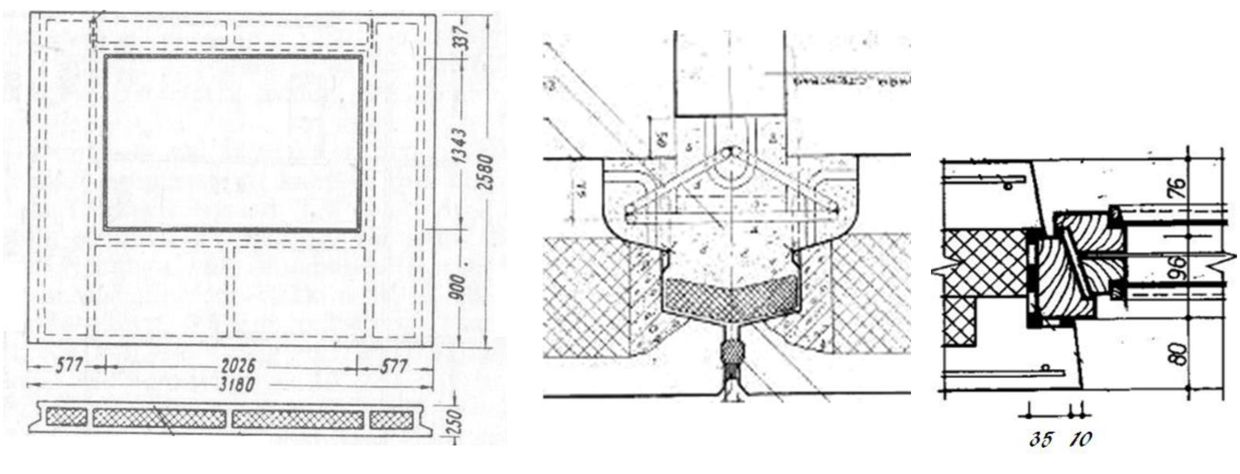


Figure 13. Original design drawings and junctions of a case study building – external wall concrete element (left), junction of external wall/ internal wall (middle) and junction of external wall/ window (right).

Fulfilling the criteria

If the accepted level of risk for condensation or mould is exceeded, the renovation scenario will be revised. A new or improved scenario must be chosen and the framework has to be rerun.

ROUND ONE – CURRENT STATE OF THE ART

C3.2 Level 2 – Renovation strategies

In round one, the need for renovation from the current state of the art is estimated. The strategy is to confirm or falsify the hypothesis at the current standing without renovation. Renovation strategies, its tasks and stages are not yet developed and qualified partners not yet needed here.

C3.3 Level 3 - Analysis

Consultation

Problems related to thermal bridges and possible condensation/ mould growth with similar buildings in cold climate are summarised based on previous research and experience. Research results related to thermal bridges are presented in (Ilomets et al. 2011, Ilomets et al. 2014).

Parameters impacting the thermal bridges

Criticality of the thermal bridges depends on many parameters:

- Indoor climate
- Outdoor climate
- Building envelope
- Assessment criterion

In the current evaluation of the framework, parameters at general levels marked with yellow (see top rows in Figure 14) were measured and taken into account.

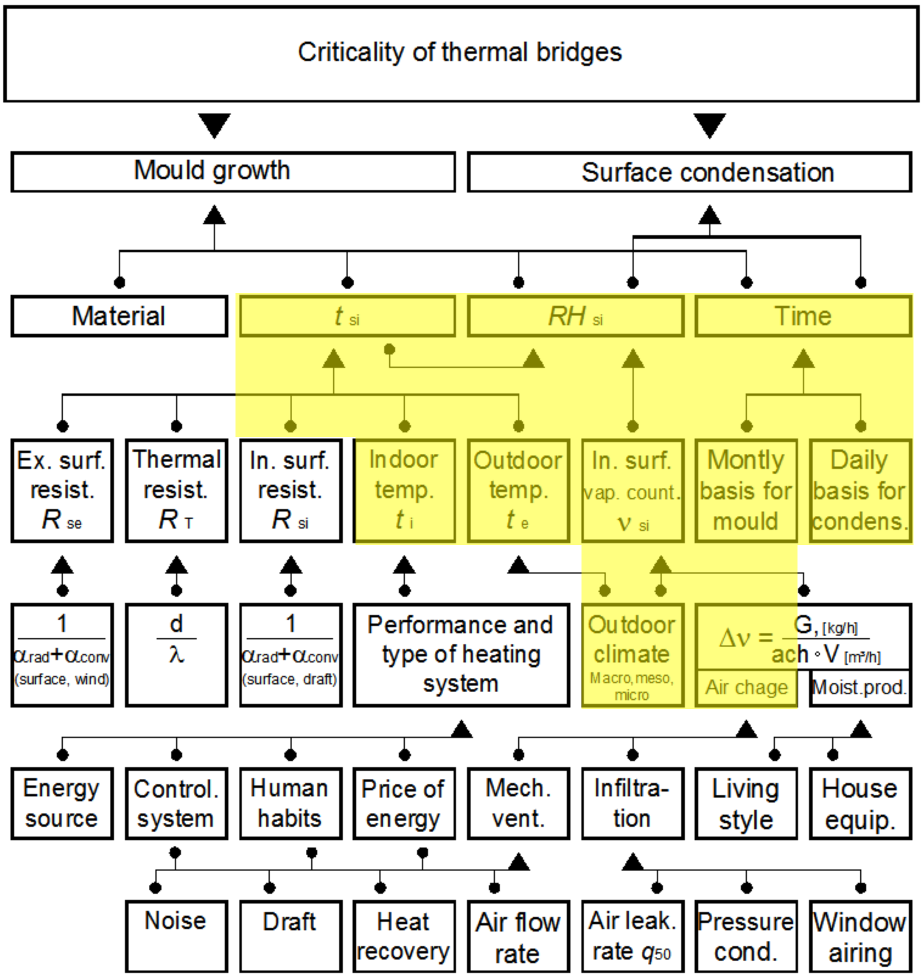


Figure 14. Fault tree analysis of parameters influencing the criticality of thermal bridges. Parameters taken into account in this study are marked with yellow.

Measurements and numerical analysis

Thermography and climate measurements of a building should be performed in round one to explore the current technical condition. In this case study, available information about the current situation of $f_{Rsi,res}$ was collected by using thermography in four apartments, including one from bottom, top and tip part of the building. Alternative simplified approach is the use of previous research or standards, i.e. EN ISO 13788 to calculate $f_{Rsi,load}$ or EN ISO 10211 to calculate $f_{Rsi,load}$.

In our case-study, thermography measurements in the buildings showed that the critical thermal bridges are located in:

- horizontal and vertical joints between external wall elements; f_{Rsi} 0.68...0.80
- junctions of the external wall and the balcony slab;
- junctions of the external wall (especially end sides) and the flat roof; f_{Rsi} 0.61...0.65
- bonds of elements inner and outer layers of the external walls;
- foundation wall elements; f_{Rs}i 0.43...0.62
- junction of the external wall and the window/ door f_{Rsi} 0.66...0.70.

Available information about the current situation of $f_{Rsi,load}$ was collected by measuring the indoor temperature and RH during a few months in a heating season. Measurements and thermography were taken in the same apartments.

Based on the indoor and outdoor climate (temperature and RH) data and assessment criteria (surface condensation and mould growth), critical temperature factors were calculated (Figure 15). Depending on the hygrothermal loads, large variations between different apartments can be seen. Each curve represents the maximum monthly average (for mould) or daily average (for surface condensation) temperature factor $f_{Rsi,load(mould,condensation)}$ at the corresponding outdoor temperature. Maximum temperature factors $f_{Rsi.load}$ from different apartments for surface condensation varied between 0.40...0.55 and for mould growth, 0.36...0.57 (Figure 15 left).

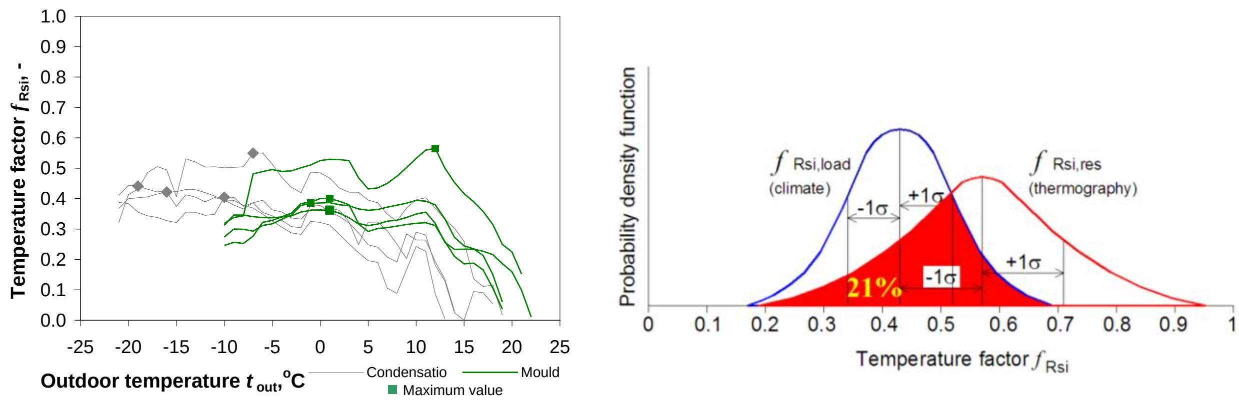


Figure 15. Critical temperature factors $f_{Rsi,load(mould,condensation)}$ calculated from climate measurements (left). Graphically presented risk 21% of failure is in case of mould growth (right). Probability for surface condensation is 25%.

C3.4 Level 4 – Evaluation of current state of the art

Probability of condensation and mould growth was calculated according to Eq. (4) by comparing the distribution of the temperature factors measured with the thermal camera $f_{Rsi,res}$ and the critical temperature factors calculated from the indoor climate measurements $f_{Rsi,load}$. Figure 15 right presents the result for mould growth before the renovation: 21%. This confirms the hypothesis that visual mould growth has originated from the thermal bridges and can be expected in approximately 13 apartments out of 60. Probability for surface condensation is 25%. Risk for both phenomena is unacceptably high and renovation of the building must cover the thermal bridges.

ROUND TWO – ASSESSMENT OF A RENOVATION SCENARIO

C3.5 Level 2 – Renovation strategy

There are four main renovation strategies that can be chosen or combined:

- Installation of additional external thermal insulation: thermal conductivity and thickness of insulation material must be chosen.
- Improved ventilation to guarantee healthy indoor climate, thermal comfort and energy efficiency. Mechanical exhaust/ supply system with heat recovery should be used.
- New two-pipe heating system with room thermostats must be installed.
- Moisture loads can be decreased by using a laundry with a dryer or by improving the awareness of inhabitants.

In the renovation strategy of this case study we used additional thermal insulation with a thickness of 150 mm to the external walls, 100 mm to the foundation wall, 300 mm to the roof and 25 mm to the jamb (also named cheek or return in the literature) of a window. Old windows were replaced at their original position. New mechanical exhaust ventilation with fresh air inlets was installed. Heat recovery was solved based on the heat pump. A new two-pipe heating system with new batteries and room thermostats was installed.

Identify tasks and stages

Renovation could be divided into stages but a complete end-solution should be provided. Additional insulation decreases the heat loss and raises the surface temperature of the building envelope that improves thermal comfort. Ventilation guarantees fresh air and dissolves problems related to high humidity. Sufficient room temperature has to be achieved with a heating system since low temperature causes higher RH (see also Figure 14).

Identify qualified partners

No extraordinary skilled design or workmanship was needed during this renovation case study.

C3.6 Level 3 – Analysis

Consultation

Performance of renovation solutions and information from reliable databases should be collected and analysed, at the same time taking into account local peculiarities while approaching the evaluation/ decision phase (Level 4). To demonstrate renovation of apartment buildings in the Baltics, principles to select a renovation scenario are reported in (Zavadskas 2008) for Lithuania and a renovation example based on Estonian experience is described in (Kuusk et al. 2014) and (Ilomets and Kalamees 2013).

Parameters impacting the thermal bridges

These parameters were presented in round one, see section 3.3, Figure 14.

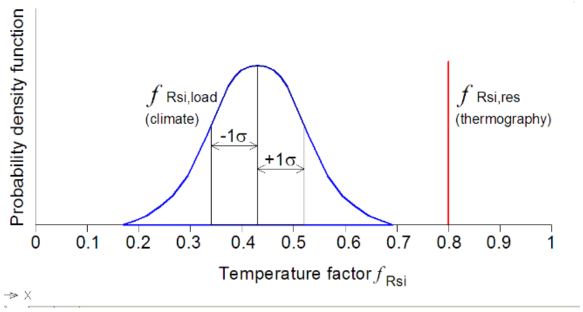
Measurements and numerical analysis

In the decision process, when using the finite element heat transfer software, the numerical analysis of the temperature factor should be performed to evaluate the improvement of $f_{Rsi,res}$. It is appropriate to do the analysis after completion of the first version of the design documentation (including junctions). The calculated values of the temperature factors can be validated against the measured ones in round one.

In our analysis Therm 6.3 software was used to assess the performance of the renovation strategy. In addition, it was also possible to measure surface temperatures after the renovation and compare pre- and post-renovation situation directly.

C3.7 Level 4 – Evaluation of renovation

Probability of surface condensation and mould growth for round two was calculated according to Eq. (4) (as in round one). It resulted in 2% at both criteria graphically presented in Figure 16 (right). We were able to measure the surface temperatures also after the renovation ($f_{Rsi,res}$) while in a typical case these values in round two are calculated based on the solution from the design documentation. The critical temperature factor $f_{Rsi,load}$ from the indoor climate was kept unchanged to see only the impact of the building envelope additionally insulated. The renovation scenario entails no notable limitations and we assumed a normal distribution of data. A goal for risk level was chosen 0% (Figure 16 left) but it was not achieved since the measured temperature factors were lower than those calculated. Improvement of the HVAC systems is out of scope of this analysis but it was renovated as described in the renovation scenario in section 3.5.



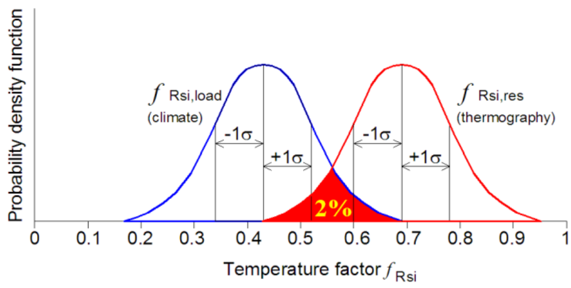


Figure 16. Temperature factor f_{Rsi} was set at 0.8 to reach the goal 0% of risk at design process (left). Distribution of the measured temperature factors with thermography $f_{Rsi,res}$ after the renovation gave 2% of risk for surface condensation and mould growth (right). Critical temperature factor $f_{Rsi,load}$ from indoor climate used in analyse was kept the same.

C4 CONCLUSIONS

This paper has evaluated the framework proposed in Subtask-3 of Annex 55. In our case study we used the framework and ran it twice. First, it was used to assess the need for renovation at the current state of the art and secondly, to study the performance of the renovation scenario. The temperature factor $f_{Rsi,res}$ from the surface temperature measurements with thermography and the $f_{Rsi,load}$ calculated based on the climate measurements were used as the criteria.

As a result, probability of surface condensation at pre- and post-renovation standing was 25% and 2%, respectively. Probability of mould growth was 21% before and 2% after the renovation. The design goal 0% for risk of failure with temperature factor 0.8 was not achieved.

Our conclusion is that the framework is a helpful tool and can be used by an expert or a designer in the future. It enables us to evaluate the need for renovation or the performance of a renovation scenario and, unlike the deterministic approach, also calculate the risk of failure.

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D. Evaluation of the framework for probabilistic assessment of performance of retrofitted buildings – A window retrofit case

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IVL Swedish Environmental Research Institute

Summary

This report shares experiences and results from a case study performed following a framework for probabilistic assessment. The study demonstrates several difficulties in interpretation of calculation results of indoor thermal comfort caused by window retrofit in an office building using some simple tools. The study conclusions underline that the results needs to be carefully analysed to avoid erroneous conclusions. Examples of dominating errors or interpretation mistake sources is tool simplifications in temperature setting resolution, averaged effects of sunshade use and effects of HVAC system settings. The framework approach resulted in a better understanding of the difficulties to reach a reliable result with spread. A worst case approach seems to be much more manageable for a problem like this. For e.g. passive house dwellings without comfort cooling is a worst case approach probably not acceptable and would require use of more advanced tools or methods based on advanced calculations. The tools Parasol and TEKNOsim are used in this study. Parasol is rather detailed and calculates thermal comfort data for specific points in time and space but lack functions to summarise thermal performance in time and space. TEKNOsim can summarise thermal comfort for the summer case but handle e.g. window shading operation in a rather simplified way. The framework evaluation is further elaborated in the end of the report.

D1 INTRODUCTION

Thermal comfort is important in several aspects. It is one of the primary services a building should provide. Thermal comfort is sometimes considered as conflicting with low energy use in buildings, for example as in the argumentation that building users should sacrifice thermal comfort for the benefit of energy conservation. However, there are several reasons to consider good thermal comfort actually supporting efficient energy use. For example, low thermal comfort may result in window airing counteracting the HVAC system or increased domestic hot water use when a frozen apartment owner takes long, hot showers. A large number of dwellings are still produced worldwide where thermal comfort is not expected due to poor building envelopes. However, we can expect that building users increase their demand for thermal comfort if their household economy grows. This may result in increased energy use in the future when building users install climate control equipment to compensate for a bad building envelope. In this sense thermal comfort can be regarded as a necessary condition for an energy efficient building.

The reader of this report is interested in an example of how the framework developed in subtask 3 can be used and/or the possibilities to use simple tools to assess thermal comfort effects from retrofitting measures – perhaps an engineer in a property management organisation. Assessments of thermal comfort effects from retrofitting are probably often handled without quantitative investigations.

This case study aims to assess the expected uncertainties in performance for a future window retrofit case – a quantification of expected spread of results. Moreover, what is the result difference between internal or external sunshield? *Performance* is here limited to calculated thermal comfort in retrofitted areas. This limitation is chosen simply because this is considered challenging in comparison with assessment of e.g. economic results due to energy conservation. Thermal comfort is quantified using the recognised concept of Predicted Percentage of Dissatisfied (PPD) in this study.

The case study considers a specific building but the approach is general. The work has mainly been performed by an energy and building expert at a research institute. The work has generally been performed trying to use free or cheap, easy-to-use tools with the aim at finding practical methods for non-academics.

D1.1 Thermal comfort in an office – effects of a window retrofit

The case study procedure is presented following the headings from the framework. Each framework heading in this report is followed by corresponding framework description text in *light italics* except in the iterative procedure – returning to sections already addressed once. The description follows the actual performed work and each section reflects the actual approach even though lessons learned later on in the work provides better approaches.

D2 SCOPE

D2.1 System

Spatial scale of the project: whole building, building part, building envelope, and/or building material.

A window retrofit as the only refurbishing measure is considered for an old 20 000 m^2 culturally valuable office building in Gothenburg, Sweden. The property management has received thermal comfort complaints from tenants in the building and the old windows, which need some kind of refurbishment anyway, are planned to be replaced. One of the main goals of the retrofit is to improve the thermal comfort in the building.

D2.2 Targets (performance criteria) and consequences

Energy performance, moisture performance, IAQ, total cost of the project, and/or cost of operation What are the consequences if the targets are not fulfilled?

An improved thermal comfort and improved building energy performance are the goals of this retrofit. Several economic targets are relevant to consider in a case like this. This study is however focused on the assessment of improved thermal comfort due to the window retrofit. Decided targets and consequences are listed in Table 10.

Table 10 Listed targets and consequences

Targets		Consequences if targets are not met
Cost (not addressed)	Investment	Economic loss
	Future maintenance cost	Economic loss
	Future energy cost	Economic loss
Indoor Environmental Quality	Few building users dissatisfied with thermal comfort. PPD level: maximum 10 % (The PPD concept will be described below)	Insufficient Indoor Environmental Quality Reduced building value Reduced performance among those working in the office

The target in this case is set to maximum 10 % PPD. This value corresponds to the highest classification in the Swedish Green Building Classification System *Miljöbyggnad*[2]. The BREEAM system also uses this limit [3].

Predicted Percentage of Dissatisfied

Predicted Percentage of Dissatisfied (PPD) is a concept described in e.g. *ISO 7730 Ergonomics of the thermal environment.* PPD is used in building certification systems and guidelines[4]. The concept is based on empirical studies and related to the Predicted Mean Vote (PMV).

The thermal climate can be quantified with PPD, using input data for temperatures, clothing etc. A certain combination of personal activity, clothing, air temperature, air velocity, radiant temperature, and relative humidity is experienced differently by different individuals. There is however empirical established Predicted Mean Votes (PMV) connected to each input combination – votes such as +3 for hot, -1 for slightly cool, 0 for neutral, etc. Further is there a correlation between the PMV and the PPD. The red arrows in Figure 17 illustrate a climate situation which has a PMV of -0.5 – that climate will on average leave 10% dissatisfied. Moreover does the graph illustrate that there are no climate

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[2] Miljö byggnad Bedömningskriterier för befintliga byggnader (assessment criteria for existing buildings) + Miljö byggnad Bedömningskriterier för nyproducerade byggnader (assessment criteria for new buildings)

[3] BREEAM Europe Commercial 2009 Assessor Manual gives one credit for meeting category B in EN ISO 7730 (maximum 10 % dissatisfied and four additional criteria for local discomfort)

[4] E.g. BREEEAM (BRE Environmental Assessment Method), Sweden Green Building Councils *Miljöbyggnad*, Swedish HVAC Technical associations guidelines for specification of indoor climate *"R1" (VVS Tekniska föreningen*)

situation that everybody are completely satisfied with. See e.g. Healthy HEATINGs web[5] for a more detailed explanation on PPD.

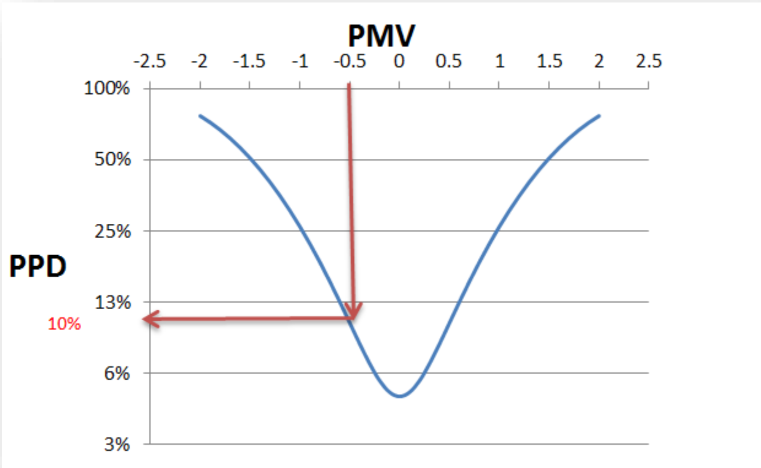

Figure 17 The PPD – PMV correlation according to ISO 7730.

The PPD concept offers a method to describe indoor thermal climate which is much better than to only use indoor temperature.

There is more to thermal comfort than PPD, ISO 7730 above also cover local draught and local discomfort. EN 15251 also addresses thermal comfort.

Existing conditions and information

Collect facts and data. What motivates the choice of retrofit strategy?

Windows are in need of renovation or replacement. New windows offer a chance to act on the insufficient thermal comfort at the same time.

Retrofit strategies

Consider alternative retrofitting measures in order to make room for relative assessment ranking

The two alternatives considered are new windows – triple paned, low emissive coating, argon filled and:

1. External awnings
2. Internal venetian blinds

Limitations and assumptions

Declare what is assumed to be fulfilled and also what is not comprised by the analysis

The analysis should result in predictions on thermal comfort in retrofitted areas including result spread based on variation of input data.

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[5] http://www.healthyheating.com/solutions.htm

Economic and energy use assessment of the refurbishing measure is not included in the study – however are these issues highly relevant in a retrofit like this.

Moisture performance is not included in this study – however is the window connection to the building envelope important regarding moisture safety.

D3 IDENTIFICATION OF BENEFITS AND HAZARDS

D3.1 Influential parameters and their uncertainties

For example, intensity of HAM loads in indoor and outdoor environment

In the perspective of window replacement and thermal comfort, the parameters in Table 11 are identified as highly influential regarding thermal comfort and reasonable to take into account. Parameters are sorted in three different classes: design choice, varying or fixed – reflecting their expected status in this case study. Uncertainties, or input data variation, are further specified in the quantitative analysis.

Table 11 List of parameters and uncertainties that are highly influential regarding thermal comfort and reasonable to take into account in an assessment of thermal comfort

	Parameter	Design choice	Varying	Considered fixed
Window performance	Glass properties	X		
	Inert gas filling	X		
Sunshield	Internal /external	X		
	Performance	X		
	Regulation		(X)	(X)
HVAC	Heating & cooling regulation		(X)	(X)
	Indoor air temperature		(X)	(X)
	Supply air temperature			X
	Supply air volume flow			X
	Local air velocity		X	
User behaviour	Clothing		X	
	Activity		X	
External	Ground reflectance		X	
	Relative humidity		X	
	External temperature		X	

D3.2 Perform QUALITATIVE probabilistic analysis

Explore the existing knowledge in form of recommendations, quality insurance systems and similar, or perform another form of qualitative analysis – fault trees and similar

It is “well known” that poor windows may affect the thermal indoor environment negative by increasing downdraft during cold periods, increasing non uniformities in thermal climate[6] and increase cooling demand during cooling periods. Consequently, the replacement of an old two clear glass window with a window with lower U-value and a lower g-value in combination with sun shielding should improve the thermal climate in the building.

Generally, it should be underlined that an improved thermal comfort has the potential to improve work ability and work results. Seppänen & Fisk, according to ASHRAE[7], presents a correlation between relative performances of office work versus deviation from optimal temperature based on several studies. This correlation indicates e.g. that 3 °C above optimal temperature correlates to about 2 % lower work performance. This may serve as a qualitative indication of the economic value of thermal comfort.

D3.3 First evaluation of the results

Pros and cons with the retrofitting, for example, areas identified where performance could be good or bad can be included directly in final reporting, while those ‘in between’ should go for further evaluation.

Thermal performance goals are set. Calculations will be made to support choices leading to the goals.

Directly reported

- Work ability issues above
- Underline importance of appropriate window fitting regarding moisture safety

D4 QUANTITATIVE PROBABILISTIC ANALYSIS

D4.1 Method of analysis

Assessment of predicted thermal comfort in buildings depending on influential parameters is possible to handle using available tools. Examples of tools are, according to Sweden Green Building Council[8]: Pro-Clim, IDA Indoor Climate and Energy, TEKNOsim and ParaSol. ParaSol is chosen in this case, due to its window focus and the fact that it is a free tool. This tool offers a wide range of options of different sunshield products.

The building will be modelled by a representative room in the building. Different design options and reasonable variations of parameters in Table 11 will be varied and simulated in relevant combinations. The pre-retrofit situation with 2-glass windows will be included in the calculations for reference.

Three tools used in this study are briefly described below.

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[6] See e.g. ASHRAE FUNDAMETALS HANDBOOK 2009, chapter Thermal comfort

[7] ASHRAE FUNDAMETALS HANDBOOK 2009, chapter Thermal comfort

[8] Miljö byggnad Bedömningskriterier för nyproducerade byggnader (assessment criteria for new buildings)

ParaSol

ParaSol[9] is a free tool that, among other things, calculates PPD. The results are detailed and show PPD for different positions in the room. ParaSol admits PPD calculation of *one* room with *one* external wall containing *one* window. Input data comprise room geometry, external wall thermal performance, window data, sunshield performance and regulation, etc. – everything at a detailed level. The PPD output format is graphical and the software allows for individual preference on output settings for colours etc. **Error! Reference source not found.** shows a Room plan PPD output for a room at 1.2 m above floor level. The red and yellow areas indicate, in this case, local warmer climate from solar radiation through the window. A high PPD near a window does however not necessarily indicate higher temperature but might reflect a cold environment from a window with poor thermal insulation properties.

ParaSol output is chosen for one instant situation (a chosen hour a chosen day from one year in the software's climate file). The user can chose a relevant day and see how the PPD varies in different areas of the room during the day. Some change of input data require a new calculation run which takes some time.

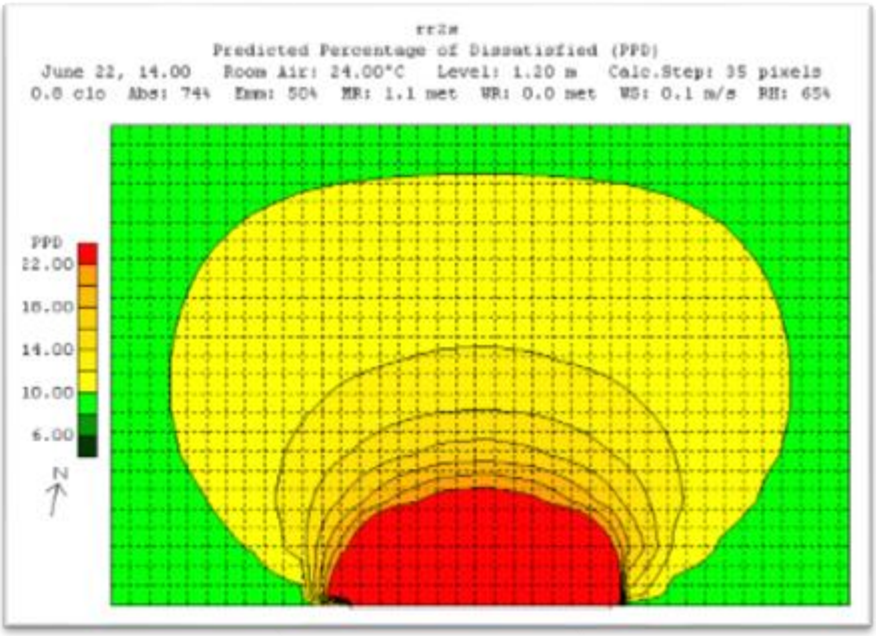

Figure 18 Example of PPD output from ParaSol – a room plan view

TEKNOsim

TEKNOsim[10] is a (cheap but not free) tool calculating PPD. The tool is primary aimed at cooling system design. The results are area averaged and show PPD for the room as one value. TEKNOsim admits PPD calculation of one room with more than only one external wall and one window. Input data comprise room geometry, external wall thermal performance, window data, sunshield performance and regulation, etc. The parameters are generally on an average level, e.g. "automatic external awnings" are modelled as their assumed average solar protection value.

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[9] http://www.ebd.lth.se/english/software/parasol/

[10] http://www.lindab.com/global/pro/software/ventilation/Pages/TEKNOsim.aspx. Free evaluation for 15 days

Several different PPD calculations are offered. Summer conditions are calculated for a dimensioning climate situation and showed in a graph covering the hours of the dimensioning day (see example in Figure 19**Error! Reference source not found.**). Winter PPD output is one value for the dimensioning or freely chosen winter day. Other PPD related data can be calculated, such as hours of the year with certain air- and operative temperatures and radiation temperature for some points in the room.

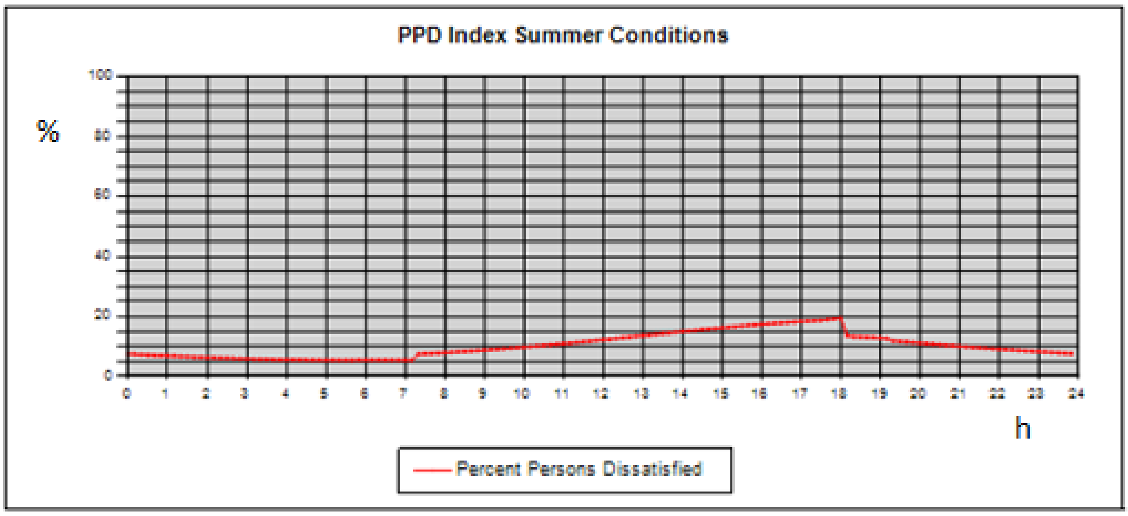

Figure 19 Output example from TEKNOsim

A web based thermal comfort calculator

The screen dump in Figure 20**Error! Reference source not found.** shows a web based PPD calculator. Six different input data is entered and corresponding PPD is displayed. In the example are 30.5 % of the average rabbits not satisfied. This is an effect of all input – but e.g. a lower air speed and/or more clothing (encircled values in the figure) would result in lower PPD.

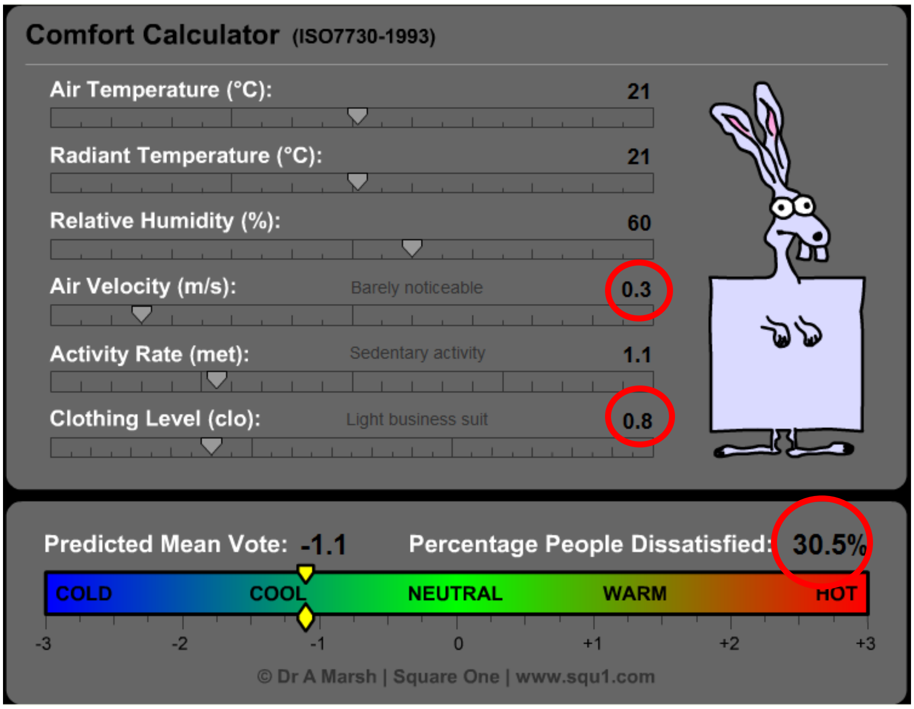

Figure 20 A screen dump from the online comfort calculator at Healthy HEATING: http://www.healthyheating.com/solutions.htm

D4.2 Define probabilities

Initially only climate probabilities are set. Other parameters are decided to be tested for sensitivity before deciding probabilities. It is important to isolate the important parameters. The number of simulated combinations must be reduced to keep simulation work at a reasonable level. Table 12 shows the preliminary approach of parameter variation.

Table 12 Parameter variation and probabilities W = winter, S = summer

Parameter	Variations	Simulation approach	Probability
Window	Old 2-pane and new 3-pane low energy	With 20 different representative weather conditions based on data sorting in climate file[11]	Corresponding probability for each climate condition during office hours according to climate file
Sunshield	None, internal, external		
Clothing absorption factor	50 % - 75 %	With two extreme climate conditions for sensitivity test	Decide later
Metabolic rate	1,0 - 1,2 W/m^2		
Clothing factor	W: 0,9 - 1,1 S: 0,7 - 0,9		
Ground reflectance	7 % - 85 %		
Air velocity	0,1; 0,2; 0,3 m/s		
Relative humidity	W: 20 % - 50 % S: 50 % - 80 %		
Indoor temperature	W: 18˚C - 22 ˚C S: 22˚C - 26 ˚C		
Climate	(See Window and sunshield)		

The ParaSol tool delivers graphical output that need to be analysed for every simulation run. The table in the next section shows, for practical reasons, the probability to reach the goal of maximum 10 % PPD during office hours in the building [12] .

D4.3 Calculate performances

The simulation result[13] is presented in Table 13.

Table 13 Calculation result: <u>per cent represent odds meeting the set goals of maximum 10 % PPD</u>

2- glass			3-glass LE & Argon		
No sunshield	Awning	Internal venetian blind	No sunshield	Awning	Internal venetian blind
61 %	54 %	53 %	61 %	51 %	50 %

[11] Based on outdoor temperature and direct solar radiation

[12] It is not possible to present one PPD value because it is different in different parts of the room model and different hours

[13] Calculations are only made for the south façade

According to these results, the added sunshield and efficient windows result in lower odds to meet the set goals of maximum 10 % PPD and hence make thermal climate slightly worse! (This will be addressed in next section.)

The sensitivity analysing simulations, using two extreme climate situations, indicate that air velocity, clothing, activity, indoor temperature and relative humidity all are powerful influential parameters. Less powerful parameters seems to be clothing colour and, perhaps no surprise, ground reflectance.

D4.4 Second evaluation of the results

Check the reliability of the results, e.g. in the form of probability density functions (pdf's) of performance parameters, and the chosen method of analysis. Report all efforts, not just the final method that has shown appropriate.

The results in the previous section seem strange[14]. Some winter results in Figure 21 indicates that good thermal climate in many situations only are met in the sun beam. Further, it seems that the cold radiation from the external wall (with very poor thermal performance) influence the thermal climate near the wall and possibly also in the entire room. The results don't seem to reflect an answer to our question and are so far not useful for our analysis (further discussed in next section).

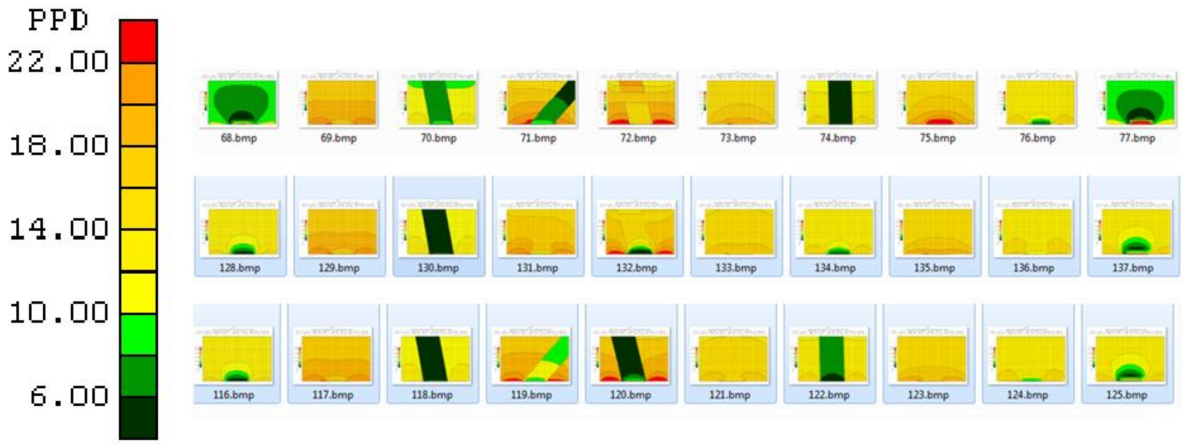

Figure 21 Graphical results from winter simulations. Green areas of the room plan represent thermal comfort within the set goal maximum 10 % PPD. Good thermal climate in many situations are only are met in the sun beam. Further, it seems that the cold radiation from the external wall (with very poor thermal performance) influence the thermal climate near the wall and possibly also in the entire room. The results don't seem to reflect an answer to our question

[14] Possibly partly due to some software problems during simulation.

D5 QUANTITATIVE ANALYSIS - ROUND TWO

Further analysis of the first framework round and some additional Parasol sensitivity tests indicate that:

- Thermally low performing walls and windows occurring in this study can always be compensated with higher indoor temperature, resulting in good thermal comfort. A thermally better wall (U-value: 0.4 instead of 0.9 W/(m²K)) require lower indoor temperature for the same thermal comfort (however, the difference is lower than one degree Celsius).
- The indoor temperature for winter conditions was set to 20˚C in the first round – this has a large impact on the result. One or two degrees higher indoor temperature would give significantly better PPD results
- The difference in output between external and internal sunshield is negligible. The input air temperature is handled, by the tool, such as that the heating and cooling system have the capacity to keep that temperature and the only difference in software output is a difference in energy use
- Simulation result without sunshade in south comprise a beam of totally different PPD compared to the rest of the room during some office hours – it is not reasonable to account manually (interpretation of graphical output) for the amount of simulations necessary to account for this result properly
- In the first round a PPD goal was set and two retrofit options that might or might not meet the criteria were also set, and the results were collected in fail or success for the different calculated situations – this gave a result hiding much information not revealing actual PPD levels.
- In the first round, twenty different weather conditions were used for some simulations and two climates for sensitivity analysis. Analysing the results shows that the result difference between twenty instead of three climates are small, and in the same range as uncertainties due to graphical interpretation.
- Relative humidity variation, within normal variations for the season, makes small effects on the results
- The output difference between north and south is small as long as sunshield is used
- Simulation runs takes time and the number of simulations must be kept down

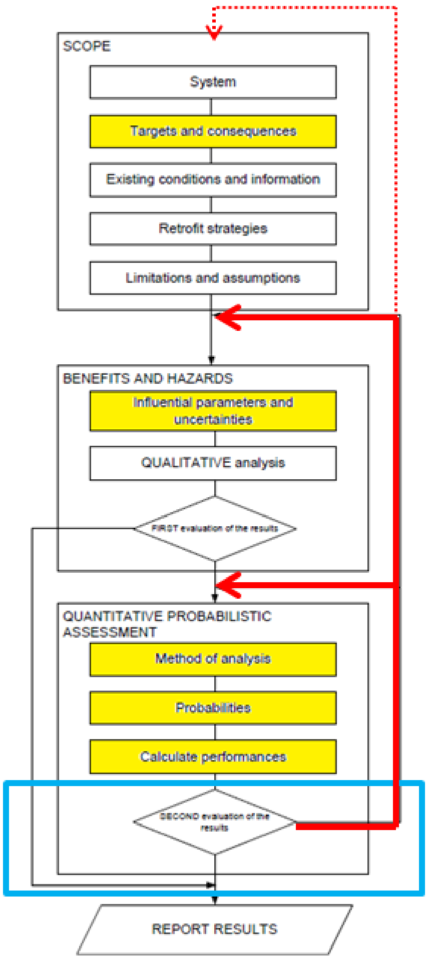

Figure 22 The framework with coloured boxes that will be approached again

A second iterative round in the framework is necessary. Figure 22 shows which boxes needs to be addressed again.

D5.1 Targets (performance criteria) and consequences 2

Instead of assessing areas that meet maximum 10 % PPD the actual PPD output value will be used as result – this approach give much more useful information. Still the 10 % PPD is kept as a goal in the sense that we like to reach it. The original target is changed to a question: "What PPD can we expect from a window retrofit like this"

D5.2 Influential parameters and their uncertainties 2

Because the choice between internal or external sunshield doesn´t affect the PPD output in this setup (due to the tool's unlimited cooling power), simulation tool and because data for simulations without sunshade is hopeless to handle in large amounts due the output format, and because the difference between north and south is small as long as sunshield is used – only the north façade will be simulated. Based on the analyses opening round two – several parameters are kept fixed in this set up. With this approach we drop the sunshield question and limit the study to comfort effects related to heat losses through the window. Table 14 shows the new parameter approach

Table 14 List of parameters and uncertainties 2. More parameters are fixed in this approach compared to the first, based on the sensitivity analysis in round one

	Parameter	Design choice	Varying	Considered fixed
Window performance	Glass properties	X		
	Inert gas filling	X		
Sunshield	North: none	X		
	Performance	X		X
	Regulation			X
HVAC	Heating & cooling regulation			X
	Indoor air temperature			X
	Supply air temperature			X
	Supply air volume flow			X
	Local air velocity		X	
User behaviour	Clothing		X	
	Activity		X	
External	Ground reflectance			X
	RH			X
	External climate		X	

D5.3 Method of analysis 2

ParaSol will be used again with the new input data variation approach. The result will be averaged for the entire room by weighting against representative areas. Relevant combinations will be simulated. The set probabilities for each parameter will be multiplied for each run and allocated to the resulting PPD. PPD probabilities will then be summarized in a histogram.

D5.4 Define probabilities 2

Table 15 shows the new parameter variation approach. Used values are reasonable examples. Another building used in another way would need other data and would give different results.

Table 15 Parameter variation and probabilities

Parameter	Variations	Probability
Window	Old 2-pane and new 3-pane low energy	-
Climate	Three representative climates	Corresponding probability during office hours according to climate file.
Clothing absorption factor	60 %	Always
Metabolic rate (activity measure)	1.0; 1.1; 1.2 W/m^2	25/50/25 %
Clothing factor summer	0.7; 0.8; 0.9	25/50/25 %
Clothing factor winter	0.9; 1.0; 1.1	25/50/25 %
Clothing factor medium climate	0.8; 0.9 ; 1.0	25/50/25 %
Air velocity	0.1 ; 0.2 m/s	70/30 %
Relative humidity summer	65 %	Always
Relative humidity winter	40 %	Always
Relative humidity medium climate	40 %	Always
Indoor air temperature summer	23 ˚C	Always
Indoor air temperature winter	22 ˚C	Always
Indoor air temperature medium climate	22 ˚C	Always

D5.5 Calculate performances 2

The results from the simulations are presented in Figure 23. To make the output more useful – PPD from cold, medium and warm outdoor climates are presented using different colours.

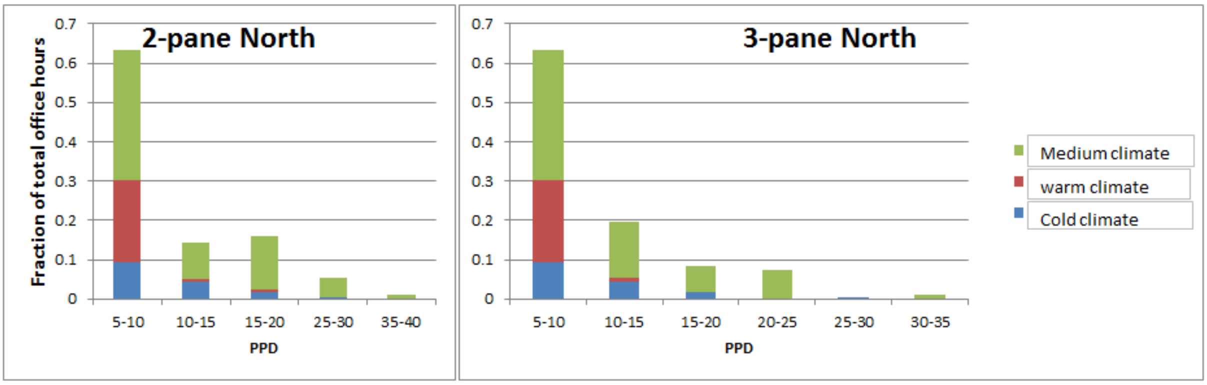

Figure 23 Result from run 2 – histogram representation showing the odds for different PPD situations. The colours indicates which weather condition that are tied to corresponding results

D5.6 Second evaluation of the results 2

According to the graphs, the thermal comfort is slightly improved with three glass windows – but no noticeable increment in how often PPD results will stay within the goal (maximum 10 % PPD) can be seen. With further analysis of the graphs and with knowledge about simulation input, it can be concluded that over-temperatures seems to be no problem during summer. Some problems are predicted with the thermal climate during the winter, but most thermal comfort problems seem to stem from medium external climate situation. This indicates that assumption on input data, except from window data, and adherent variation have large impact on results and seems to dwarf the window related output.

Experience and conclusions from the work:

- Simulation takes lots of time when varying some parameters
- The output is graphical and conversion to numbers is time consuming and introduce uncertainties
- Looking at the results in Figure 23 and then wanting to change something require new simulations and manual handling of data – this is not reasonable to handle in a manageable assessment
- Analysis of the output indicates that the result seems to reflect the window retrofits only to a minor extent and that other parameters have the largest influence.
- One conclusion can be that the thermal comfort does not depend so much on windows as long as the climate system can deliver optimal temperature.

D6 QUANTITATIVE ANALYSIS - ROUND THREE

Another simulation tool is introduced – TEKNOsim. This tool is described earlier.

The same approach will be used as in round two as far as it is possible in the TEKNOsim tool.

D6.1 Influential parameters and their uncertainties 3

The major difference in parameter approach is that indoor temperature is allowed to wary slightly during summer due to limitations in cooling capacity – this is a useful option in the tool. Moreover, a south façade with internal sunshield is included.

D6.2 Method of analysis 3

The approach will be as in round two. The major difference will be regarding how to extract PPD data for a variety of different situations. The tool has primary PPD output for dimensioning climate situations. To extract PPD for other situations it is necessary to use other output such as operative temperature and radiation temperature output and use this in another tool to extract PPD. For this, is the web based tool from Healthy HEATING, earlier described, used. The conversion from TEKNOsim output to the HEALTHY Heating input is based on the correlation between air temperature, radiation temperature and operative temperature[15]. This approach introduces a small uncertainty and some manual work[16].

Further differences compared to round two is the yearly summarised hours for representative summer climate which now will be based on the feature in TEKNOsim that count hours with certain over temperature. Winter climate will be simulated for several conditions as the tool and the approach allows a relatively fast procedure.

D6.3 Define probabilities 3

The difference from round two is the probability for different climate situation following from above. This gives eight winter climates, five summer climates and one climate representing the rest of the year.

D6.4 Calculate performances 3

The results from the simulations are presented in Figure 24.

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[15] The correlation is simplified and not 100% correct.

[16] This method is used anyway based on the idea that PPD output might as well have been supplied by TEKNOsim and then would the method be easier and have better precision.

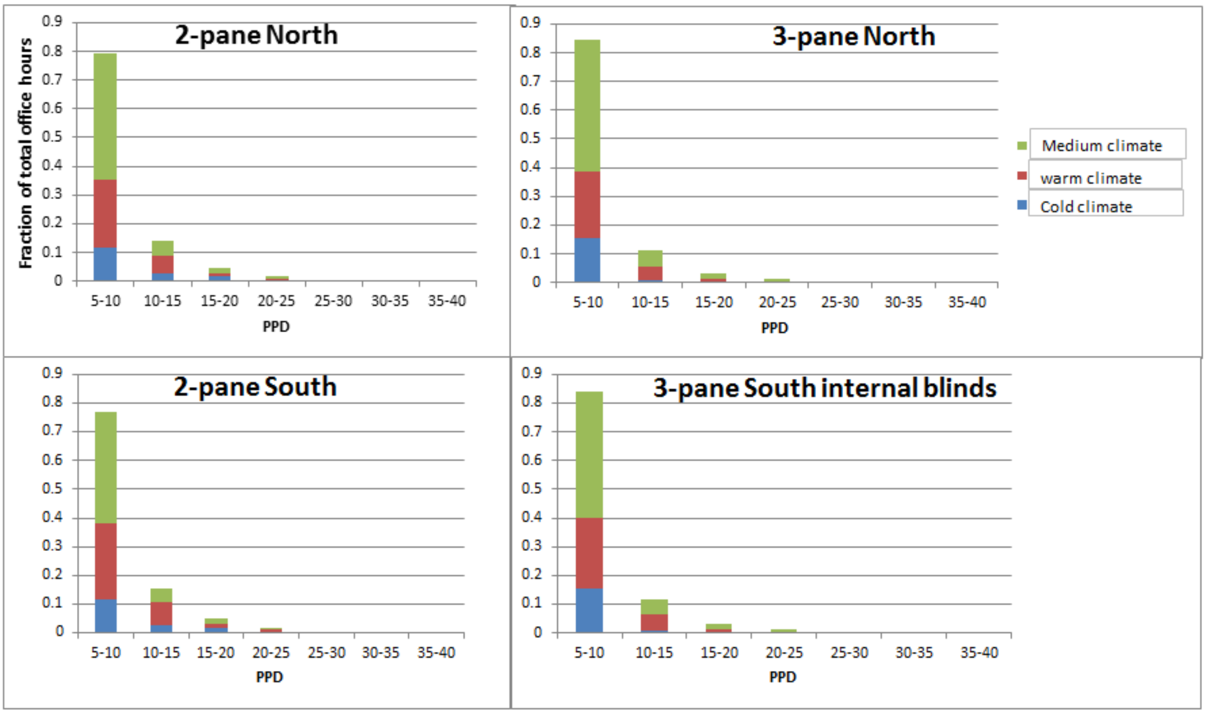

Figure 24 Results from third round – histogram representation. The colours indicates which weather condition that are tied to corresponding results

D6.5 Second evaluation of the results 3

The results are different from the ParaSol simulations – TEKNOsim indicates better thermal comfort both with and without window retrofit than ParaSol. The calculated retrofit improvements for the winter cases are small but noticeable. "Poor" thermal comfort during summer (above 10 % PPD) appears due to the fact that the model includes slightly limited capacity for cooling.

D6.6 Complementing approach discussion

If instead the maximum PPD value is in focus and we look at the probability for variation during a worst case situation, instead of trying to asses all hours of the year, the work is much more reasonable using these kinds of tools. The same data used in round three but only for the coldest and warmest day give the results presented in Figure 25. The winter case shows some improvements with the three pane window and the summer case shows large improvements. Note that the summer improvement mainly depends on that the cooling system capacity copes better with the lower cooling load due to external sunshade. It should be underlined that the actual data in these bar graphs not should be seen as representative for anything else but the specific case.

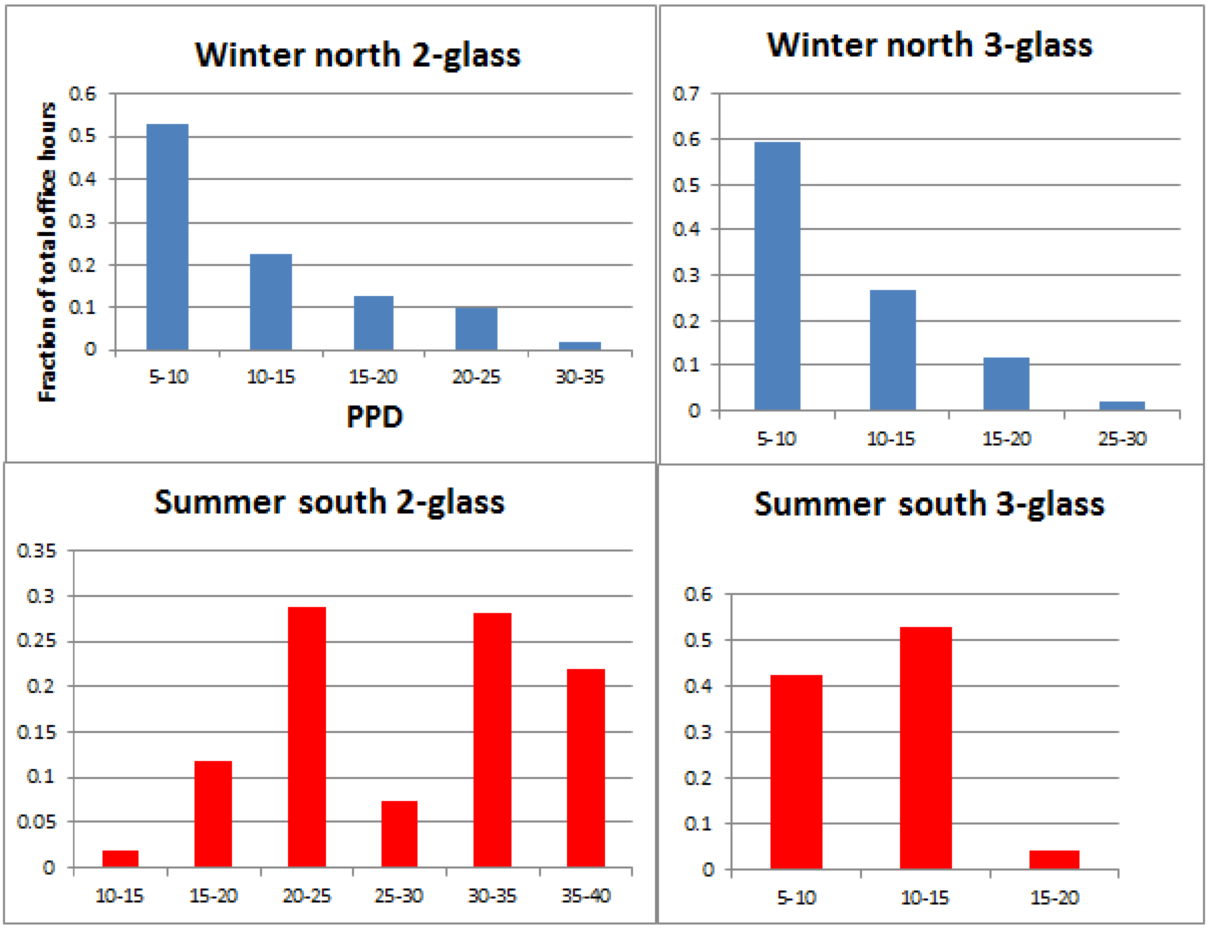

Figure 25 Worst case results – histogram representation of the same data used in round three but only for the coldest and warmest day. Note that the summer improvement mainly depends on that the cooling system capacity copes better with the lower cooling load due to external sunshade

D7 RESULTS

This case study aimed to assess the expected variability in thermal comfort performance for a future window retrofit case – **a quantification of expected spread of results**. Moreover the result **difference between internal or external sunshield** was addressed. The original target set was maximum 10 % PPD. Reconsideration in iterative rounds changed the question to: "**What PPD can we expect from a window retrofit like this**".

A quantification of expected spread of results was calculated with different tools, but subsequent analysis shows that the result depends heavily on other parameters than the window performance and the results are not good as decision support. "Round three" suggests that the positive impact, from the window retrofit, on the thermal climate in this case result in approximately 5 % predicted better odds to meet the goal of maximum 10 % PPD in the building. Still this goal is not met during about 15 % of the time and this is to a large extent during non-challenging climate conditions and hence probably not majorly window related.

The assessment of the thermal comfort **differences from use of different sunshield** was not solved with the tools used in the predetermined way. This would require good data on cooling capacity and a tool that includes both limited cooling capacity and detailed sunshade regulation modelling.

Which PPD to expect *from a window retrofit like this is probably stronger related to the climate system in the building and the regulation of it than to the window performance.*

No really reliable results regarding result spread was established. The simplified "complementing" approach to simply look at some worst case situation and the result distribution on such days based on assessed parameter variation show a large improvement for the summer case – this is however mostly due to external sunshade and corresponding improved cooling capacity compared to cooling load.

D8 CONCLUSIONS

Improvement of thermal climate due to the suggested window retrofit is expected – this is however more related to the lower cooling- and heating load together with current cooling- and heating capacity.

Note that the window retrofit will reduce energy use for heating and cooling. The cooling demand reduction can be large if external solar shading is used.

Goals and use of tools in this study

Generally, as these tools are configured today they are not easy to use to support a probabilistic approach where PPD result hour by hour is assessed with corresponding uncertainty. Simplifications, graphical analyses, sun shielding average values, limited temperature input possibilities, etc. complicates the analysis.

Building certification systems generally require a maximum value of PPD during a dimensioning situation. Such an approach does not provide information regarding how the result is spread over the year but within which boundaries – which might be seen as good enough in some cases. It is moreover probably manageable to look at the worst case climate situations and assess a spread in PPD results as in Figure 25 based on odds for each other input data. Both ParaSol and TEKNOsim seem suitable for such an approach. For other cases such e.g. passive house dwellings without comfort cooling is a worst case approach probably not acceptable. Short periods of poor thermal comfort may be accepted but not during a longer period. This would require use of more advanced tools or methods based on advanced calculations.

Recommendations

Abandon the approach to assess variations in thermal comfort during an entire year. Select suspected dimensioning locations for summer and winter cases. Consider above all:

- Rooms with relatively large window areas
- Rooms exposed to a lot of sun

- Work locations with highest/lowest air velocity considering the ventilation system
- If sun shielding can be expected to be used when necessary (manual or automatic regulation)
- Temperature settings in heating and cooling system
- To what extent is heating and cooling system expected to cope with set temperatures
- What kind clothing is expected
- Details on known thermal comfort complaints

Generally

- Include energy use and cost in the assessment
- If external sunshield may be unacceptable from an architectonic / cultural preservation point of view, consider window glass with both solar heat gain reducing and heat loss reducing properties
- Vary as few input parameters as reasonable.

D9 LEARNING OUTCOMES FROM THE ASSESSMENT PERFORMED

The case study work has generated some issues that will be discussed below in connection to each of the three main segments in the framework. Each issue will be concluded as an input to the framework if it is considered to be relevant at a general framework level.

Foremost, an unnecessary method of analysis is chosen in this study including all office hours of a year. This was partly deliberately to challenge the tools. In a real case, probably a worst case climate situation would be used. This generated some work without results, but on the other hand it provided some learning too.

Scope

The study did not really follow the framework because the window approach was set before starting. If the approach had been "how to act on thermal comfort", then perhaps the scope section would have guided this study towards another retrofit strategy. (However this study was set towards thermal comfort assessment using simple tools.)

In this case study it was necessary to iterate the scope section in "Targets (performance criteria) and consequences" reformulating the target. Moreover the collection of facts in "Existing conditions and information" was not detailed enough – an inexperienced investigator needs to iterate this section.

In this perspective the framework flowchart should have one iterative arrow embracing the scope section.

Identification of benefits and hazards

Influential parameters and their uncertainties should be addressed in this section. Three classes were introduced: design choice, varying or fixed parameters. The framework text could perhaps address uncertainties in relation to known variations. This study was performed without any clear distinction between uncertainties and known variations. **Known variations and random variations perhaps need to be addressed in the framework supporting text**.

Quantitative probabilistic analysis

Large efforts in this study were spent on working with the PPD tools and learning what they could deliver. In the section "Method of analyses" it was difficult to set up a clear strategy not knowing the functions of the software's.

Define probabilities: Especially the approach *how large room area will fall within the goal* was a bad idea which hid valuable information. **Mistakes like this might be counteracted in the framework including an underlining to keep data transparent.** Moreover, the "define probabilities" section has no guiding text in the framework and the user may interpret this as probability for a specific scenario or probability for specific states of influential parameters. **A clear definition of terminology could facilitate the framework interpretation.**

Second evaluation of the results: In this study, an unrealistic result was reached in the firsts run. This was obviously not useful. But what if the figures would have looked reasonable – would they then have been trusted, possibly for the wrong reasons? **The framework could include a further underling on the importance of result evaluation.**

Framework feedback conclusions

- The framework supported the process and if it had been followed better it would have supported the process further
- The framework flowchart can be complemented with one iterative arrow embracing the scope section
- There could be a framework text underlining to keep data transparent
- The framework should include a further underling on the importance of result evaluation.
- Known variations and random variations could be clarified in the framework supporting text.
- A clear definition of terminology could facilitate the framework interpretation.

E. Risk Assessment on External Wall Retrofit – Interior Supplementary Insulation

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E1 INTRODUCTION

E1.1 Purpose

In total there are about 2.44 million apartments in Sweden, of which more than half were are constructed between 1950-75 (VVS-Företagen 2009). About 20% of the apartments are owned by non-profit housing corporations (Statistiska 2010).The rate of retrofitting measures in non-profit housing corporations in Sweden is 11000 apartments a year, which corresponds with 3-4% of the estimated number of apartments in need of measures (Jardfelt 2010). If the same ratio is applied on the entire number of apartments, approximately 1.6 million apartments of the buildings in Sweden are in need of some retrofitting measure.

A major concern when improving the performance of the building is the moisture safety. About 1/3 of the buildings in Sweden have a moisture related damage which may have an effect on the indoor air quality, IAQ (Boverket 2010). The moisture damages are usually a result of falsely design in the technical solution. Today these buildings require new and adapted technical solutions suitable for the present conditions and the new demands of energy use.

Critical moisture levels in building materials of the building envelope increase the risk of deteriorated IAQ which has a negative effects on the human health (Nielsen 2002). In terms of moisture safety, several concerns arise when choosing the most suitable technical solution for a retrofitting measure. The challenge is to find a solution with a low risk of future moisture related problems or damages. In addition to knowledge and expertise, such analysis requires a holistic view in order to estimate the hygrothermal impact when retrofitting the existing building envelope or part of it.

The concerns of finding low risk solutions are also of great interest on an international level. In the spring of 2010 an annex within the International Energy Agency, IEA started with the title Reliability of Energy Efficient Building Retrofitting. The main mission of the annex is to come up with answers to the question; *How do we design and realize robust retrofitting with low energy demand and life cycle costs, while controlling risk levels for performance failure?*

E1.2 Framework for Probabilistic Assessment

The procedure of the risk assessment in this study is performed with the application of the risk analysis process presented in Figure 26. The process is a modification of a probabilistic approach intended for technological system that was presented in the doctoral thesis of Katarina Ljungquist (Ljungquist 2005). The modified analysis process has been developed to facilitate the probabilistic assessment of various issues in building physics design such as energy performance, moisture durability, thermal comfort or IAQ(Sasic Kalagasidis and Rode 2011).

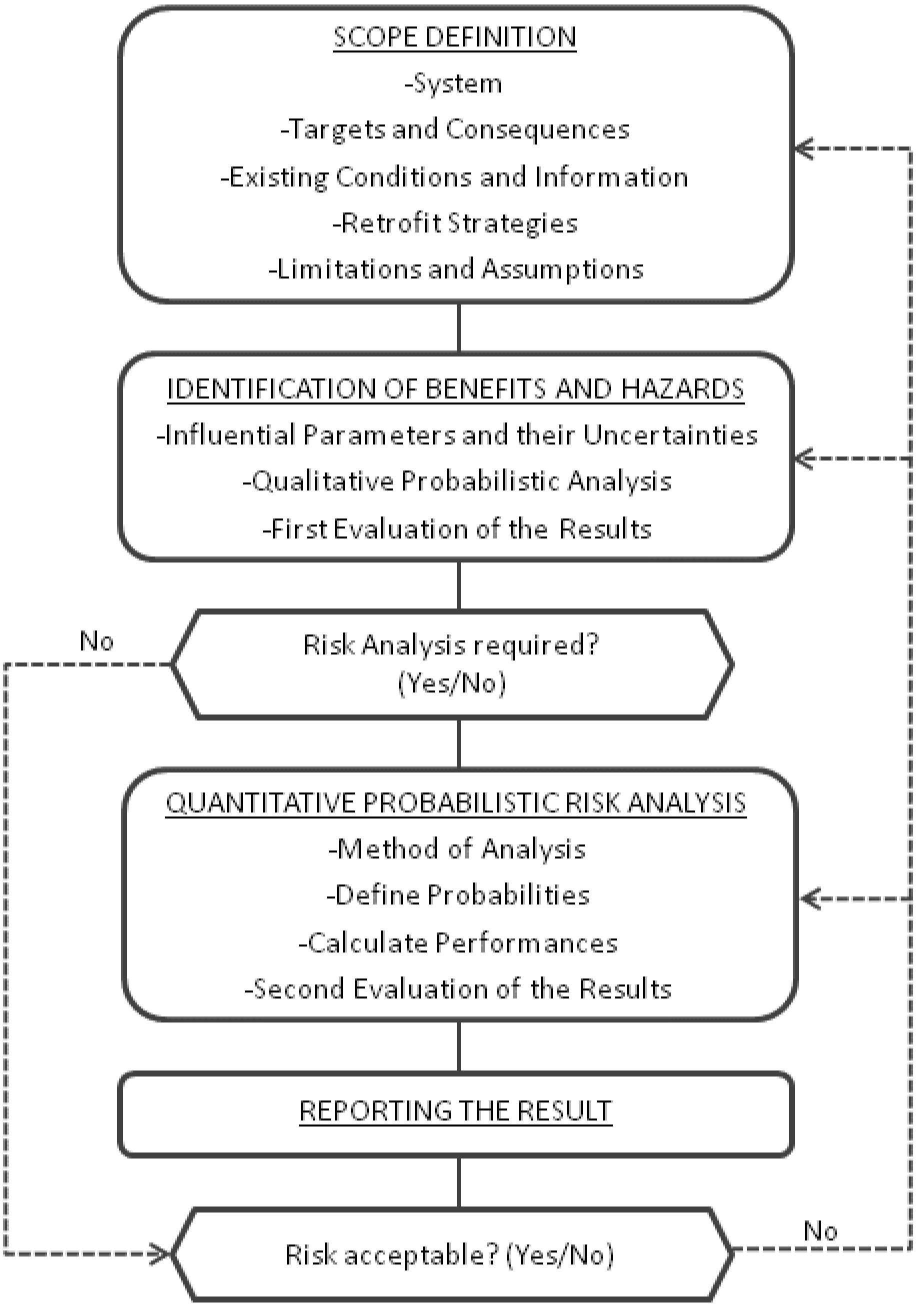

Figure 26 A Risk analysis process developed to facilitate the probabilistic assessment of various issues in building physics design such as energy performance, moisture durability, thermal comfort or IAQ (Sasic Kalagasidis and Rode 2011). The dashed lines with arrows indicate possible by-passes or throwbacks based on the decisions made during the analysis process.

The analysis process presented in Figure 26 initiates with a *Scope Definition*. In this section the main purposes of the retrofitting measures are defined. The *System* describes the spatial scale of the project; the wall, the roof or the whole building envelope. *Targets and Consequences* are the performance criteria of the analysis. What are the concerns; energy performance, moisture performance, IAQ, total cost of the project, and/or costs of operations? What are the consequences if the targets are not fulfilled? *Existing Conditions* and *Retrofitting Strategies* reflect on the motives concerning the choice of retrofitting strategy. What are the alternatives for retrofitting based on available information of the existing building or parts of it? *Limitations and Assumptions* announce what is assumed to be included in the analysis, premises and what will not be comprised in the study.

The section of *Identification of Benefits and Hazards* is basically the procedure of performing a qualitative probabilistic analysis. Hazards and consequences of the Retrofit are determined in *Influential Parameters and their Uncertainties*. Simple analysis methods may apply such as Fault tree and Event tree analyses, FMEA, VMEA, HAZOP[17] etc. The identification is followed by a *Qualitative Probabilistic Analysis* where the benefits are compared with the consequences. The purpose is to gather an in-depth understanding of the interaction between the hazards and the uncertainties. The result of the first analysis is presented in *First Evaluation of the Result* where also decisions on the necessity of further analyses are made. Is the result dependable and applicable; what are the options?

If required, a *Quantitative Probabilistic Analysis* is performed. The Performance indicators are defined with the purpose of facilitating the evaluation of the result. What are the options and methods for the analysis; computer simulations of future hygrothermal performance, uncertainty analysis with Monte Carlo and/or sampling methods? In *Define Probabilities* the stochastically varying input parameters are presented together with their distributions and uncertainties follow by *Calculate Performances* where a complete quantitative probabilistic analysis is executed. Finally, the result is evaluated and the reliability is checked. Sensitivity analyses of the performance criteria or the input parameters and their influence on the outcome of the results. All efforts are reported.

In *Reporting the Result* the products of the risk analysis are presented. Consequences are compared with the Performance indicators and predefined concerns. Discussions and recommendations on further analyses are made and suggestions on possible alternatives of redirecting. Ultimately a decision is made on the acceptance of the risk.

E2 SCOPE

An existing outer wall is to be retrofitted. Due to preserving interests of the existing façade the outer wall must not be affected by the intended measures. The wall is completely solid and with no empty compartments hence any improvement of the inner wall structure is not possible. Consequently, retrofitting measures must be constructed from the inside of the wall if an improvement of the thermal performance is to take place.

[17] FMEA stands for Failure Modes and Effects Analysis, VMEA - Variation Modes and Effects Analysis, HAZOP – Hazard and Operability Study

E2.1 System

The purpose of this study is to make a risk analysis of a technical solution designed for a retrofitting measure in an existing outer wall. No consideration to adjacent parts of the building will take place in the analysis other than the building materials which are included in the structure of the wall. The results of the analysis will be based on stochastically varying parameters such as the weather, the indoor moisture production and the ventilation system.

E2.2 Targets and Consequences

The intention of the retrofit is to improve the thermal performance and to construct a durable and moisture resistant wall structure. It is of great concern to create a technical solution which enables a satisfying interaction between the supplement of building materials and the existing wall.

Concerns of the retrofit are potential changes in air movements coupled to the flow of heat and moisture. The impact on moisture safety and the Indoor Air Quality, IAQ is also of interest.

E2.3 Existing Conditions and Information

The thermal performance of the existing wall is not acceptable hence a retrofitting measure of the wall is requested if the net energy demand during heating season is to be decreased. The chosen retrofitting measure must be applicable on common residential buildings in Scandinavia based on interior impact only due to the preserving interests of the façade.

E2.4 Retrofit Strategies

Four alternatives of interior retrofitting are presented in Figure 27. Each alternative is either recommended by a manufacture or documented as an actualized technical solution. The alternatives differ in the structure of the existing wall and in the technical solution of the interior supplementary insulation as following;

Alternative *A*: An existing massive concrete or masonry wall. The supplementary insulation is supported with a timber framework. The insulation material is glass wool and with a thickness of 95mm. A gypsum board is attached to the framework facing the inside followed by an application of a wall paper Sjöberg and Wichlay 2007).

Alternative *B*: Same as in *A* but the existing external wall is instead a timber framed wall with intermediate glass wool insulation. A vapour retarder is assumed to be present on the inside of the existing wall between the timber framework and the gypsum board (Paroc 2009). The vapour retarder is assumed to be in satisfying condition.

Alternative *C*: An existing massive concrete or masonry wall. Cellular plastic boards with a thickness of 55mm are fastened with glue, screws and nails on the inside of the existing wall. Subsequently, the boards are rendered with a primer followed by a cement-based paste, wallpaper or acrylic latex paint (Paroc 2009).

Alternative *D*: Same as in *C* but the existing external wall is instead a timber framed wall with intermediate glass wool insulation.

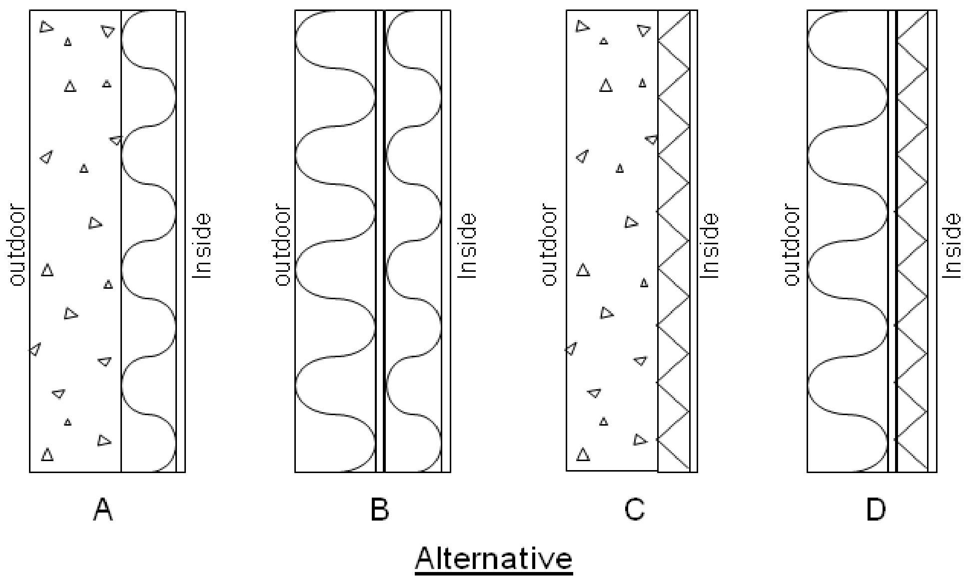

Figure 27 Four recommended alternatives of retrofitting measures are presented in a simple section drawing. The intention of the retrofit is to increase the thermal resistance of an existing outer wall by an interior supplementary insulation. Alternative A and C have an existing massive concrete or masonry wall. Alternative B and D have an existing timber framed wall. The alternatives are either retrofitted with glass wool insulation or with cellular plastic.

Alternative *B* is chosen to be investigated further based on available information from the manufacture (Paroc 2009). The details of the recommended retrofitting measure of alternative *B* are presented in Figure 28. An existing timber framed wall with an insulation thickness of 120mm is supplemented with a new timber frame. The intermediate insulation of the new frame has a thickness of 95mm. In between the two frames are also an existing vapour barrier and a gypsum board.

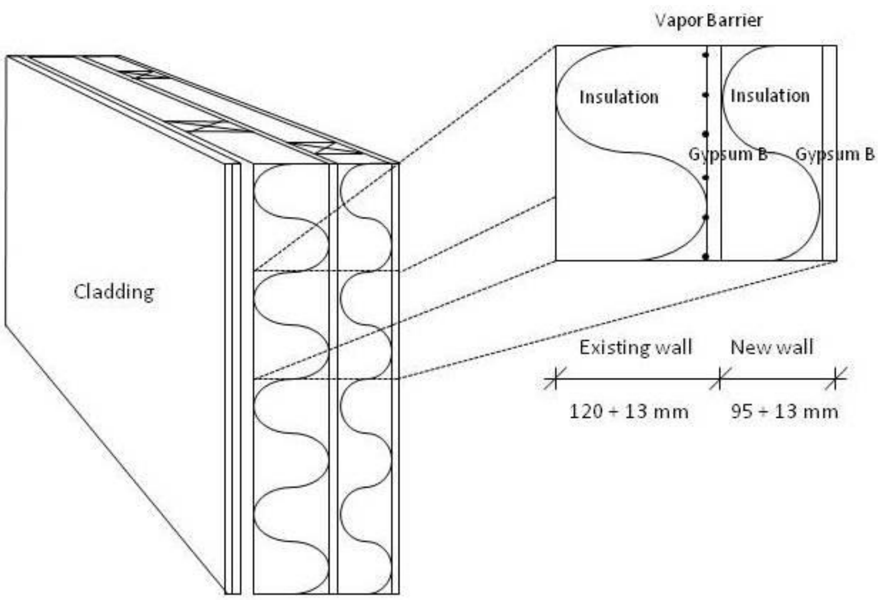

Figure 28 The technical solution of the recommended retrofitting measure of alternative B will be analysed further. The existing outer wall consists of the following building material; Cladding, a timber frame with intermediate insulation (120mm), vapour barrier and a gypsum board. The new wall which is to be constructed onto the gypsum board consists of the following; a timber frame with intermediate insulation (95mm), a gypsum board and wall paper.

E2.5 Limitations and Assumptions

The retrofitting measures will be analysed in the climate of Gothenburg, Sweden and is assumed to be applied in residential buildings.

The condition and function of the existing building materials are considered to be acceptable. Existing building materials will be replaced if not fulfilling any of these criteria.

The new wall is assumed to be constructed with satisfying workmanship.

E3 IDENTIFICATION OF BENEFITS AND HAZARDS

E3.1 Influential Parameters and their Uncertainties

The types of hazards which are to be identified are governed by the consequences of interests. An unwanted consequence is mould growth in building materials. The development depends on the nutrients in the building material, the temperature, the relative humidity, RH and the fluctuation and exposure time (Viitanen 2001; Johansson, Samuelson et al. 2005).

A Fault Tree Analysis, FTA is suitable for the determination of hazards when a consequence is defined. In this study the top item in the FTA moreover the consequence, is defined as mould growth in any part of the new or the existing wall. The result of the FTA is presented in Figure 29.

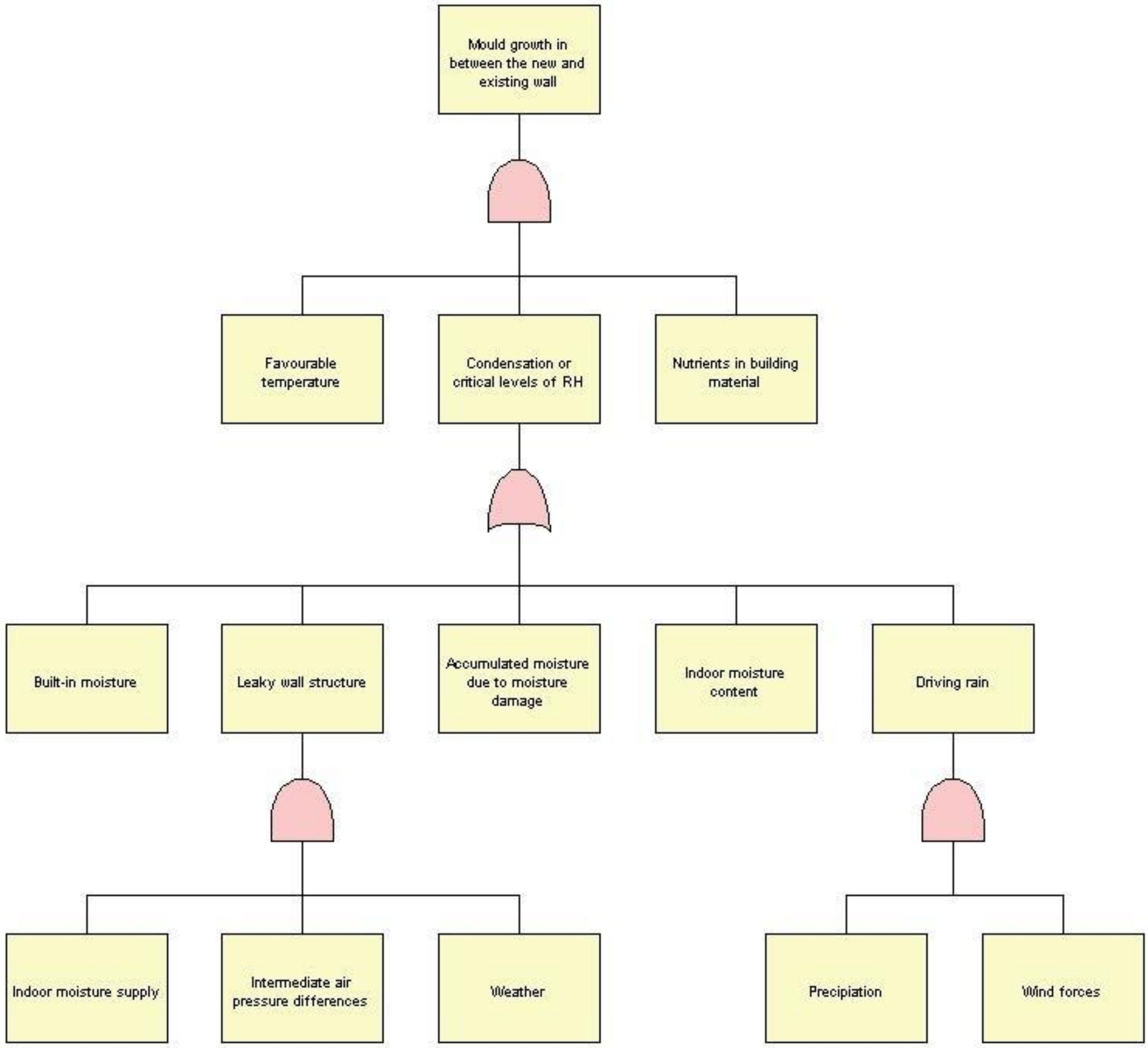

Figure 29 A Fault tree analysis of the risk of mould growth when performing a retroffiting measure of an existing outer wall. The lowest box of each branch corresponds with a defined hazard.

Some of the most common hazards concerning the risk of mould growth in an outer wall are defined in Figure 29. The hazards are moisture content of the outdoor air, precipitation together with wind forces and the indoor moisture supply. Further, a leaky wall structure may result in intermediate air movements hence hazards of such sub-consequence are air pressure differences and the moisture content of the infiltrated air. Accumulated moisture of the existing wall and built-in moisture are also hazards. If the workmanship and the inspection prior to the retrofit are assumed to be satisfying, the influence of these hazards may be neglected.

When performing a retrofit of residential buildings a common hazard is the indoor moisture supply. This hazard depends on the type of dwelling, moisture generative appliances and installations, ventilation rates and the user behaviours of the tenants. Further, the weather consists of several hazards, the moisture content of the outdoor air, precipitation together with wind forces. Also built-in moisture from the building materials is considered as a hazard (Ingemar Samuelson 2007).

In conclusion, based on the FTA the two most decisive paths of the retrofit of an existing wall are basically moisture transfer due to forced or natural convection and diffusion.

E3.2 Qualitative Probabilistic Analysis

The positions of former thermal bridges in the existing wall have an increased risk of critical intermediate moisture levels post retrofit. In the direction of the heat loss, the most critical positions are assumingly where the studs of the existing wall connect with the insulation of the supplementary wall, see Figure 30. In this area the building materials will have a lower mean temperature during the heating season prior to the retrofit, consequently decreased level of moisture acceptance.

Critical positions will most likely be very common due to a shift in the placement of the existing and new frameworks. The reason behind the recommendation of a shift between the studs of the two frameworks is to avoid thermal bridges. In Figure 31, the manufacture describes how the thermal bridges are to be prevented by changing the placement of the studs (Paroc 2009).

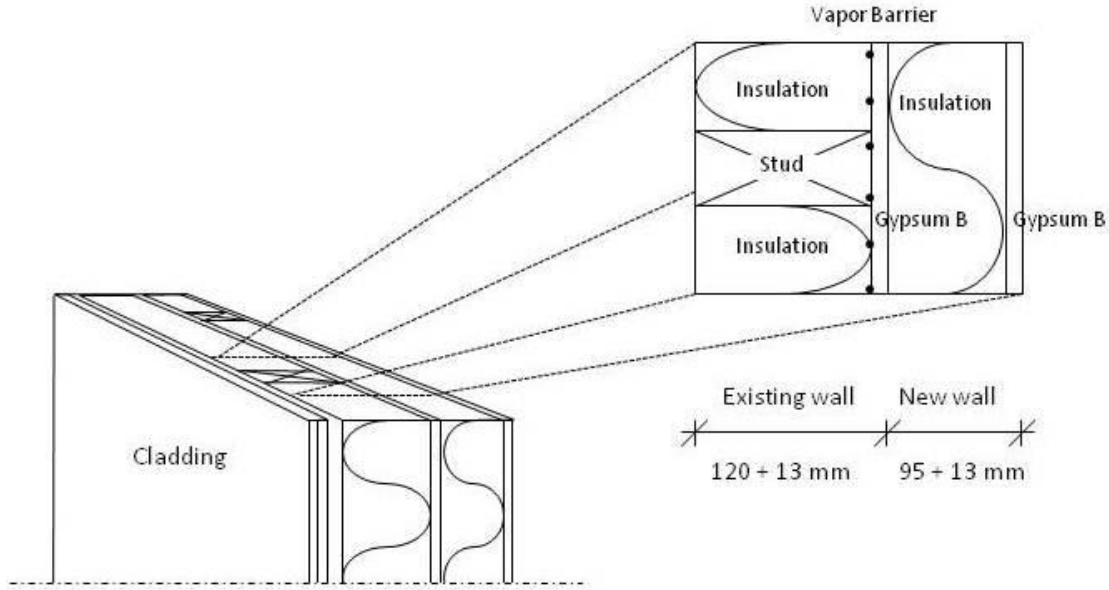

Figure 30 Critical positions due to moisture safety. Naturally, a thermal bridge exists in the positions of the existing wall studs. The supplementary insulation decreases the heat loss but also decreases the temperature in this position compared to prior the retrofit. A vapour barrier is located in between the studs and the gypsum board. This water vapour resistance together with a lower average temperature may increase the risk of critical moisture levels in the materials close the inner side of the barrier.

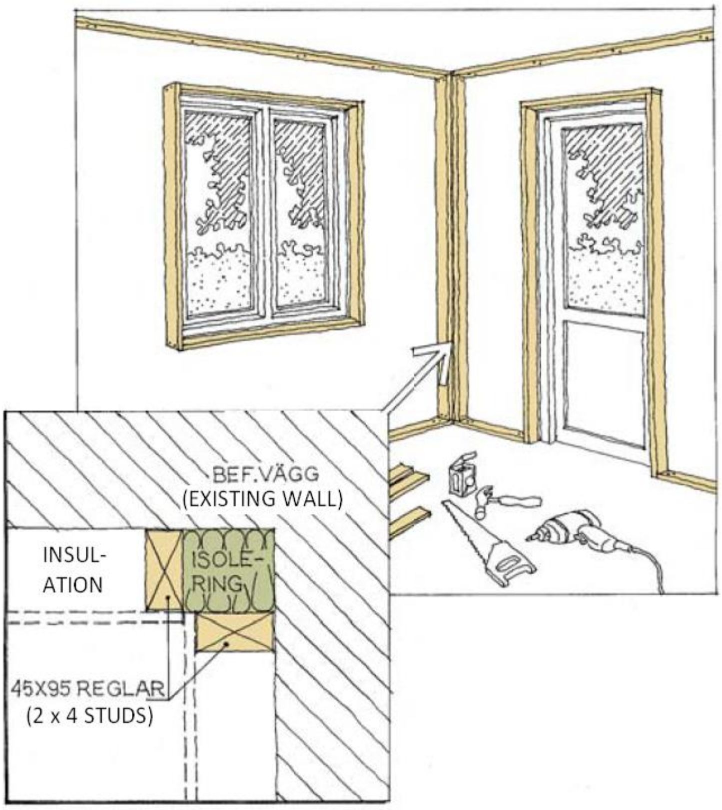

Figure 31 A timber framework is mounted on the inside of the existing wall and insulation is positioned between the studs. A shift in the placement of the new studs compared to the present framework is recommended in order to prevent thermal bridges during heating season (Paroc 2009).

An additional aspect that will affect the function and future performance of the retrofitting is possible air movements inside the wall. The timber used as building material will shrink, bend and crack depending on moisture content, temperature, quality of the material and the applied load (Breyer, Fridley et al. 1998). These movements will force the wall and its component to change in dimension and position. A plausible scenario is that minor air channels will exist between the existing and new wall structure due to these movements. The magnitude of the air channels is likely to depend on the condition of the existing wall, the properties of the new building material and the workmanship of the construction.

E3.3 First Evaluation of the Results

The FTA is a method used to identify hazards of a consequence. Unfortunately, the method does not result in any ranking of the most decisive hazards. A further analysis is required if such information is needed.

A rather extensive part of the retrofitted wall consists of the new supplementary wall. Subsequent to the retrofit the existing vapour barrier is located almost in the middle of the wall structure. There is a known risk of critical moisture levels in building materials if a vapour barrier, thus the moisture resistance, is placed too deep into the building envelope. Except from the properties of the building materials, the risk will mainly depend on the excess of moisture and the temperature gradient between the inside and the outside of the wall. The most critical position of the retrofitting measure due to moisture safety is assumingly in the existing gypsum board next to the inner side of the vapour barrier, see right-hand illustration in Figure 30. During the heating season this area will have a lower mean temperature post retrofit thus lower dew point temperature and moisture acceptance.

The recommended retrofitting measure with interior supplementary insulation has assumingly a high risk of mould growth and rot compared to prior the retrofit. The existence of these unwanted consequences will have a great effect on the present and future performance of the building envelope. The probabilities of these consequences are difficult to estimate based on existing knowledge and experience. In order to make decisions on the future performance and cost a Quantitative Probabilistic Analysis is recommended. A Sensitivity Analysis is also of interest if evaluating the options and needs of improvement.

E4 QUANTITATIVE PROBABILISTIC ANALYSIS

The relative humidity, RH is a potential performance indicator when analysing the risk of mould growth in building materials post retrofit. Moreover, the critical relative humidity, RH_{crit} defines favourable levels of growth which is a function of the temperature, described in (Hukka and Viitanen 1999). The relation between the RH and the RH_{crit} can be defined as the mould growth potential, *m* (Hagentoft, Sasic Kalagasidis et al. 2008)

$$m = \frac{RH}{RH_{crit}} \qquad (1)$$

Consequently values of *m* greater or equal to 1 are considered as favourable conditions of mould growth.

Another performance indicator is the Mould Growth Index, MGI which is based on both RH_{crit} , the fluctuation and exposure time. The MGI classifies a surface due to the development of mould based on a scale from zero to six. The value of zero defines no mould growth and the value of six defines a completely covered surface with heavy and tight mould growth (Viitanen 2001).

The values of the MGI are based on the following formula (Ojanen, Peuhkuri et al. 2011);

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02)} \cdot k_1 \cdot k_2 \qquad (2)$$

where M = Mould index

t = Time, [h]

T = Temperature, [°C]

W = Timber species (0 = pine and 1 = spruce)

SQ = 0 for other materials than wood

$k_1 = 0.53$ for M<1 and $k_1 = 0.18$ for M>1 (Paper, surface material of a gypsum board)

and

$$k_2 = \max[1 - \exp[2.3(M - M_{max})], 0] \qquad (3)$$

where

$$M_{Max} = 0.3 + 6 \cdot \frac{RH_{crit} - RH}{RH_{crit} - 100} - \left(\frac{RH_{crit} - RH}{RH_{crit} - 100} \right)^2 \qquad (4)$$

for sensitivity class = s.

During unfavourable conditions of mould growth the following degradation is expected (Ojanen, Peuhkuri et al. 2011);

$$\frac{dM}{dt} = \begin{cases} -0.00133 \ \text{for} \ t - t_1 \le 6h \\ 0 \ \text{for} \ 6h \le t - t_1 \le 24h \\ -0.000667 \ \text{for} \ t > 24h \end{cases} \qquad (5)$$

E4.1 Method of Analysis

A model of the retrofitting solution described in Figure 28 and Figure 30 is created in HAM-tools. The software works with Simulink® and is specially constructed to simulate heat and mass transport in building and building components in operating conditions (Sasic Kalagasidis 2004).

The critical position of the retrofitted wall is assumed in the direction along the existing studs and the supplementary insulation, see left-hand plan drawing in Figure 32. The simulation model has been designed to represent this critical path of heat and mass transport.

The model is created as an outer wall facing north and consists of the following layers of material;

Existing wall:

- Cladding (wood panel) 22+22 mm
- Timber frame 120 mm
- Vapour Barrier
- Gypsum Board 13 mm

New wall:

- Insulation 95 mm
- Gypsum Board 13 mm
- Wall paper

An additional model has been created to simulate the scenario of a 3mm air channel between the new wall and the adjacent building components. The air movements inside the channels are driven by pressure differences due to variations in temperature along the channels and the inner environment. The right-hand section drawing of Figure 32 demonstrates possible positions and directions of the movements caused by air pressure differences.

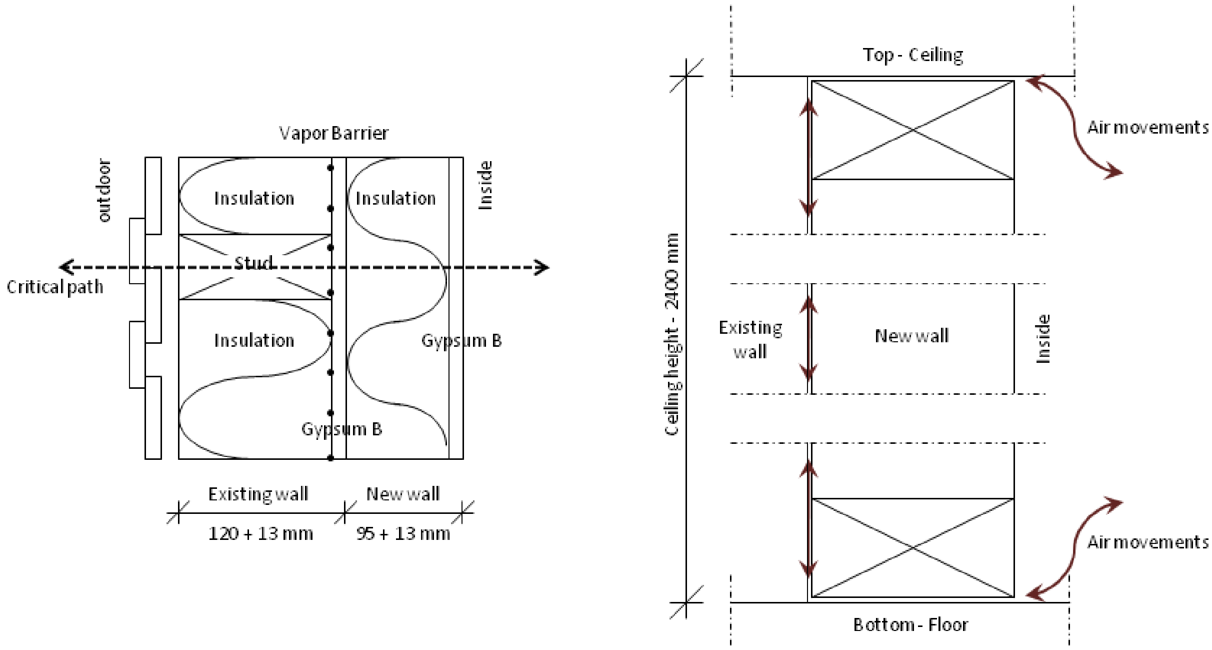

Figure 32 The left-hand plan drawing illustrates the critical path of the retrofitted wall. During the heating season, the area between the wooden stud and the existing gypsum board are likely to have a decreased temperature compared to prior the retrofit. The right-hand picture illustrates a section drawing of the simulated wall. The two-headed arrows demonstrate possible positions and directions of air movements.

A stochastic distribution of the performance indicators is obtained by making multiple iterations of simulations with varying parameters. In this study the varying parameters are the weather, the indoor moisture production and the ventilation rate. Prior to the start of each simulated year the varying parameters used in the model are randomly chosen. The input data used in the model is based on both measurements and simulations.

E4.2 Define probabilities

The weather data consists of 44 simulated years of the climate of Gothenburg, Sweden (Nik 2010). The data is presented in hourly variations of the weather i.e. precipitation, solar radiation, wind velocity, temperature and relative humidity.

The ventilation rates used in the model are based on measurements made in 417 apartments in Sweden from 2008 to 2009 (Boverket 2009). The measurements were performed during two weeks in each apartment and the type of ventilation system varied from natural ventilated to mechanical exhaust and supply systems. Figure 33 presents a distribution of the mean air exchange rate during the measured period in each apartment. The ventilation rates were measured using a trace element technique (Boverket 2010).

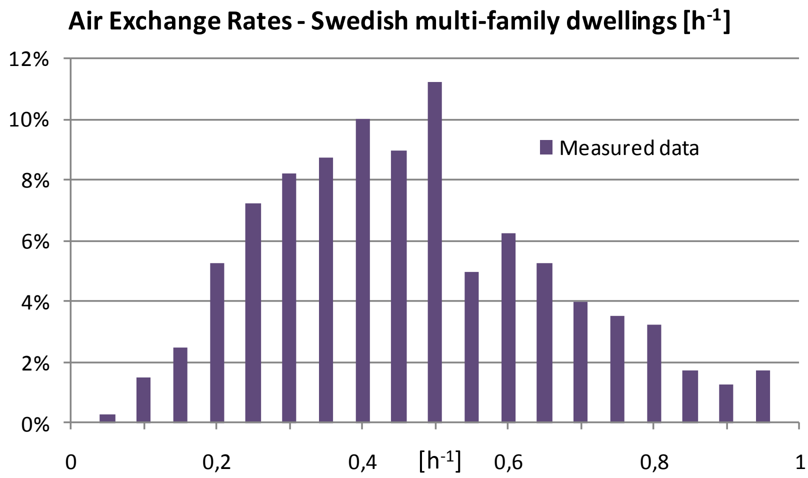

Figure 33 The variation of the mean air exchange during the period of two weeks in 417 multi-family dwellings in Sweden .The distribution is obtained from measurements using a trace element technique(Boverket 2010).

The input data of the moisture production is based on simulated hourly distributions from earlier studies (Johansson, Pallin et al. 2010; Pallin, Johansson et al. 2011). In the simulation model of the indoor moisture production the compositions of Swedish households is determined using statistics regarding the type of dwelling, number of family members and the incidences of household appliances and installations. The probability of each constellation is obtained by comparisons with statistical information. Furthermore, for each household the user behaviour, the occurrence and expected duration of moisture productive activities is simulated. This information is then combined with expected moisture production rates from measurements of typical residential moisture sources. The result of the simulations is stochastic variations of the hourly indoor moisture production in Swedish dwellings (Pallin, Johansson et al. 2011). A distribution from 1000 simulated Swedish households is presented as annual averages of the indoor moisture production in Figure 34.

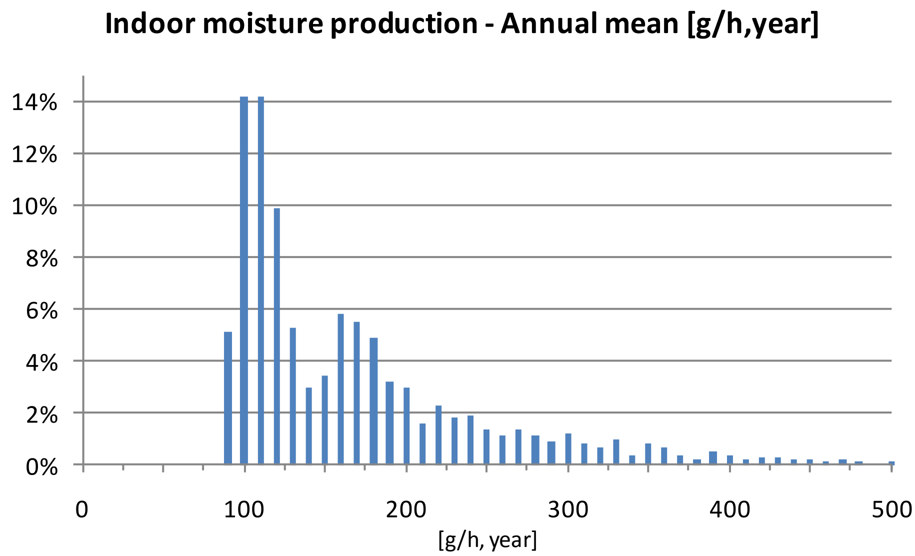

Figure 34 The distribution of the annual mean of indoor moisture production rate per hour from 1000 independent years of simulations. The result from the simulations corresponds with housholds in Swedish multi-family dwellings.

The simulation model of this study is programmed to choose a constellation of the input data for each run of simulated year. Subsequently the program chooses another constellation for the next simulated year and continues until the requested number of iterations has been executed.

Stochastic distributions of the performance indicators are of interest. These distributions are obtained by making 500 iterations of annual simulations. For each year, the simulation program chooses between 44 years of weather data, 417 values of ventilation rates and 500 different years of hourly moisture production rates. These three parameters are uniformly chosen though their distributions within the data are based on their probabilities of incidence; see Figure 33 and Figure 34.

E4.3 Calculate performances

The position between the existing gypsum board and the supplementary insulation is assumed a critical position in the retrofit of this study, see section 0. The results presented of the quantitative probabilistic analysis are simulated moisture conditions of this area post retrofit.

The annual average of RH is a performance indicator which gives an estimation of the moisture conditions in a position of interest. Unfortunately it doesn't provide any information of the fluctuation or the duration of the levels of RH. However, an annual average of RH is useful when comparing different simulated years.

The probability density function of 500 simulated years is presented in Figure 35, where the stochastic variations represent the annual average of RH in the inner part of the existing gypsum board. There are two different scenarios, with or without an assumed air leakage channel as described in Figure 32. The two distributions are somewhat shifted. The scenario with assumed air leakage channels has higher values of annual RH thus a higher risk of mould growth. 43 percent of the simulated years in the scenario of an assumed air leakage channel between the existing and the supplement wall have an annual mean of RH greater than 80 percent. In the scenario of no air leakage the corresponding value is 32 percent.

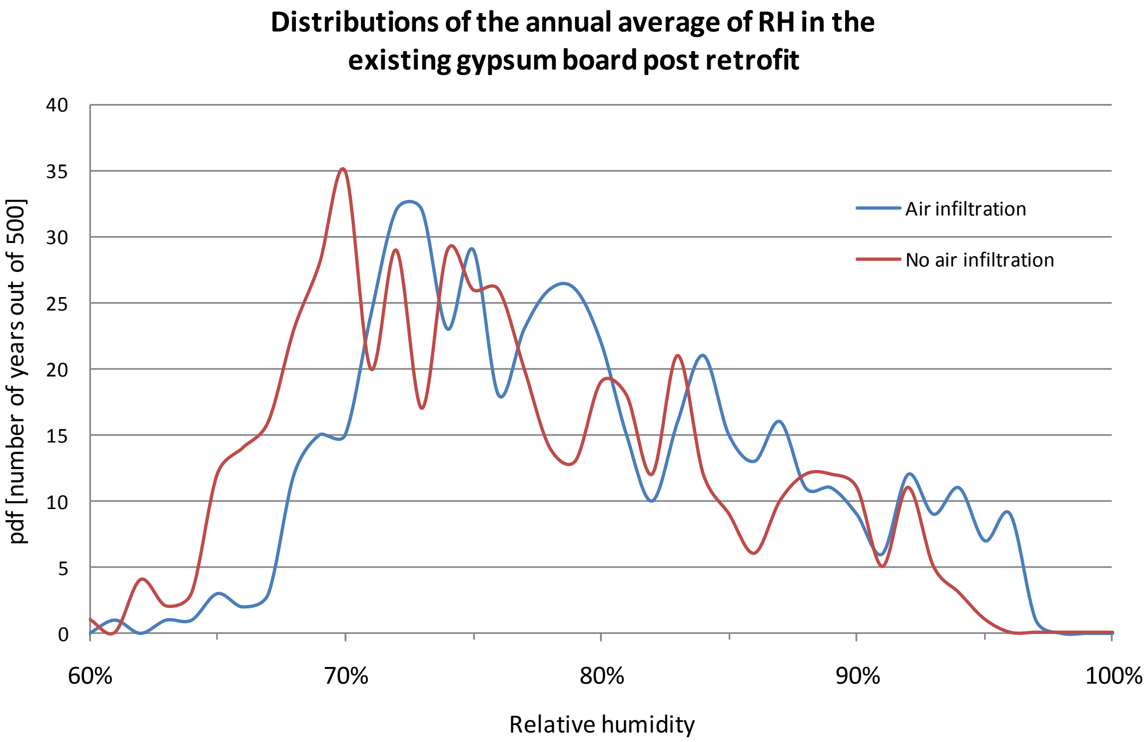

Figure 35 Probability density functions of the annual average of the RH in the gypsum board between the existing and the new framework of the retrofitted outer wall. The simulated distributions are a result of 500 simulated years in the climate of Gothenburg. The red curve represents the distribution with no air leakage channel between the existing and new wall and the blue curve represents the distribution with an assumed air leakage channel of 3mm. The critical level of RH due to mould growth at temperature greater than 15°C is at 80 % (Hukka and Viitanen 1999).

The result from 500 independent simulated years due to MGI is presented in Figure 36. Each distribution in the Figure corresponds with the annual progression of MGI on the inner surface of the Gypsum board starting after the completion of the retrofit. The distributions represent the scenario of an evenly distributed air leakage channel of 3mm between the existing and newly constructed wall.

In Figure 37 five different curves of the progression of MGI are presented in percentiles varying from 10, 25, 50, 75 and 90.

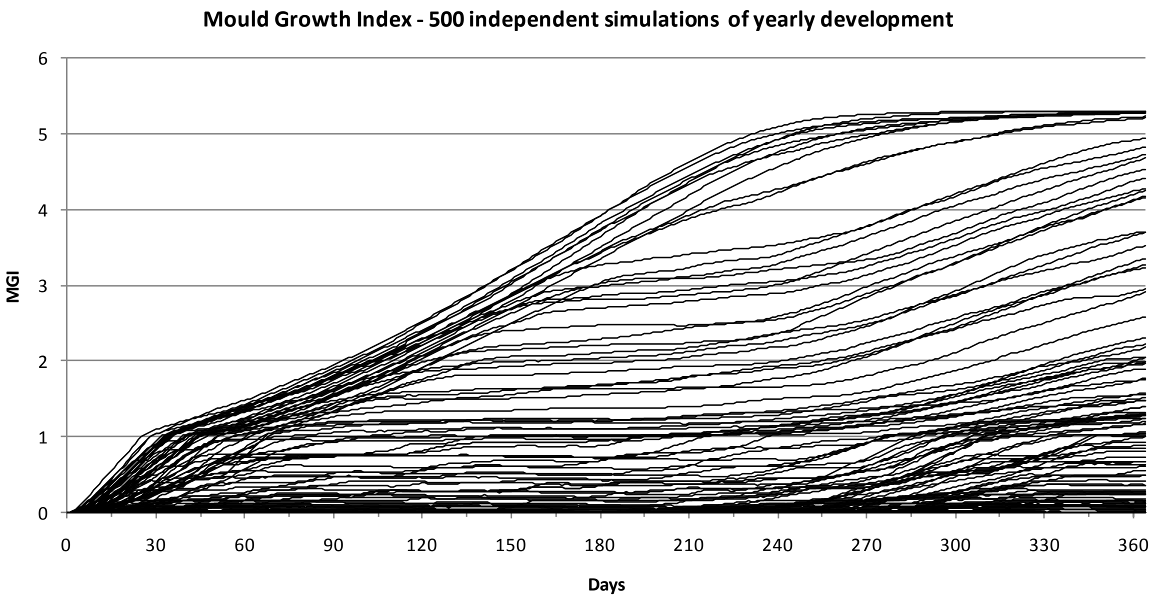

Figure 36 The annual progression of mould growth on the inner surface of the existing gypsum board post retrofit, next to the supplementary insulation. The distributions represent the result from 500 independent simulations and with an assumed air leakage channel of 3mm between the existing and newly constructed wall.

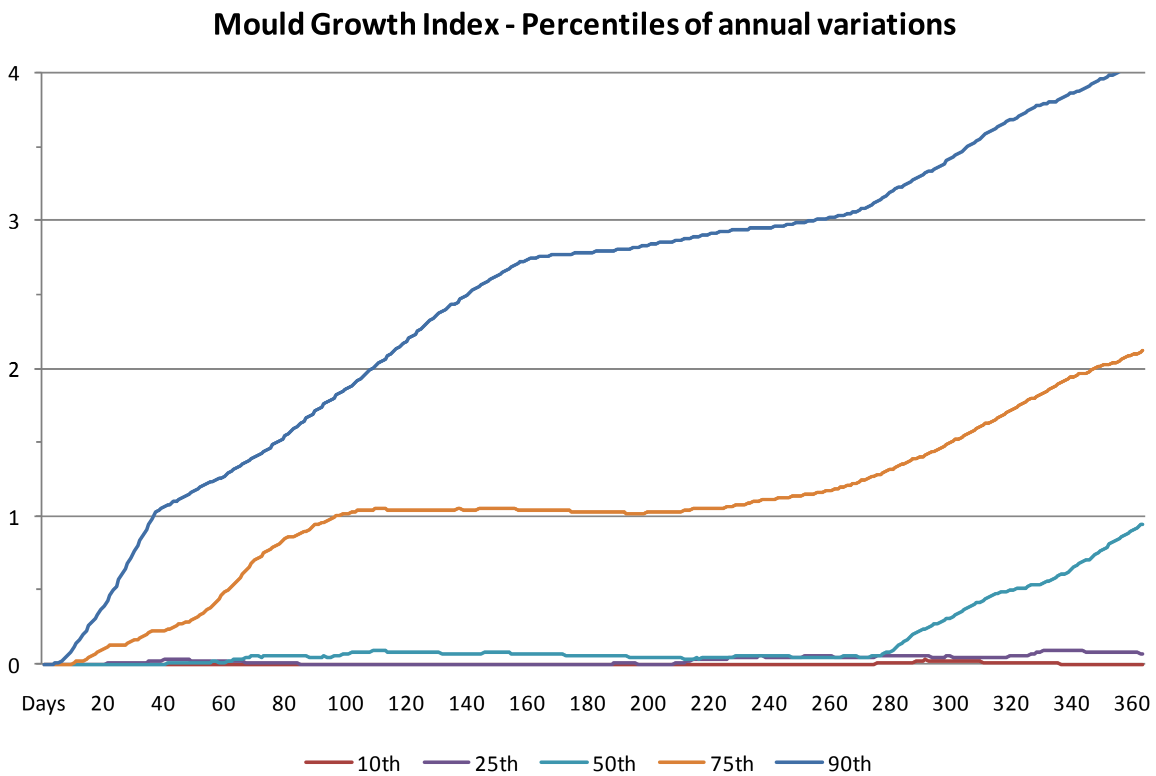

Figure 37 Five different annual progressions of mould growth on the inner surface of the existing gypsum board post retrofit, next to the supplementary insulation. The five progressions of MGI represent the percentiles of 10, 25, 50, 75 and 90 from 500 simulated years. The result corresponds with the scenario of an assumed air leakage channel of 3mm between the existing and newly constructed wall.

The chosen performance indicators of this study are the RH, the mould growth potential, *m* and the MGI. Depending on the selected indicators, the results are likely to be perceived and interpreted differently. An option of determining the correlation between the indicators is to perform a Spearman's ranking correlation r_s (Bedford 2001)

$$r_s = 1 - \frac{6 \cdot \sum \Delta R^2}{n(n^2 - 1)} \qquad -1 \le r_s \le 1 \qquad (6)$$

where ΔR is the difference in ranking between the two correlated variables. (In this case the performance indicators.)

n is the sample size.

Values of r_s close to 1 or -1 indicate high correlation between the compared indicators and values close to zero indicates low correlations.

In this study 500 simulated years have been analysed according to Spearman's ranking correlation and between the chosen performance indicators. Each simulated year is ranked with a number. The ranking starts with the value of 1 for the simulated year with the lowest risk and ends with the highest value of 500 for the year with the highest risk. The RH has been ranked based on the annual mean hence the simulated year with the lowest annual mean of RH has received the ranking value of 1. The *m* has been ranked based on the number of hours with favourable conditions of mould growth and the MGI has been ranked due to the annual mean of the progression.

Three different comparisons are presented in Figure 38 to Figure 40. In each figure two different performance indicators are compared. The linear line corresponds with the performance indicator which the second indicator is compared with. Consequently the nonlinear distribution represents the ranking of the second performance indicator at the corresponding ranking of the first indicator.

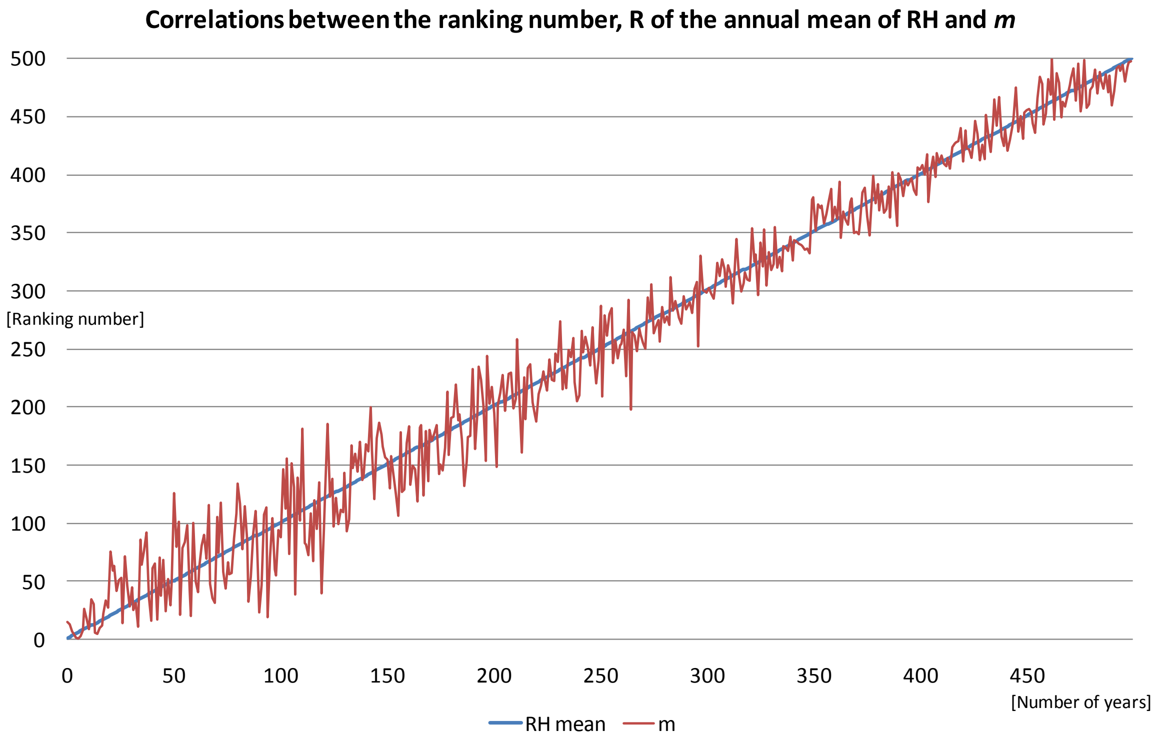

Figure 38 A comparison between the Spearman's ranking value, R of the annual average of the relative humidity and the number of hours with critical relative humidity due to mould growth, m. The blue line corresponds with the ranking of the RH and the red line represents the ranking of the number of hours with favourable conditions for mould growth at the corresponding year.

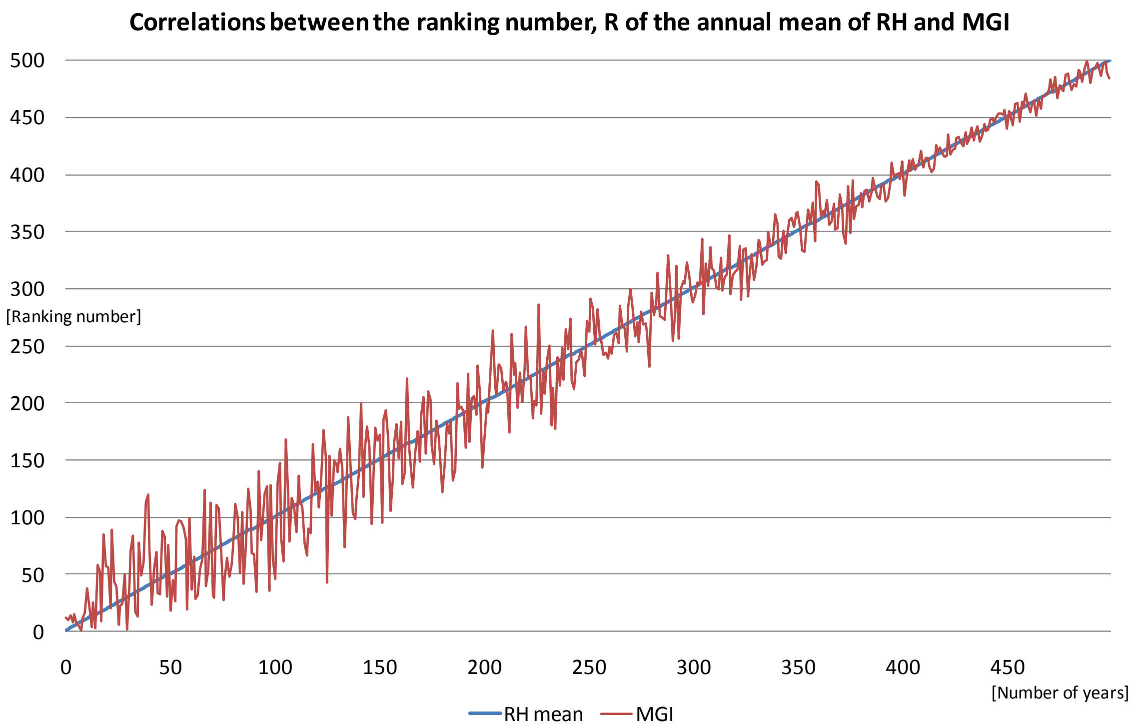

Figure 39 A comparison between the Spearman's ranking value, R of the annual average of the relative humidity and the MGI. The blue line corresponds with the ranking of the RH and the red line represents the ranking of MGI due to the annual mean of progression at the corresponding year.

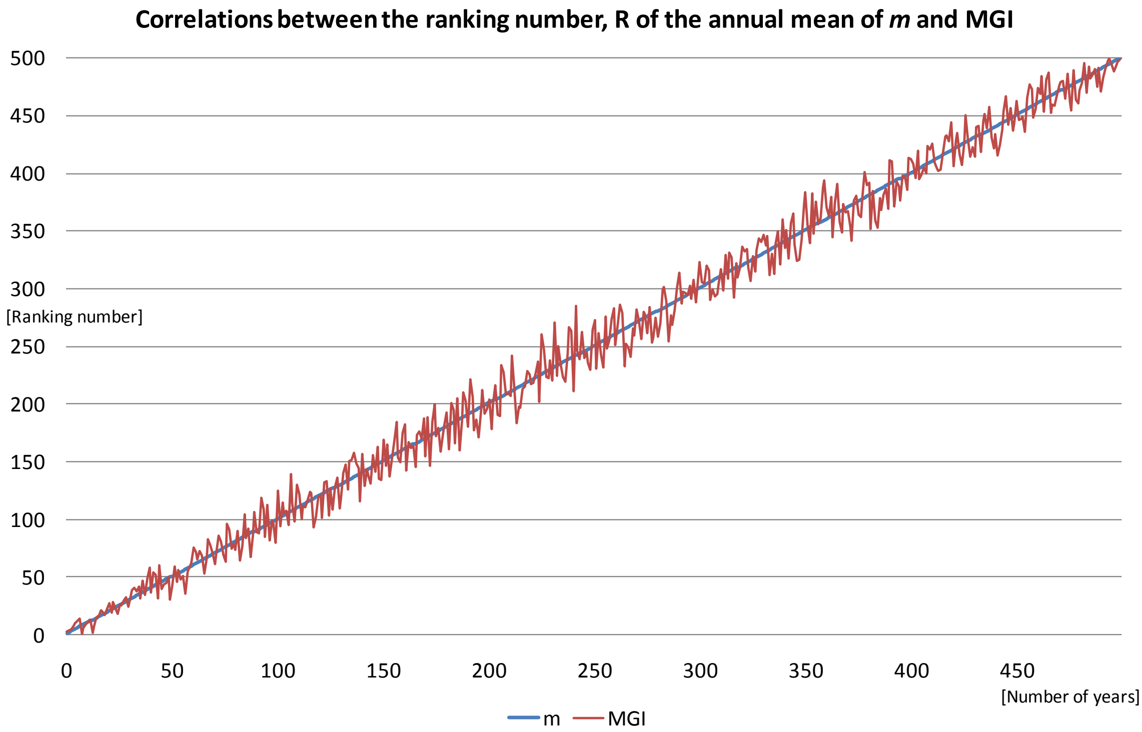

Figure 40 A comparison between the Spearman's ranking value, R of the number of hours during one year with critical relative humidity, m and the MGI. The blue line corresponds with the ranking of the number of hours with favourable conditions for mould growth and the red line represents the ranking of MGI due to the annual mean of progression at the corresponding year.

The result from the Spearman's rank correlation is presented in Table 16. According to the definition of the method, all three performance indicators are highly correlated. The most correlated indicators are the mould growth potential, *m* and the MGI. Though still very highly correlated, the annual mean of RH and the MGI are less correlated.

In addition, the comparisons between the ranking values of R in Figure 38 to Figure 40 have been evaluated using the standard deviation between the disparities in ranking. In the comparison between The RH and the *m* the standard deviation is 22.6. Corresponding value in the comparison between The RH and the MGI is 23.5. The two performance indicators with the highest correlations are the *m* and the MGI where the standard deviation is 13.8 of ΔR. In consideration of the number of simulated years the standard deviation between the *m* and the MGI can be expressed as ±2.8%.

Table 16 The result from Spearman's rank correlation, r_s of the comparisons between the annual mean of RH, the m and the MGI. The standard deviations between the ranking numbers, ΔR shows good agreement with the Spearman's rank correlation.

Comparison	Spearman's rank correlation, r_s	Standard deviation
RH_{mean} - *m*	0.988	22.6
RH_{mean} - MGI	0.987	23.5
m - MGI	0.995	13.8

E4.4 Second Evaluation of the Results

The simulations have been executed with three varying parameters. The weather, the indoor moisture production and the indoor air exchange rate. A sensitivity analysis is required in order to determine which of the parameters that is the most decisive for the outcome of the simulation result. In this study three methods of sensitivity analysis are used; the One-at-a-time sensitivity measure; the Sensitivity Index, *SI* and the Importance Index, *I*.

The idea of the first method is to repeatedly vary one parameter while holding the others fixed(Hamby 1994). Figure 41 and Figure 42 presents the result from One-at-a-time sensitivity measures on the three varying parameters. For each parameter, 100 simulated years have been performed while the others are remained to one fixed annual distribution. Consequently the hourly variations of the two parameters which are not analysed will have the same annual variation during the complete simulation of 100 independent years.

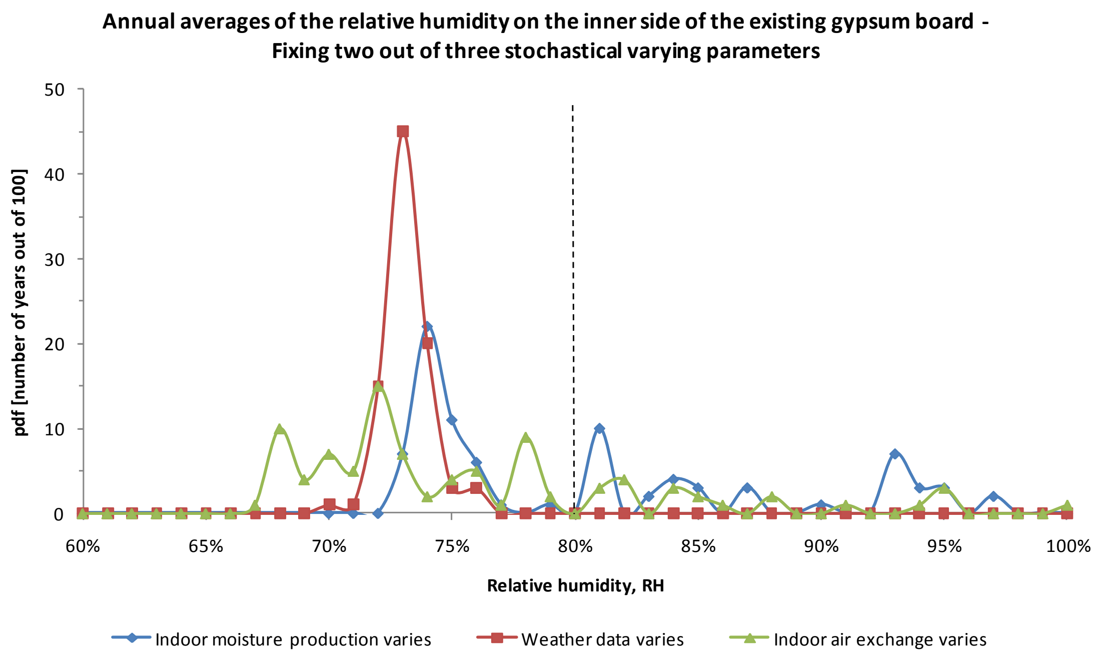

Figure 41 Probability density functions of the RH with three varying parameters of indoor moisture production, weather and indoor ventilation rate. In comparison, the spreading of RH is narrower when varying the weather data.

According to Figure 41 and Figure 42 the distribution of the RH more narrow for the One-at-a-time sensitivity measure of weather compared with the other parameters. Apparently, in that specific area of interest in the retrofitted wall, the weather will have less influence on the outcome of the simulation compared with the indoor moisture production and the indoor air exchange.

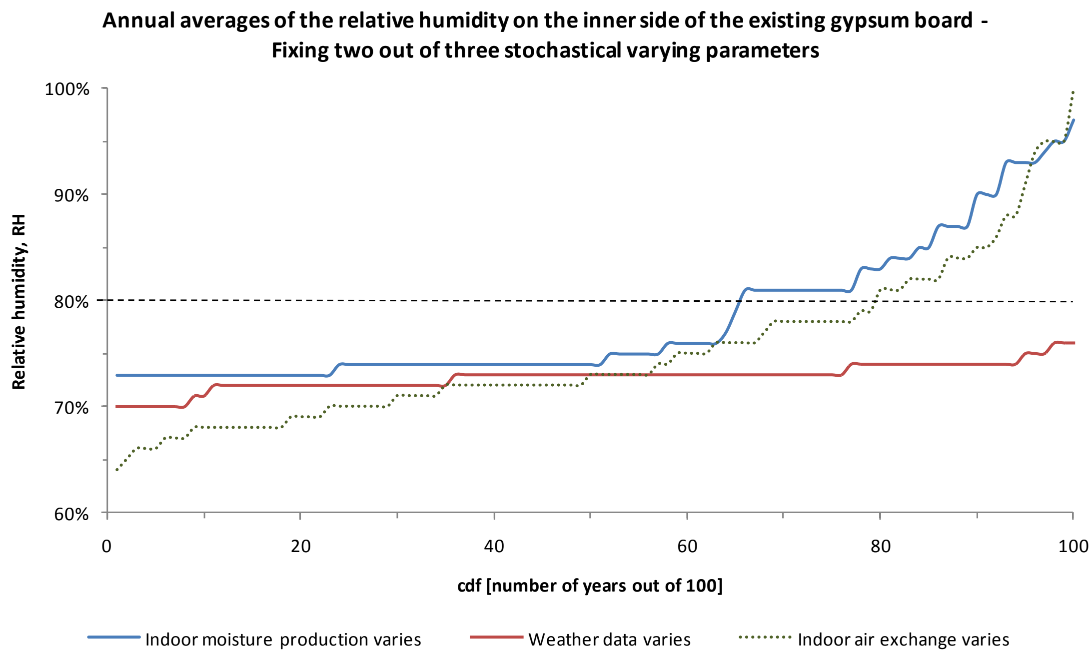

Figure 42 Cumulative density functions of the RH with three varying parameters of indoor moisture production, weather and indoor ventilation rate. As presented in Figure 41 the difference between maximum and minimum values of the result is much less when varying the weather data.

The sensitivityindex, *SI* is a simple method of determining the influence of a parameter on the final result(Hamby 1994).

$$SI = \frac{D_{MAX} - D_{MIN}}{D_{MAX}} \qquad (7)$$

where D_{MAX} = Maximum output value of the result

D_{MIN} = Minimum output value of the result

In this study a modified Sensitivity Index, SI_{mod} has also been applied. Instead of using D_{max} in the denominator, the difference between the minimum and the maximum output value from simulations with all varying parameters is used Δ_{TOT}.

$$SI_{mod} = \frac{D_{MAX} - D_{MIN}}{\Delta_{TOT}} \qquad (8)$$

where Δ_{TOT} = The difference between the minimum and the maximum output value from the simulation with all varying parameters.

The result from the analysis of the *SI* and SI_{mod} are presented in Table 17.

The disadvantage with both the Sensitivity Index and the modified method is that they disregard the distributions of the parameters. Hence only the maximum and minimum values are used in the methods there is no consideration to nonlinearity and asymmetry. The distributions of the parameters presented in Figure 41 and Figure 42 show great irregularity. Even if most of the results are intensified around certain values, only one maximum and minimum will define the spreading of the parameter.

The method of the Importance Index, I is applied in order to consider the spreading and the irregularity of the parameters. The importance Index considers the variances of the parameters on the final outcome.

$$I = \frac{\sigma_X^2}{\sigma_Y^2} \qquad (9)$$

where σ^2 is the variance of a given parameter.

The X and Y refer to the result with one varying parameter and the result from the simulation with all varying parameters respectively.

The result from the analysis of the Importance Index is presented in Table 17.

Table 17 The result from a sensitivity analysis based on three methods; the Sensitivity index, SI a modified method, SI_{mod} and the Importance Index, I. The three methods indicate that the indoor air exchange is the most influential paramater on the simulation result.

All parameters fixed but	SI	SI_{mod}	I
Indoor moisture production	0.25	0.63	0.76
The weather data	0.08	0.15	0.11
Indoor air exchange rate	0.36	0.92	0.80

According to the values presented in Table 17 the weather is the parameter with lowest influence on the result. The modified Sensitivity Index, SI_{mod} is only 0.15 which means that the range between the minimum and maximum is only 15% of the corresponding total range of the simulation result. A low Importance Index indicates a dense and narrow shape of the One-at-a-time sensitivity measure of the weather data, as seen in Figure 41.

The indoor air exchange rate has the highest influence on the outcome of the simulations according to the three methods of sensitivity analysis used in this study. The indoor moisture production also has a high influence and a spread which is very equal to the parameter of the indoor air exchange but the range of the maximum and minimum values are not that significant.

E5 REPORTING THE RESULT

Both a qualitative and quantitative analyses have been performed. The qualitative analysis identified risk due to critical levels of moisture post retrofit. A Fault Tree Analysis recognized natural or forced convection and diffusion to be the most decisive hazards of mould growth. In concerns of moisture safety the most critical position of the retrofitted exterior wall is in the existing Gypsum board which is located next to supplementary insulation. Due to the presence of a vapour barrier in the existing wall and a decrease in the average temperature during heating season, the Gypsum board will have a reduced moisture acceptance. Additional outcome of the qualitative analysis was that further analyses were recommended.

In the quantitative probabilistic analyses a model of the retrofitted exterior wall was created in HAM-tools. Multiple iterations with varying input parameters of indoor moisture production, indoor air change rate and weather data of the hygrothermal performance of the retrofit. The result was presented due to the predefined performance indicators; the relative humidity, RH; mould growth potential, *m* and the mould growth index, MGI.

It is of great concern to emphasize that the presented results are the hygrothermal performance of the existing Gypsum board post retrofit. Consequently, the distributions of the performance indicator, correlations and sensitivity analyses are the results of multiple simulations of the critical position. Other position of the retrofitted wall or building materials must be analysed separately. Hence the results and analyses are not applicable in positions other than in the existing Gypsum board of the retrofitted exterior wall.

The annual average of the RH in the existing Gypsum board is presented in Figure 35. The distributions are the results from 500 iterations of simulations with two different scenarios; with or without an assumed air leakage channel of 3mm between the existing and supplementary wall. 43 percent of the simulated years in the scenario of an assumed air leakage channel have an annual average of RH greater than 80 percent. In the scenario of no air leakage the corresponding value is 32 percent.

There is a high correlation between the RH, the *m* and the MGI. According to Spearman's ranking the value of correlation varies between 0.987 and 0.995 between the performance indicators. Consequently either performance indicator is applicable for this study.

A sensitivity analysis was performed with the methods of the One-at-a-time sensitivity measure; the Sensitivity Index, *SI* and the Importance Index, *I*. The result from the first method served as the input of the two other methods. The idea of the first method is to repeatedly vary one parameter while holding the others fixed(Hamby 1994). For each parameter, 100 simulated years have been performed while the others are remained to one fixed annual distribution. According to the result of the *SI* and the *I* the indoor air exchange is the most influential parameter in this study and in the chosen position of interest. The variation of the indoor moisture production is also very influential while the weather is not.

The influences from the input parameters in the sensitivity analysis are not only governed by the chosen position of the retrofit but also the data within the parameters. The model created for this study was simulated in the climate of Gothenburg hence other results and distributions must be expected if applied on other locations. Further, the distribution of the indoor moisture production is simulated to imitate the behaviour of Swedish households and the ventilation rates are measured in Swedish multi-family dwellings.

In conclusion, the future performance due to moisture safety of the recommended retrofit of this study is not acceptable. The risks of moisture damages may be reduced if any of the following measures are performed:

- Decrease the indoor moisture production
- Increase the indoor ventilation rate
- Assemble a vapour retarder between the supplementary insulation and the new Gypsum board
- Decrease the thickness of the supplementary insulation

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Appendix 2 Solutions to CE 2

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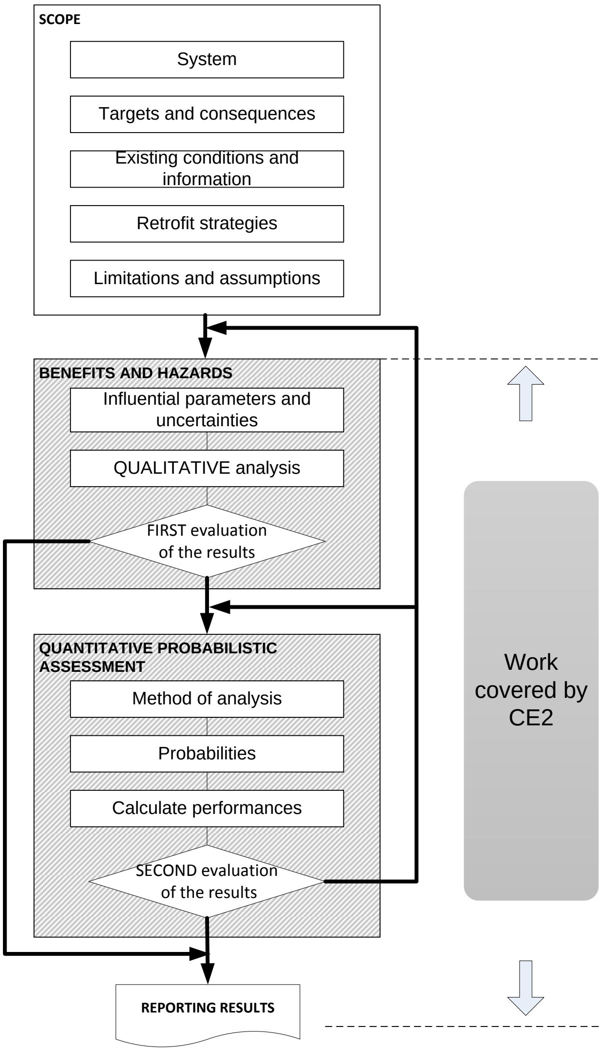
Table of Contents

Common exercise 2 - description and tasks

General information

Common exercise 2 is developed for training in using the framework for probabilistic risk assessment. To facilitate the training, all information required in the section 'Scope' of the framework is provided as input to the exercise. This includes a description of the retrofitting case, numerical modelling tool and variability of decisive input variables. Thus, the study focused on the qualitative and quantitative assessment as well as on the presentation of the results, as illustrated below.



The case study of CE2 is inspired by the retrofitting plans for the residential area Sigtuna in Sweden and focuses on the retrofit of cold attics. The main motive for choosing the cold attic as the case study is to benefit from the work done in other parts of Annex, specifically on gathering stochastic input data (Ramos and Grunewald, 2014), probabilistic calculation tools and methods (Jansen et al. 2014) and performance criteria (Sasic Kalagasidis and Rode, 2014). In this way the work is largely decreased and hopefully the time needed to complete it. However, the participants in the exercise are challenged to perform the probabilistic risk assessment and to produce the practice oriented results.

Description of Common Exercise 2

Sigtuna is a housing area in vicinity of Stockholm, the capital of Sweden, with a number of two-story apartment buildings from 1960s. The buildings are in need for renovation in order to comply with the current standards for energy use for heating of buildings. Among others, the retrofitting plans comprise additional insulation of the ceiling towards the existing attics and, in some houses, an addition of a further story to the existing buildings and a completely new attic on top of it.

The target of the retrofit is to reduce the heat loss through the ceiling by at least 50 % in comparison to the present state. The retrofit should result in a moisture-safe attic, without water leakages and mould growth.

The existing attics are in good condition, i.e. without any traces of mould. The renovation includes also the retrofit of walls. It is known that the overall air tightness of the building should be improved from 1.2 l/m²s to 0.65 l/m²s (litres per square meter of the area that separates indoor from outdoor environment).

Figure 1: Appartment buildings in Sigtuna

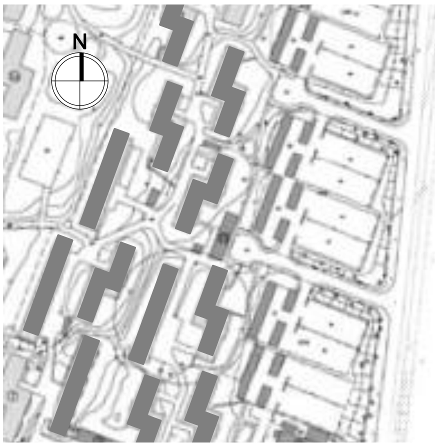


Figure 2: Spatial plan of the buildings

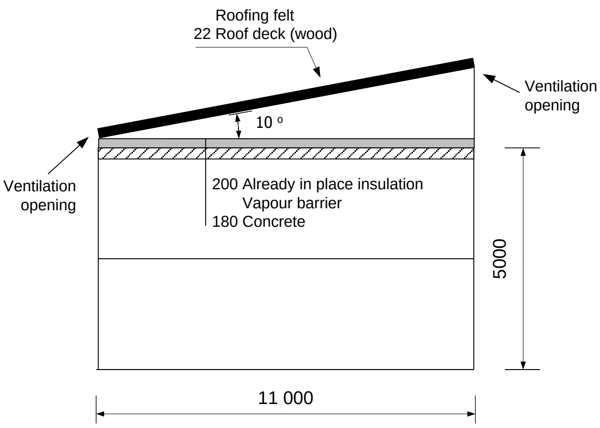


Figure 3: Vertical section through the building before retrofitting

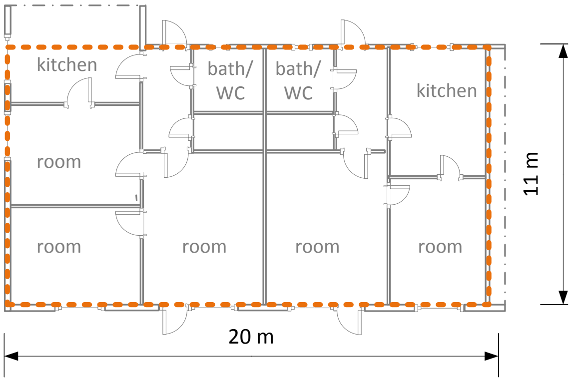


Figure 4: Layout of the appartments below each attic

Specific tasks of CE 2

There is much concern about the moisture safety of ventilated cold attics in Sweden. For the buildings in Sigtuna, the builders should choose, among six alternatives, an attic construction with the satisfactory energy performance and the lowest risk for mould growth on the roof underlay. Of course, the price also plays a role. The alternatives for the new attics are presented in the table below and in Figure 5.

Alternatives	1	2	3	4	5	6
Concrete floor	X	X	X			
Timber framed floor				X	X	X
Insulated floor (at least 200 mm)	X	X	X	X	X	X
Insulated roof (optional)		X	X		X	X
20 mm wide ventilation openings along roof eaves	X	X		X	X	
Ventilation through gable vents[1]			X			X

The new attics will be of type 'cold attics', i.e. with major insulation part laid on the attic floor. The roof slope of the new attics will be the same as in the current roof in order to preserve the appearance of the buildings.

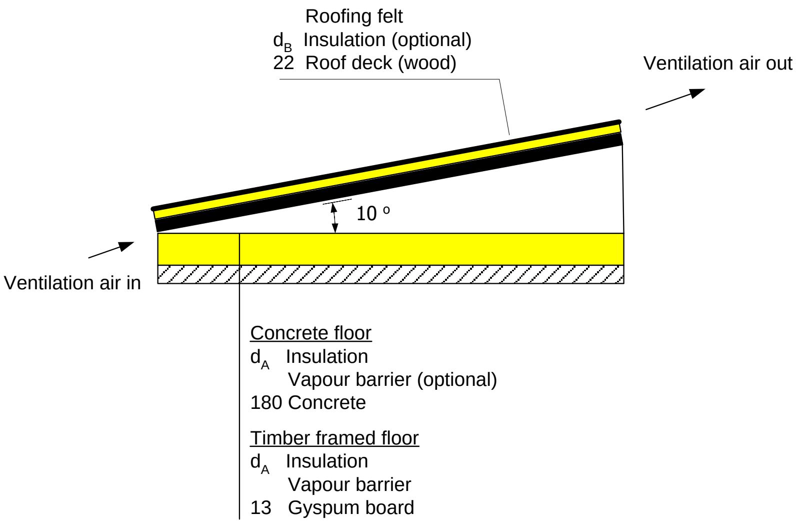


Figure 5: Alternative constructions of the new attic

The tasks are:

a. to rank the attic alternatives in respect to their energy performance (heat loss through the attic floor) and moisture safety of the roof underlay
b. to organize and report the work according to the framework for probabilistic risk assessment.

Available data and tools

Size of the attic

It is assumed that the apartments below the attic are cross-going from east to west side, and that there are two apartments below each attic compartment. Rough dimension of the attic floor is 20x11 m^2. Other dimensions of interest can be found in Figure 3.

Airtightness of the ceiling

[1] App. 10-20 times less airflow rate than through 20 mm wide openings along roof eaves

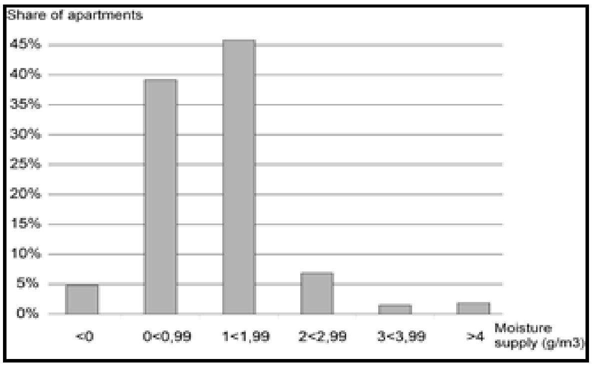
Airtightness of the buildings before retrofitting is estimated to 1.2 l/m²/s. This number corresponds[2] to n_{50}=2.5 1/h for the apartment. The airtightness of the of the ceiling is not known, but here are some orientation numbers:

Construction of the ceiling	Air leakage rate through the ceiling	Leakage area[3]	
		m²	m² /m²
Poor air tightness of the ceiling (timber framed construction)	$n_{50\_ceiling}$=0.3 1/h	$8.4{\cdot}10^{-4}$	$3.8{\cdot}10^{-5}$
Good air tightness of the ceiling (concrete slab)	$n_{50\_ceiling}$=0.05 1/h	$1.4{\cdot}10^{-4}$	$6.4{\cdot}10^{-6}$

Indoor temperature

Average indoor temperature in Swedish buildings is about 22 °C (Boverket, 2009).

Indoor moisture production



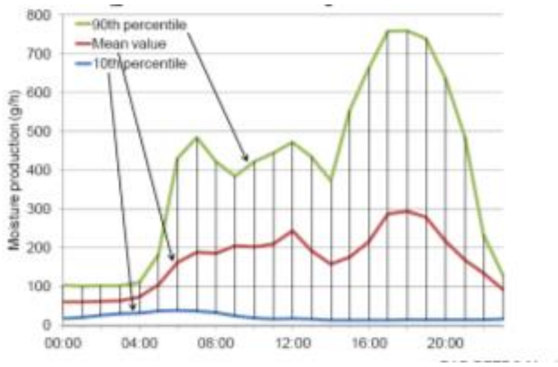


Figure 1 To the left: indoor moisture production in g/h Swedish apartments based on probabilistic simulations. From: "Risk Assessment Model Applied on Building Physics: Statistical Data Acquisition and Stochastic Modeling of Indoor Moisture Supply in Swedish Multi-family Dwellings" by Pär Johansson, Simon Pallin, Mohammad Shahriari. Paper presented at IEA A55 in Copenhagen, 2010. To the right: indoor moisture production in g/h in Swedish apartments. From: "Stochastic Modeling of Moisture Supply in Dwellings Based on Moisture Production and Moisture Buffering Capacity", by Simon Pallin, Pär Johansson, Carl-Eric Hagentoft, Presentation at IEA A55 in San Antonio, 2011

Hygrothermal model a ventilated cold attic

Cold_Attic_5.m is a Matlab-based numerical model of a cold attic. Unlike from the previous versions, in version 5 the maximum indoor relative humidity is limited to 80 %.

Manager_Cold_attic_5.m is a user-interface that maintains Monte-Carlo simulations with Cold_Attic_5.m. It provides possibilities to assign inputs to Cold_Attic_5.m and to store the results of the simulations.

Climate data

30 years of hourly weather data for Stockholm are provided in two data files (Matlab *.mat files)

Weather_WEST_Cold_Attic.mat
Weather_EAST_Cold_Attic.mat

[2] Assuming that the apartments on the last floor consist of two outdoor walls and a ceiling. Rough dimensions are then: 20x2.5 m² for the external wall, and 20x11 m² for the ceiling.

[3] Based on orifice equation

where ‘WEST’ and ‘EAST’ denote data for the west and east roof orientation, and for 10 degrees pitch. Each data file contains the following variables:

Weather_Te – outdoor air temperature, °C
Weather_Teq – equivalent outdoor temperature, °C
Weather_WindAngle – wind angle, deg
Weather_WindSpeed – wind speed, m/s
Weather_vee – humidity by volume in outdoor air, kg/m^3

Only the variable ‘Weather_Teq’ differs between the west and east roof orientation.

The same model of the attic is nowadays available as a stand-alone application. The model can be downloaded from SimpleColdAttic, placed on www.byggnadsteknologi.se under downloads.

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Solution A

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A1 SUB-QUESTION A - RANKING OF ATTIC ALTERNATIVES

The ranking of the attic alternatives in respect to their energy performance (heat loss through the attic floor) and their moisture safety has been performed applying the given MATLAB code. The attic alternatives chosen for analysis are listed in Table 1.

Table 1 Attic alternatives

1	2	3	4	5	6	Alternatives
x	x	x				Concrete floor
			x	x	x	Timber framed floor
x	x	x	x	x	x	Insulated floor (at least 200 mm)
	x	x		x	x	Insulated roof (optional)
x	x		x	x		20 mm wide ventilation openings along roof eaves
		x			x	Ventilation through gable vents

A2 METHOD

In order to analyse and rank the six attic alternatives the Monte Carlo method will be applied. Table 2 describes the six attic alternatives. As it can be seen floor insulation are required for all alternatives; this leaves five changing parameters. A change of floor construction will affect the ”Leakage area (m^2/m^2)”, a change in the insulation of the roof will affect the ”Resistance of roof insulation Rr(m^2K/W)”and a change of the ventilation openings and the gable vents will affect the ”Venting area per meter eave (m^2/m)”.

In order to analyse the attic alternatives, 12 of the 15 input parameters are randomly chosen (within the given interval) while the three variables mentioned above are fixed in accordance to the attic alternative (In Section 2.2 the calculation method for each variable is listed).

Performing a suitable number of simulations (200), the average and standard deviation of the Peak Mould Index (-) and heat loss in January (kWh/m^2) are both cumulated for each attic solution. To rank the attic solutions a plot containing the resulting values is printed and analysed in accordance to the Peak Mould Index, PMI. and Cumulated Heat Loss, CHL.

A2.1 Input Data

```
%Random variables:
S(1)=4+rand*(8  4);            %Height of building H (m)
S(2)=50+rand*(200  50);        %Area of ceiling and roof A (m2)
S(3)=0+rand*(180  0);          %Orientation of one of eave sides (0 180)(  )
S(5)=7+rand*(20  7);           %Length of building (eave side) L (m)
S(6)=0.01+rand*(0.02 0.01);    %Thickness of wooden underlay d (m)
S(7)=randn*2e 7+1e 6;          %Vapour diffusion coefficient of wood ?v (m2/s)
S(8)=0.5+rand*(0.9 0.5);       %Initial relative humidity of wood ?0 ( )
S(9)=randn*0.02+0.13;          %Thermal conductivity of wood ?roof (W/mK)
S(12)=0.2+rand*(1 0.2);        %U value of the ceiling Uc (W/m2K)
S(13)=randn*1.5+20;            %Indoor temperature Ti ( C )
S(14)=randn*0.002+0.005;       %Indoor moisture supply (kg/m3)randi(10,1,5)
S(15)=randi(30,1,1);           %Year of climate data used (1 30) ( )
S(16)=randi(6,1,1)             %Attic alternative

%Fixed variables:
if S(16) == 1;
    S(11) = 6.4*10^ 6 ;        % Leakage area (m2/m2)
    S(10) = 0.0001;            % Resistance of roof insulation R r (m2K/W)
    S(4)  = 0.02;              % Venting area per meter eave Ae (m2/m)
elseif S(16) == 2
    S(11) = 6.4*10^ 6 ;        % Leakage area (m2/m2)
    S(10) = 1;                 % Resistance of roof insulation R r (m2K/W)
    S(4)  = 0.02;              % Venting area per meter eave Ae (m2/m)
elseif S(16) == 3
    S(11) = 6.4*10^ 6 ;        % Leakage area (m2/m2)
    S(10) = 1;                 % Resistance of roof insulation R r (m2K/W)
    S(4)  = 0;                 % Venting area per meter eave Ae (m2/m) S(4)
          = 0.1*0.02;          % Ventilation through gable vents2
elseif S(16) == 4
    S(11) = 3.8*10^ 5 ;        % Leakage area (m2/m2)
    S(10) = 0.0001;            % Resistance of roof insulation R r (m2K/W)
    S(4)  = 0.02;              % Venting area per meter eave Ae (m2/m)
elseif S(16) == 5
    S(11) = 3.8*10^ 5 ;        % Leakage area (m2/m2)
    S(10) = 1;                 % Resistance of roof insulation R r (m2K/W)
    S(4)  = 0.02;              % Venting area per meter eave Ae (m2/m)
elseif S(16) == 6
    S(11) = 3.8*10^ 5 ;        % Leakage area (m2/m2)
    S(10) = 1;                 % Resistance of roof insulation R r (m2K/W)
    S(4)  = 0;                 % Venting area per meter eave Ae (m2/m) S(4)
          = 0.1*0.02;          % Ventilation through gable vents2
end
```

A3 ANALYSIS

As stated above the attic alternatives shall be rated in accordance with the Peak Mould Index (-) and cumulated heat loss for January (kWh/m^2). In our view the ranking must be established with significant respect to the PMI due to the fact that this potentially can affect the occupants' health and reduce the durability of the attic. We do however lack literature describing the acceptable PMI-level.

A3.1 Method I: PMI/CHL Distribution

In order to assess the 6 attic alternatives the resulting PMI and CHL values of 200 Monte Carlo have been divided into 60 PMI/CHL intervals for each alternative. The outcome within each interval has been cumulated. The outcome of this analysis is seen in Figure 2 (please note the varying scale of the 3. axis).

Analysing Figure 2 the attic alternatives should be (in our view) ranked in following order: A1, A2, A3, A4, A5, A6.

A3.2 Method II: Average Values and Standard Deviation

An analysis of the 6 attic alternatives can also be carried out by assessing the average values and the deviation of the PMI and CHL. In Figure 3 the outcome of the Monte Carlo simulation is illustrated in a plot where the first axis states the PMI and the second axis states the CHL. The "O" represents the average values of the attic alternatives, whereas the horizontal lines illustrate the standard deviation of the PMI. The vertical lines illustrate the standard deviation of the CHL. Analysing Figure 3 the attic alternatives should be (in our view) ranked in following order: A3, A2, A1, A5, A6, A4.

A3.3 Assessment of Methods I & II

Comparing the outcome from the two ranking methods applied it is seen that some deviations occurs. Both methods do however indicate that it is the floor type is of great importance in accordance to the attic performance (A1, A2, A3 = concrete, A4, A5, A6 = timber framed).

A3.4 Correlation between PMI and CHL

In order to analyze if correlation between the PMI and the CHL occurs the outcome of the 200 simulations have furthermore been divided into 60 PMI/CHL intervals without considering attic alternatives. The outcome of this analysis is seen in Figure 3.

Table 2: Applied illustration notation

	A	B	C	D	E	F	G	H	I	J
CHL	0, < 2	2, < 4	4, < 6	6, < 8	8, < 10	10, < 12	12, < 14	14, < 16	16, < 18	>= 18
PMI	0, < 1	1, < 2	2, < 3	3, < 4	4, < 5	>= 5				

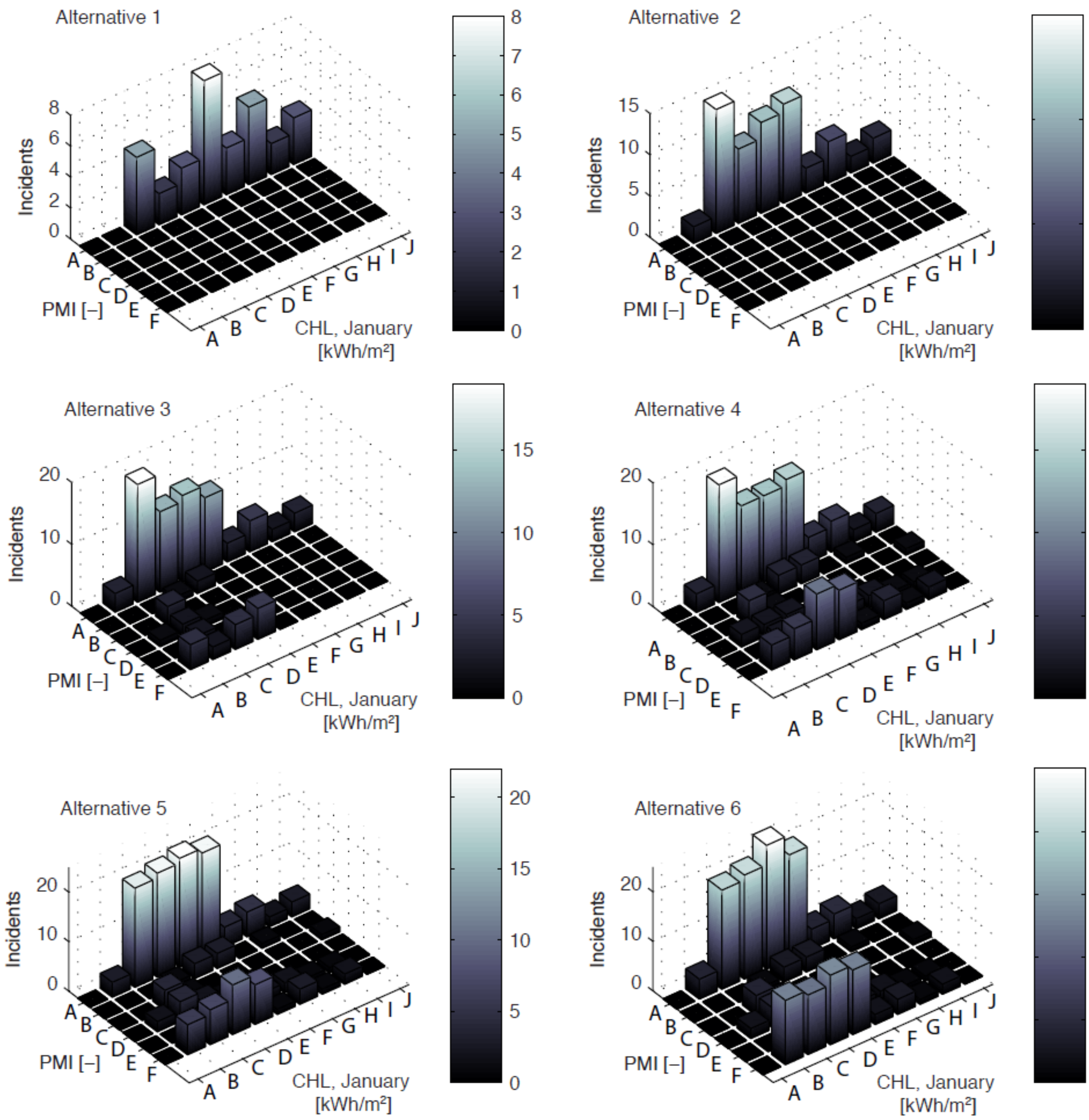

Figure 2 The resulting PMI and CHL values of 200 Monte Carlo are illustrated. The outcome have been sub plotted with respect to the 6 attic alternatives (please note the changing in the 3. axis).

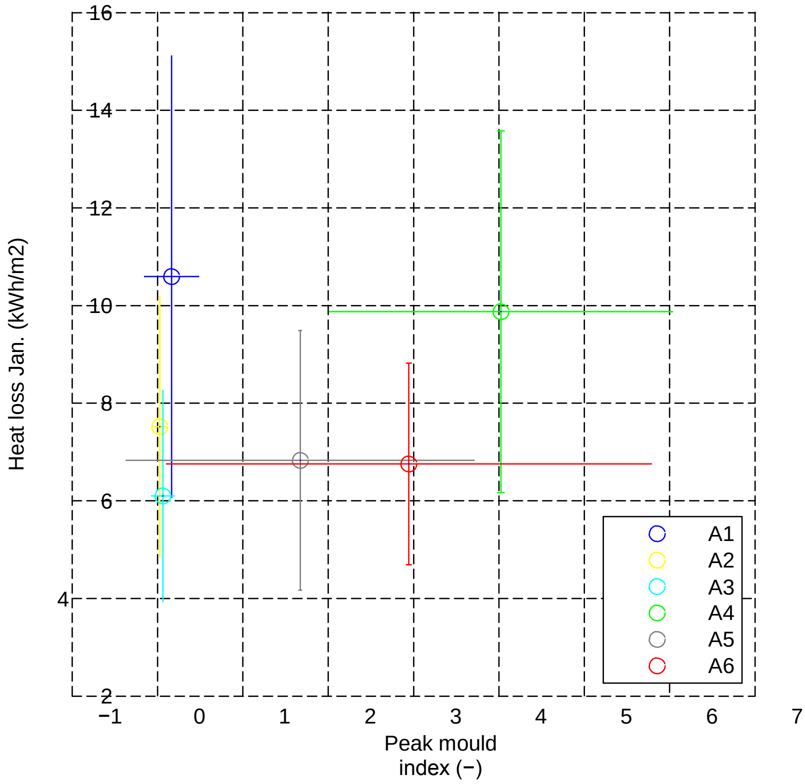

Figure 3 The resulting average values performing 200 Monte Carlo Simulations. The horizontal lines illustrate the standard deviation of the PMI, while the vertical lines illustrate the standard deviation of the CHL.

A3.5 Parameter Analysis

Since 200 simulations have been performed, a parameter analysis has been undertaken. The outcome will not be analysed further. The results can be seen below.

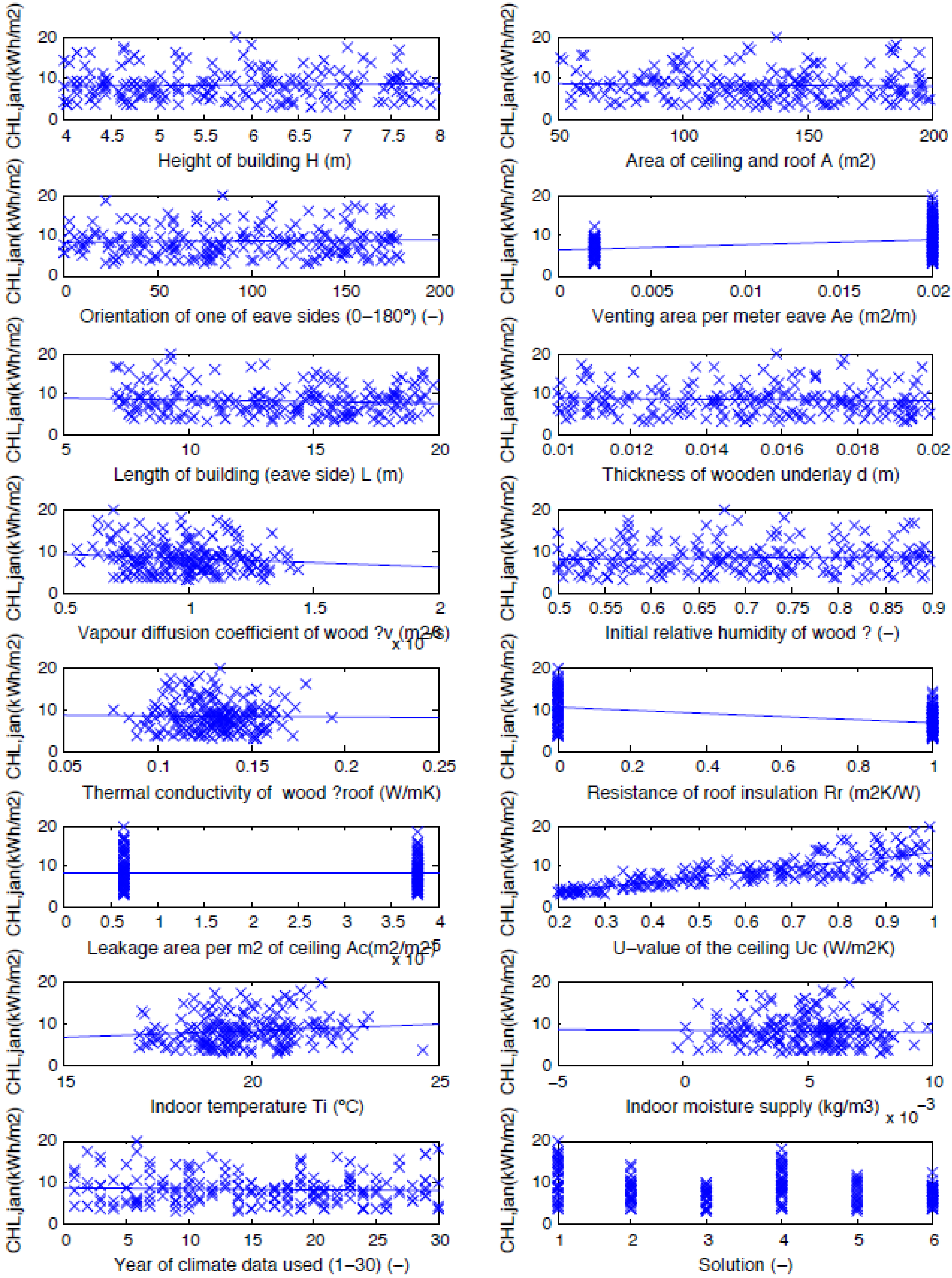
CHL,jan(kWh/m2)
Height of building H (m)
Area of ceiling and roof A (m2)
Orientation of one of eave sides (0–180°) (–)
Venting area per meter eave Ae (m2/m)
Length of building (eave side) L (m)
Thickness of wooden underlay d (m)
Vapour diffusion coefficient of wood ?v (m2/s)
x 10
Initial relative humidity of wood ? (–)
Thermal conductivity of wood ?roof (W/mK)
Resistance of roof insulation Rr (m2K/W)
Leakage area per m2 of ceiling Ac(m2/m2)
x 10
U–value of the ceiling Uc (W/m2K)
Indoor temperature Ti (ºC)
Indoor moisture supply (kg/m3)
x 10−3
Year of climate data used (1–30) (–)
Solution (–)

Figure 4

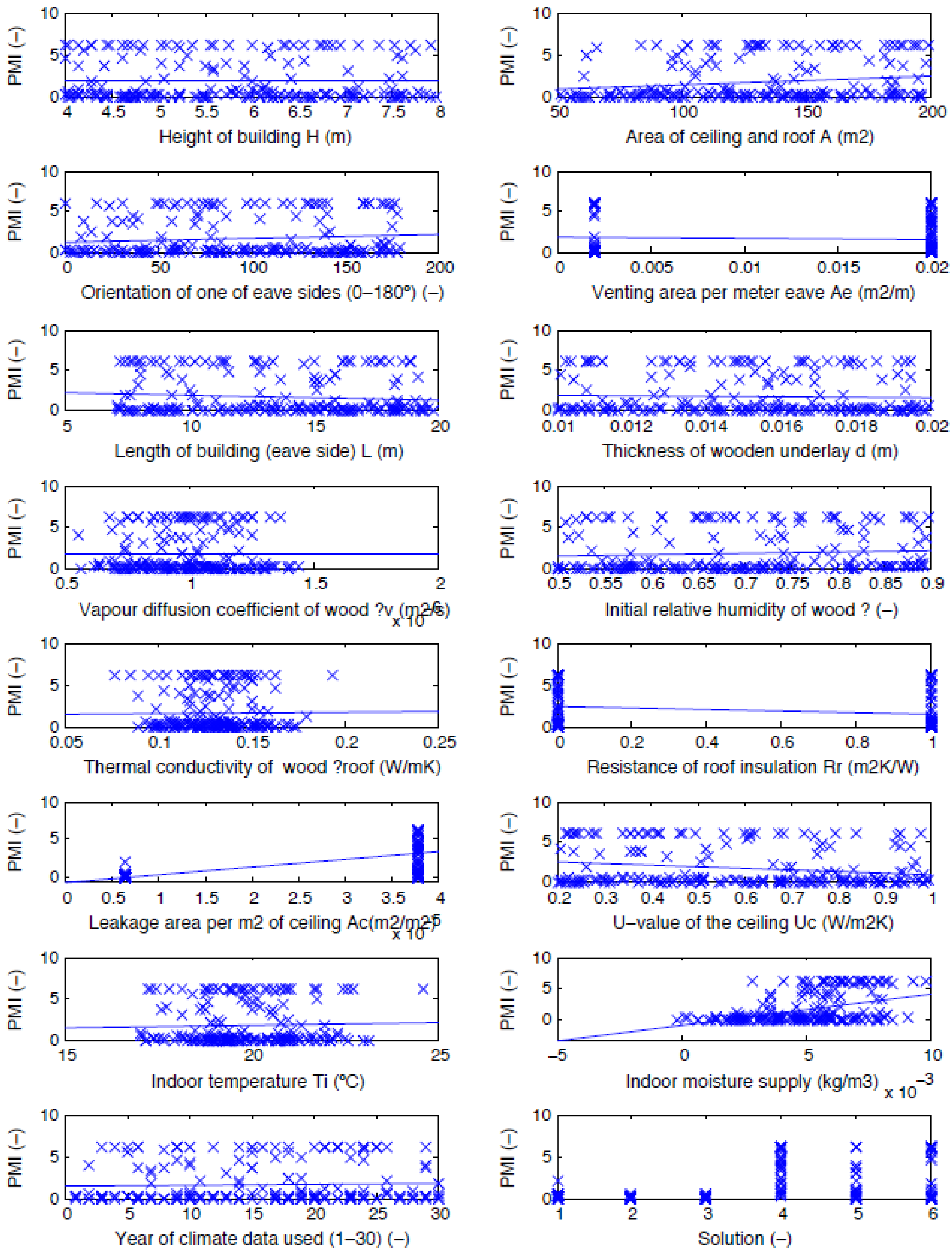

Figure 5

A4 SUB-QUESTION B - FLOW CHART

We find it difficult to follow the flow chart for this assignment since the six predefined alternative construction solutions are already given in the exercise as well as the needed input variables, and thus it was not needed to follow the flow chart in order to answer Sub-question A. Therefore the flow chart question has not been applied during our answer to the Common Exercise. We suggest that in next phase of the Common Exercise, the same case study can be analyzed, but leaving the scopes and targets more open, such that a designer can freely work with the problem and test ways to progress through the flow c hart.

Solution B

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B1 INTRODUCTION

This report describes the work flow applied when solving the Common Effort 2 (CE2) within Subtask 3 (ST3) which deals with retrofitting of a ventilated attic in Sigtuna, Sweden. The first part of the report describes the work flow of this “quantitative probabilistic analysis”. The second part describes the results from the actual quantitative probabilistic analysis of the retrofitting case along with a simplified sensitivity analysis.

One of the goals within Subtask 3 is to develop a framework for “quantitative probabilistic analysis” when retrofitting measures are applied in buildings (in the context of energy savings, building physics and potential risks related to the applied retrofitting measures).

As a starting point, the author of this contribution was previously involved in Subtask 2, Common Effort 3 which dealt with methods for sensitivity analysis which is an essential part of a quantitative probabilistic analysis. In the case study in ST2 CE3 a similar attic construction was considered (same numerical model, similar inputs, similar outputs etc.). Hence, the experience from ST2 CE3 affected the work flow when conducting ST3 CE2. Many steps in the process were done more or less in the same way as in ST2 CE3. Therefore, the proposed framework was actually not utilized until the last stage of the process - when the applied method was to be compared with the framework.

B2 METHOD AND WORK FLOW

The actual flow of work is described in the following bullets:

1. **<u>Looking at the potential risks.</u>** Two major risks were identified. But the risks was basically given in the description of the ST3 CE2:
    a. Not reaching the energy saving goal (i.e. the cumulative heat losses through the attic floor)
    b. The moisture performance in the wooden underlay in the roof construction is not sufficient (i.e. by looking at the peak mould growth index)

2. **<u>Consider input data</u>**. Which input parameters need to be included in the analysis?
    a. <u>Gathering stochastic inputs:</u> The probability distribution of input parameters was basically given in the task description.
    b. Which parameters can be seen as <u>constant parameters</u> not influencing the spread of the results?

    A decision was made to include the thermal insulation thickness as a stochastic input in the analysis. The uniform probability distribution [0.2, 0.5] m set up a quite high variability in the results.

3. **Generate probability distributions**. Probability distributions for each of the risks were generated by means of Monte Carlo Simulation.
   a. Select numerical model: The tools needed to perform a quantitative probabilistic analysis were given to the participants in the common effort.
   b. Sampling method: For random sampling of input data the Sobol sampling method was applied (handy method from an engineer's perspective).

4. **Set failure limits.** What are the acceptable PMG and CHL levels? Acceptable CHL levels where given by the description of ST 3 CE2 (i.e. 50% reduction). Due to a lack of knowledge of the author, the different attic solutions where ranked based on the generated probability distribution (PMG) without define a specific "acceptable" limit for the PMG value.

5. **Study the sensitivity of probabilistic input data.** The sensitivity analysis was an important step in order to understand the difference between the attic solutions. The purpose of the simplified sensitivity analysis was to determine which parameters that are the important ones and which are the sensitive ones. This step in the work flow was very informative. Especially in order to get an understanding of why the results differs from case to case.

B2.1 Lessons learned

A successful retrofitting was in this case defined as a 50% CHL reduction. Looking at the results, in many of the samples the CHL value is higher than this value, in comparison to the reference case. The target of the retrofitting is actually missed. The wide spread in the insulation thickness is the cause. Hence, defining the insulation thickness as a stochastic input parameter may need some quantification of the lower limit of the insulation thickness (referring to this specific retrofitting case). The lowest possible insulation thickness in the sampling of input data should still fulfil the 50% CHL reduction. An early simple deterministic calculation may quantify reasonable limits of the scope of the retrofit measure.

Furthermore, the insulation thickness is an important design parameter in the retrofitting design. For a specific retrofitting case, the actual spread of the insulation thickness is low. As a customer/construction manager, you order/quantify a defined amount of thermal insulation. The standard deviation would probably be in the range of a few cm in case of loose fill insulation in an open ceiling. By defining the insulation thickness as a stochastic variable within a wide uniform span, we have introduced a high degree of variability in the probabilistic analysis. For a specific retrofitting case this is incorrect. In reality, the variability introduced from the amount of thermal insulation is much less than applied in this study.

If the study would have been made for "retrofit measures of outdoor ventilated cold attics" in general, the approach of defining the insulation thickness as a stochastic parameter (large span) would have made more sense. However, instead of defining a wide uniform spread of the insulation thickness, it is appealing (at least for the author) to study different populations of attic constructions. One population could be "highly insulated" retrofitted attics, another population is more "reasonable insulated" attics and so on. In each of the population the spread of the insulation thickness would then be small – it refers to the method of applying the actual insulation product (i.e. a few cm variations).

B3 QUANTITATIVE PROBABILISTIC ANALYSIS

B3.1 Method of analysis

Monte Carlo simulation was performed for the current state of the building (un-retrofitted reference) and for 6 predefined retrofit cases according to the guidelines given in ST3 CE2. The outline of the 6 cases were defined by Figure 4 in SB3 CE 2.

The provided Matlab HAM model of the cold attic was applied (version 5).

B3.2 Selection of probabilistic data

Data for the quantitative analysis are given by Table 2 and Figure 6.

The total thickness of the thermal insulation may vary uniformly between 0.2-0.5m. In the case of insulated outer roof construction (case 2, 3, 5 and 6) is a fraction of the total amount of insulation allocated to the roof construction. The fraction may vary uniformly between 5-30% of the total insulation thickness. Hence, the U-value of the ceiling and the thermal resistance of the roof are not directly random variables in the sampling process.

The orientation of the building can be assigned only two values: facing east or facing west. The probability is equally assigned for the two alternatives. Analogously, the building height may be 5 or 7.5 m which corresponds to adding an extra storey to the excising building. The ceiling may be of concrete (case 1, 2 or 3) or made of wood structure (case 4, 5 or 6). The fact that it is not likely that the excising concrete ceiling will be replaced by a wooden structure without adding the extra storey is not considered.

Table 2 Applied input parameters for the probabilistic quantitative analysis.

Constant input data		
Thermal conductivity of wood	W/m/K	0.13
Vapour diffusivity of wood	m^2/s	10^{-6}
Thickness of wooden underlay	m	0.022
Area of ceiling	m^2	220
Length of building	m	20
Thermal conductivity of insulation	W/m/K	0.035
Common probabilistic input data		
Height of building	m	5 (case 0) 5 or 7.5 (case 1, 2, 3, 4 , 5, 6)
Orientation	-	East or West
Initial relative humidity of wood	-	U(0.6,0.9)
Indoor temperature	°C	N(22,1)
Year of climate data	-	U(1,30) For each sampling: weather data are selected according to the orientation of the building. (Only integers between 1-30)
Indoor moisture supply	kg/m^3	See probability distribution according to Figure 6.
Total insulation thickness	m	0.2 (case 0) U(0.2,0.5) (case 1, 2, 3, 4, 5, 6) U(0.4,0.7) (case 7)
Case specific probabilistic input data		
Fraction of insulation allocated in the outer roof construction	-	0 (cold attic – case 0, 1, 4) U(0.05,0.3) (insulated outer roof – case 2, 3, 5, 6, 7)

Venting area per meter	m^2/m	0.02 (eave ventilation – case 0, 1, 2, 4, 5) 0.02/15 (gable ventilation – case 3, 6, 7)
Leakage area per m^2 of ceiling area	m^2/m^2	U($2.56x10^{-6}$, $12.8x10^{-6}$) (concrete ceiling – case 0, 1, 2, 3, 7) U($1.27x10^{-5}$, $7.6x10^{-5}$) (wood ceiling – case 4 , 5, 6)

B3.3 Sampling method

Sample sizes of 100 are applied for the probabilistic analysis of each case (0-6). A quasi random sampling method is applied (Sobol). The Sobol routine generates a uniform distribution in the probability space. The spread in the samples for two input parameters are illustrated below in Figure 6 and Figure 7. 8 or 9 input parameters are considered in the sampling process (the number depends on the considered case).

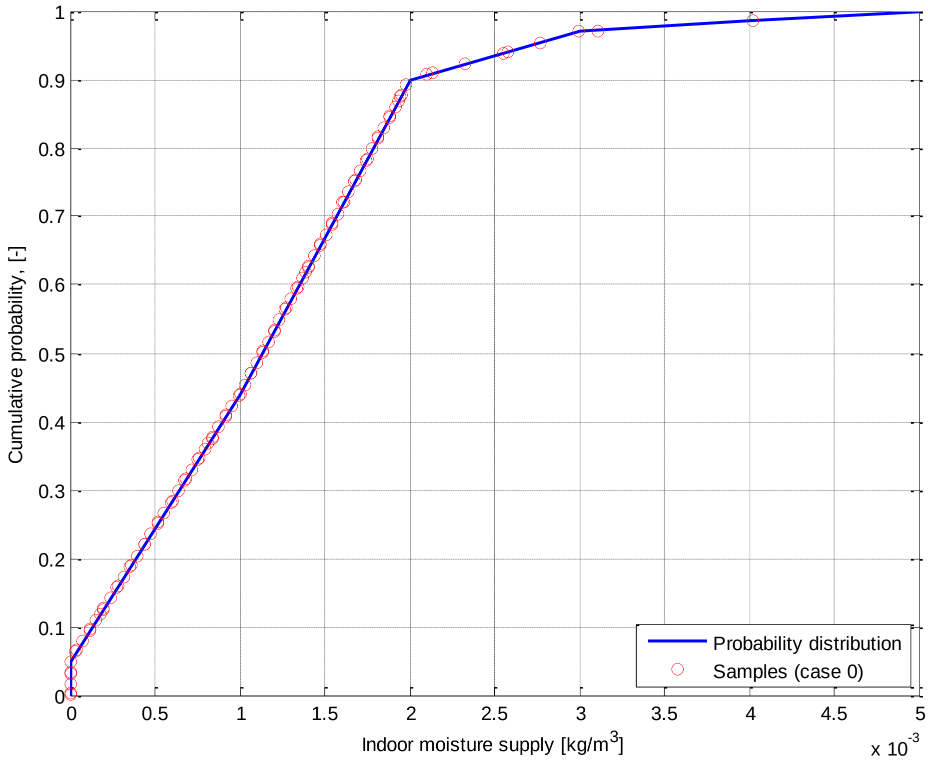

Figure 6 The probability distribution of the indoor moisture supply is generated from data published by Boverket (2009). Sobol sampling of the indoor moisture supply (case 0).

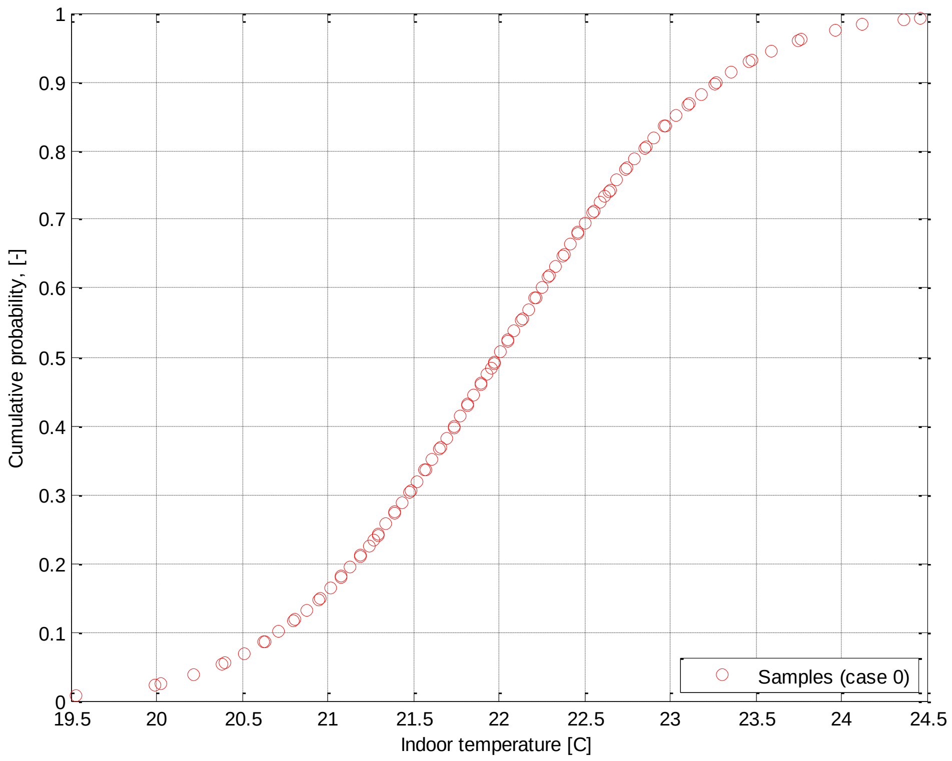

Figure 7 Sobol sampling of the normally distributed indoor temperature (case 0).

B4 RESULTS

The insulation thickness is considered as a constant input parameter in the reference case (200mm). 100% of the thermal insulation is located in the ceiling. Hence, the spread in the reference results are expected to be less than for case 1-6. The standard deviation of CHL is also found to be lower than the studied cases (1-6), see Table 2. The reduction in the CHL value of the retrofitted attic construction, based on the average CHL values, yields that the target value (50% reduction) is not reached.

However, the reference CHL will depend upon the indoor temperature, the considered year and the air tightness of the ceiling (mainly), see the cumulative probability distribution in Figure 8. Hence, the probability to reach a certain reduction of the CHL is given by Figure 9. Here the spread in the reference case is included in the analysis. The target value of 50% CHL reduction is only reached for approx. 1/3 of the retrofitted attics. The probability is approx. 5% that the retrofitted attic construction has a higher CHL compared to the reference construction. Case 6 yields the highest energy saving potential among the 6 retrofit cases with the same amount of thermal insulation. In case 7, where more insulation is applied (400-700 mm), is the probability as high as 90% that the target value is reached (50% reduction of the CHL).

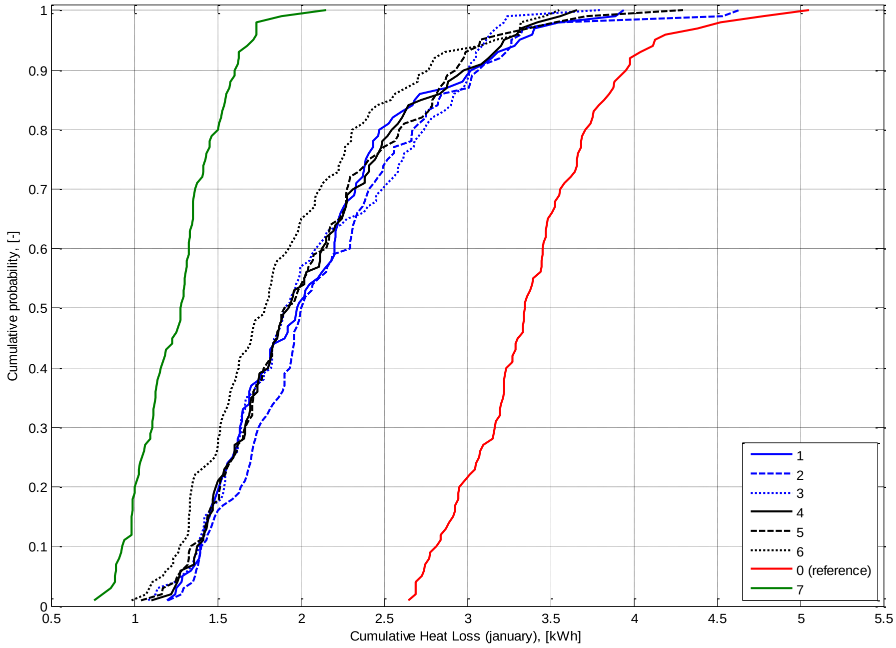

Figure 8 Cumulative probability distribution: heat loss for case 0-7.

Table 3 Mean value and standard deviation of the CHL for each case.

Case	Mean CHL	Reduction (mean CHL / mean CHL ref.)	Standard deviation CHL
0	3.40	-	0.46
1	2.09	0.61	0.63
2	2.19	0.64	0.66
3	2.09	0.61	0.62
4	2.07	0.61	0.61
5	2.07	0.61	0.63
6	1.91	0.56	0.59
7	1.27	0.37	0.26

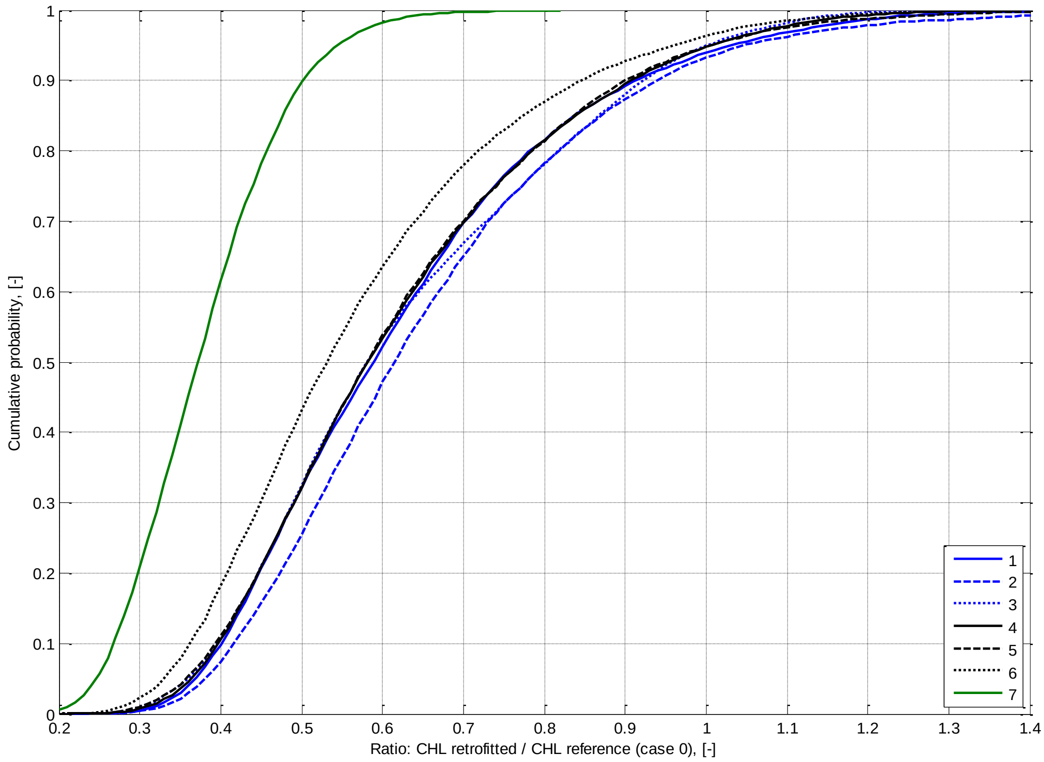

Figure 9 Cumulative probability distribution of the reduction potential of CHL (compared to the reference construction).

Cumulative probability distributions for the peak mould growth index (PMG) are given for case 0-7 in Table 4, Figure 10 and Figure 11. The reference construction (case 0) yields a low probability (or no probability) that the PMG value reaches high levels. Hence, the old attic construction is proven to be a robust solution, without mould problems.

By adding more thermal insulation to the attic ceiling, as in case 1, the probability to have PMG values equal to zero decreases. PMG values just exceed level 1.0 in case 1. Case 4 is comparable to case 1 but a wood ceiling is applied. The probability distribution assumed for the wooden ceiling changes the performance quite much. This construction shows the highest probability to fail. PMG values equal to zero are much fewer than in the reference case and all other cases. Moreover, a small probability to have severe moisture damages is revealed. PMG values between 1.0 up to 6.0 are reported in case 4.

In case 3 and 5, 5-30% of the applied insulation thickness is shifted to the external side of the wood layer in the outer roof. Hence, the wood in the roof is warmer and drier. Case 3 (concrete ceiling) yields a better PMG performance than the reference case; higher probability to have PMG values equal to zero and at the same time no tendency to have a small probability for high PMG values. The wood ceiling (case 5) show a big improvement compared to case 4; especially is the probability to have PMG values equal to zero improved. However, there is still a small probability that attics with high PMG values may exist.

The air exchange of the attic is decreased by decreasing the ventilation openings in the attic (case 3 and 6). Hence, condensation at the inner wood surface is reduced (moist from outdoor air which enters the attic by natural ventilation). However, this approach requires a sufficient air tightness of the ceiling since moisture from indoors must be ventilated out from the attic somehow. The concrete solution (case 3) seems to be improved by reducing the openings in to the external. The probability for PMG values equal to zero increases up to 0.73 which is the highest value of all cases. A small increase in the probability to exceed PMG equal to 1.0 is on the other hand revealed. Hence, this approach is not as robust as the reference case, and case 2, where the 1.0 level was never exceeded. This is probably due to the reduced capability to ventilate away indoor moisture which enters the attic by passes though the attic ceiling. The corresponding wood solution (case 6) also show an improved probability have a PMG value of zero. PMG values above 1.0 increases compared to case 5 (full attic ventilation).

Case 7 is the same as case 3, but the insulation thickness is improved quite much (400-700mm). Hence, the attic temperature is assumed to be lower, and hence, higher PMG values are expected. In comparison to case 3, a small decrease in the probability to have a zero PMG value is recorded. Moreover, the maximum PMG value increases compared to case 3, but the shift is very small.

Table 4 Probability distribution of the peak mould growth index (PMG).

Case	PMG =0	PMG > 1.0	PMG > 2.0	PMG > 3.0	PMG > 4.0	PMG > 5.0
Concrete ceiling						
0	0.32	0	0	0	0	0
1	0.25	0.01	0	0	0	0
2	0.43	0	0	0	0	0
3	0.73	0.03	0	0	0	0
7	0.68	0.03	0	0	0	0
Wood ceiling						
4	0.08	0.18	0.07	0.06	0.04	0.02
5	0.41	0.03	0.02	0.02	0.02	0.02
6	0.63	0.04	0.04	0.03	0.03	0.01

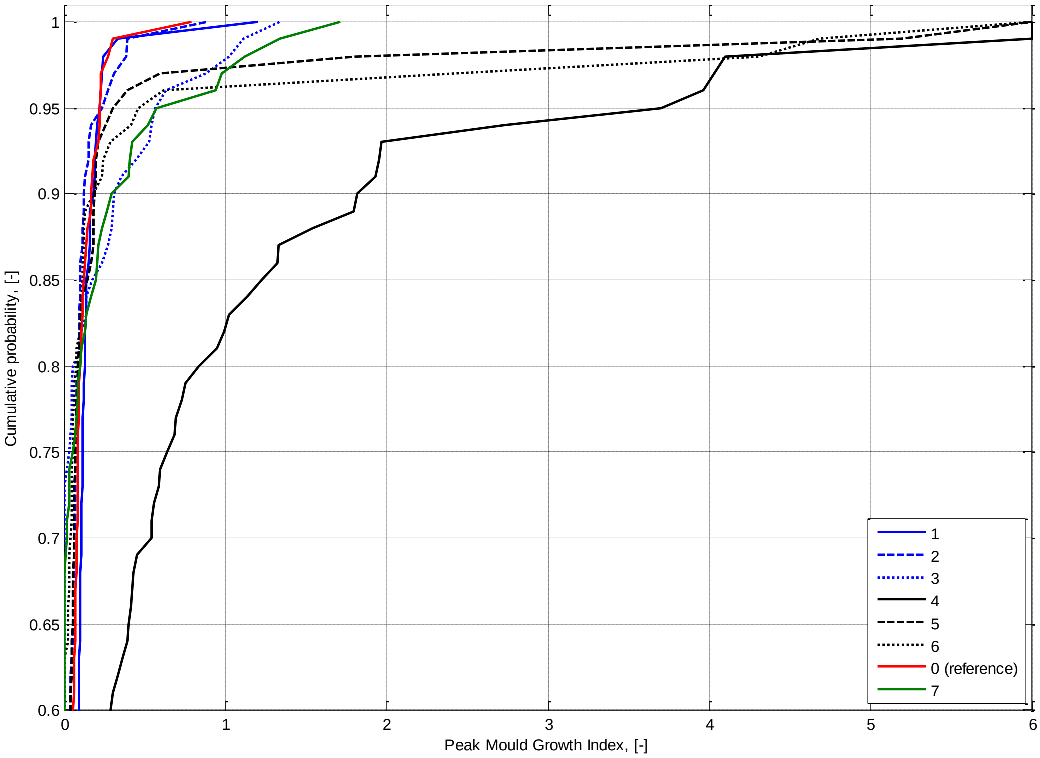

Figure 10 Cumulative probability Peak Mould Growth Index (PMG) for case 0-7.

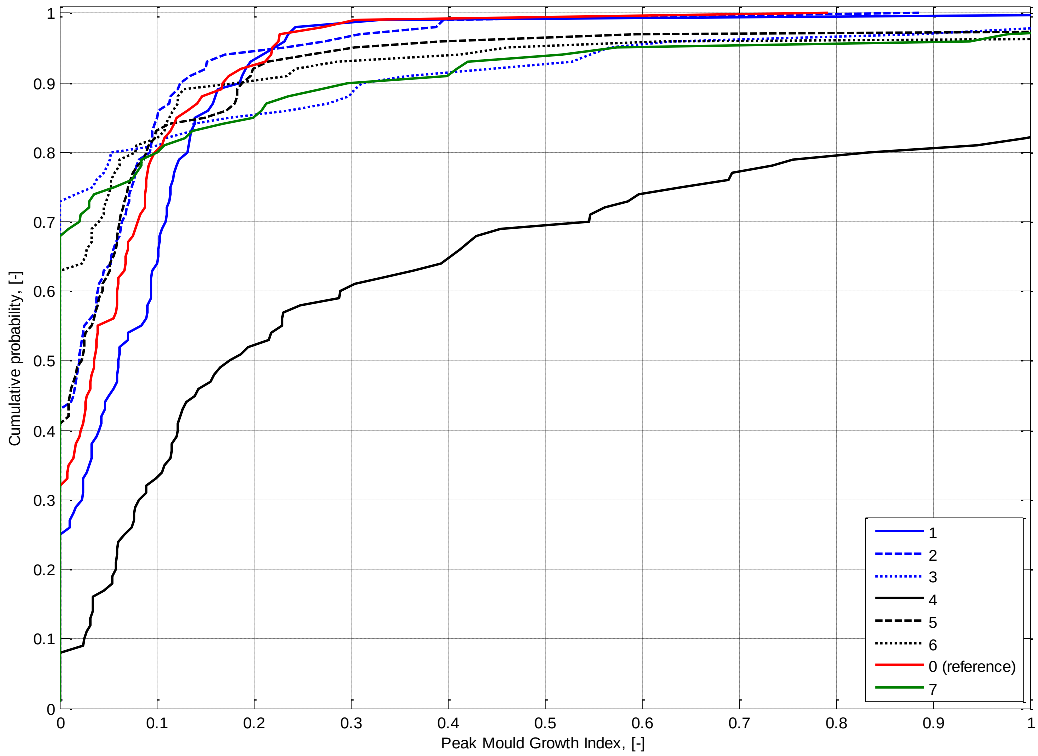

Figure 11 Cumulative probability Peak Mould Growth Index (PMG) for case 0-7.

B5 SENSITIVITY ANALYSIS (SIMPLE)

An attempt to analyse the sensitivity of the input parameters was made with a simple additive linear multiple regression model. Least square method was utilised to compute regression coefficients *a* and *b* for each of the output parameters (i.e. Matlab function *lsqr()*), see Equation 1. The additive linear regression yields a higher relative residual for CHL-values than for PMG-values consistently, see Table 5. In Figure 12 the model output (PMG- and CHL-values) and the linear regression values outputs are plotted. As an example for case 4, visually we can observe the difference in the regression quality between PMG- and CHL-values.

$$PMG = a_1x_1 + a_2x_2 + \ldots + a_8x_8$$
$$CHL = b_1x_1 + b_2x_2 + \ldots + b_8x_8$$

Equation (1)

Table 5 Relative residual for the lsqr().

Case	Relative residual CHL	Relative residual PMG
1	0.77	0.14
2	0.74	0.16
3	0.74	0.12
4	0.49	0.15
5	0.76	0.15
6	0.78	0.14
7	0.76	0.13

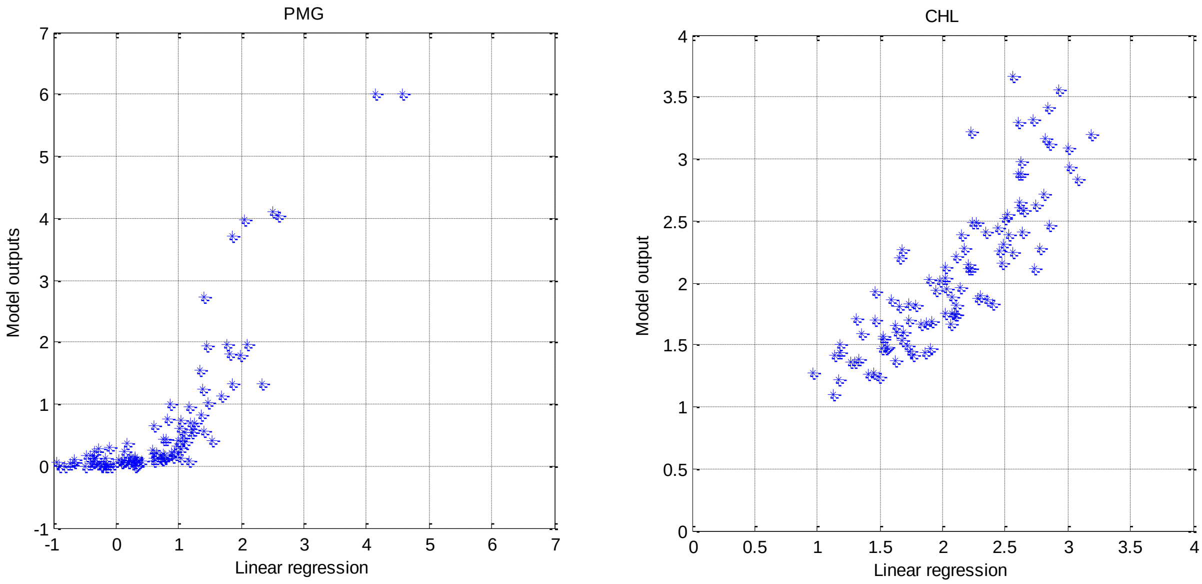

Figure 12 Model output (PMG and CHL obtained from Matlab-model) against linear regression sum (equation 1).

The regression coefficients *a* and *b* are normalized and standardized. The normalized values (*a* and *b* divided by the mean value) are then scaled/ranked according to the parameter with the highest amplitude. This parameter is given the value 1 or -1. Parameters with a high normalized value are the important parameters which has the highest influence on the output parameter. An input parameter with a normalized value near zero is unimportant; the input value of such parameter does not affect the output parameter.

The standardized values (*a* and *b* divided by the standard deviation) are also scaled/ranked according to the parameter with the highest amplitude. These values show the sensitivity of each input parameter. Figure 13 to Figure 26 show which parameters that are the important and sensitive ones.

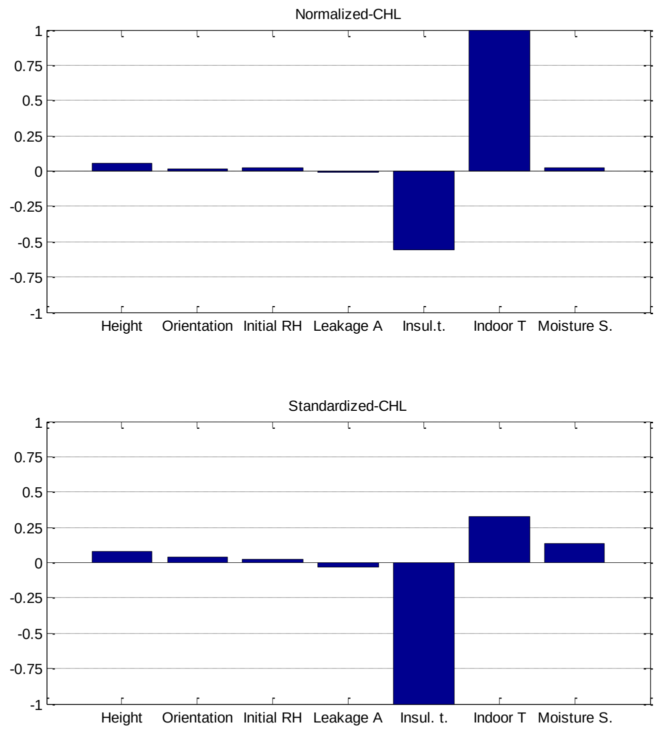

Figure 13 case 1

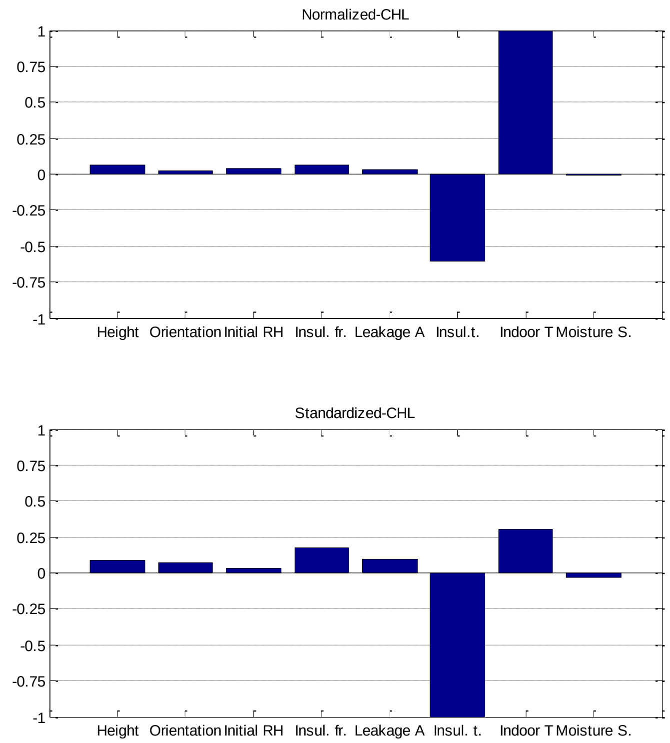

Figure 14 Case 2

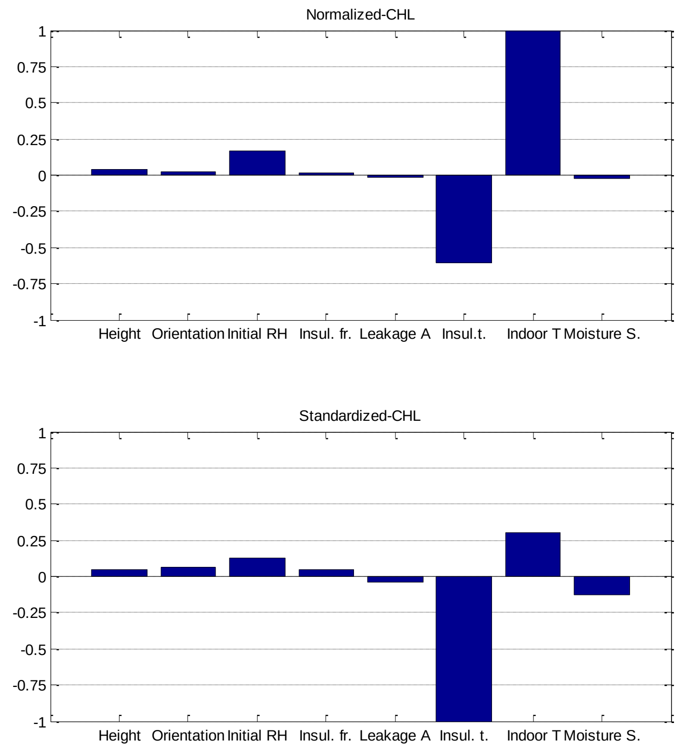

Figure 15 Case 3

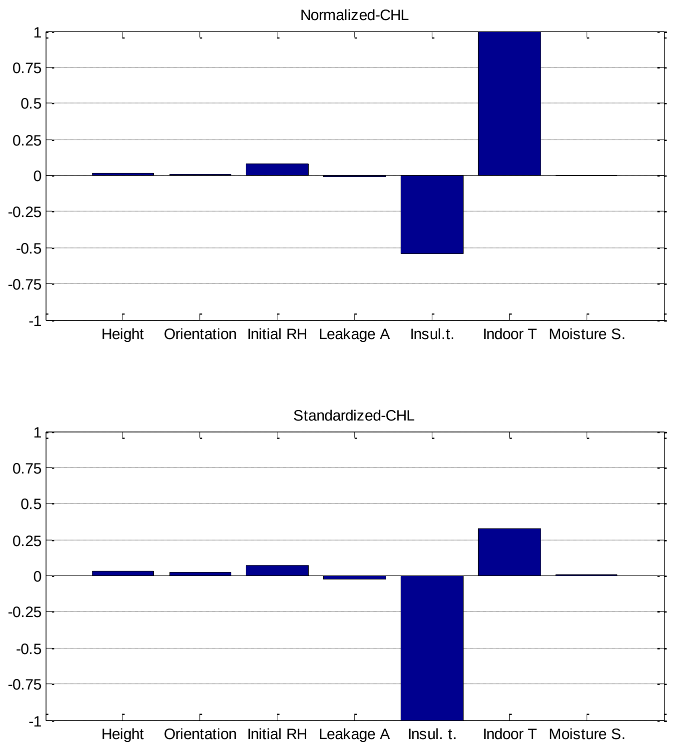

Figure 16 Case 4

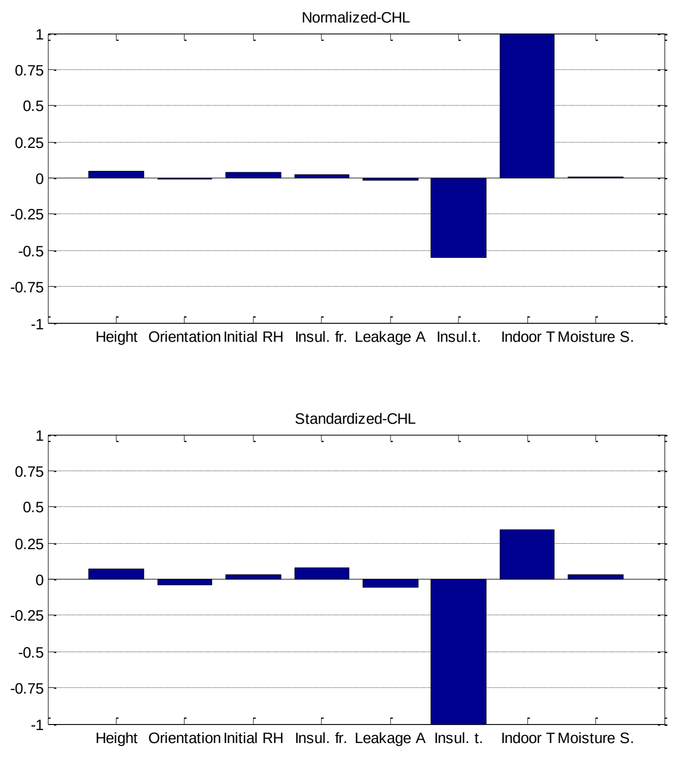

Figure 17 Case 5

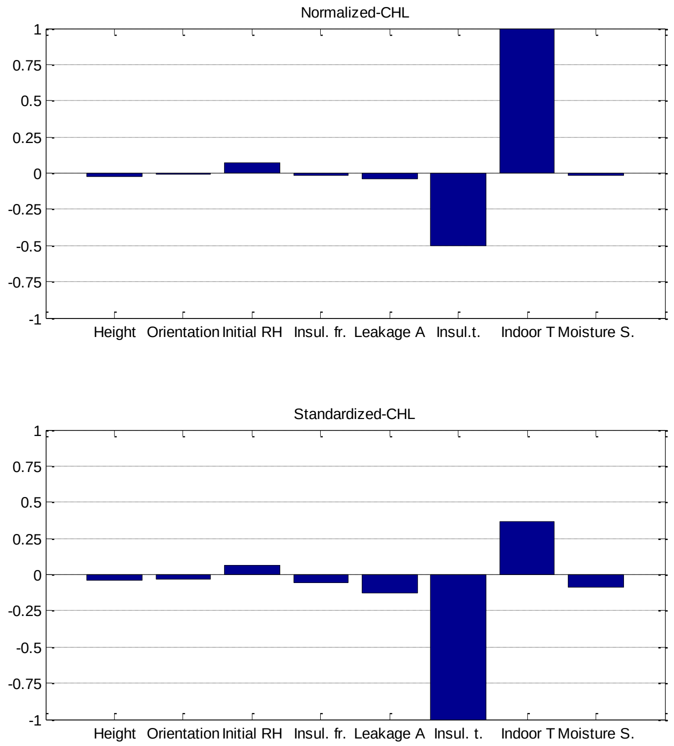

Figure 18 Case 6

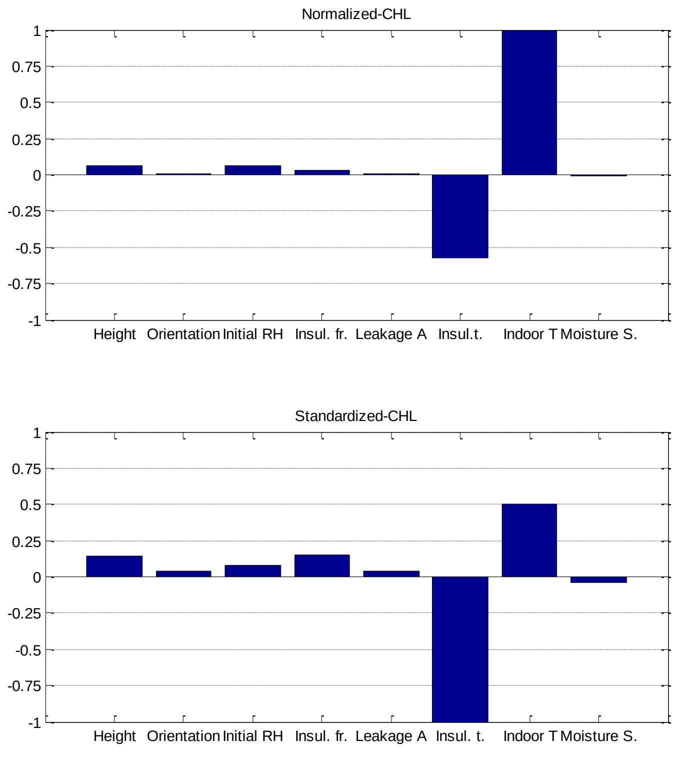

Figure 19 Case 7

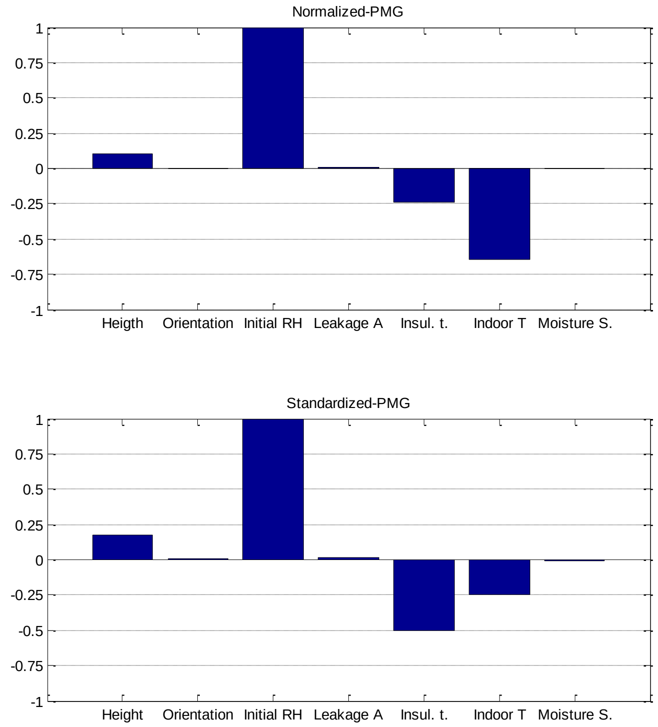

Figure 20 case 1

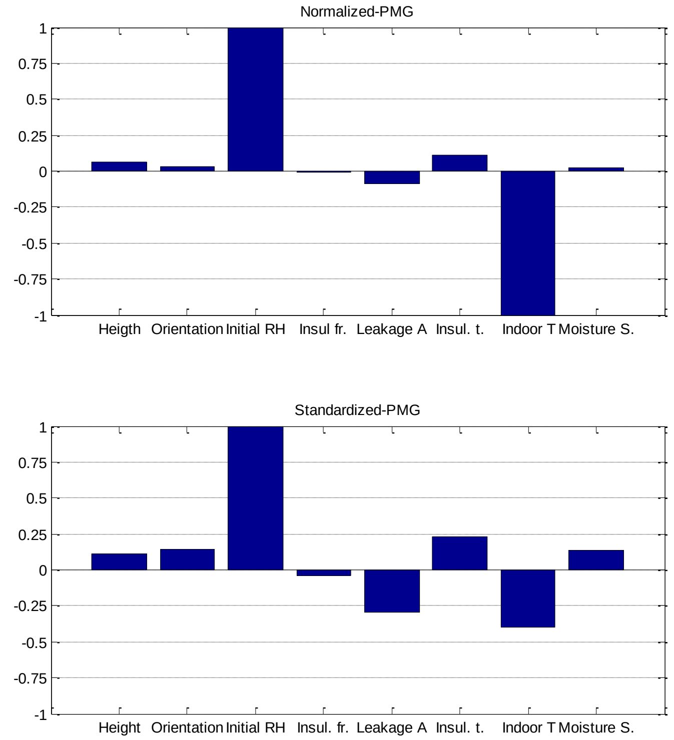

Figure 21 Case 2

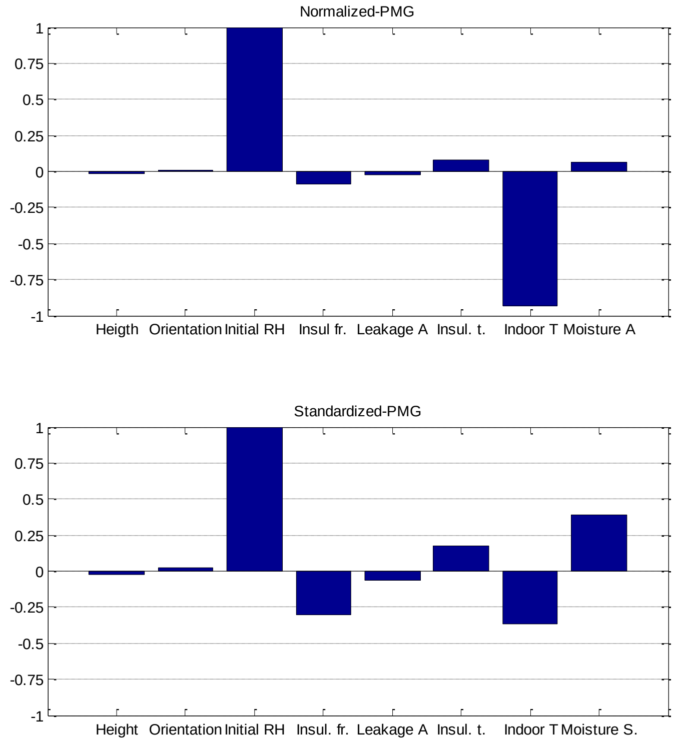

Figure 22 Case 3

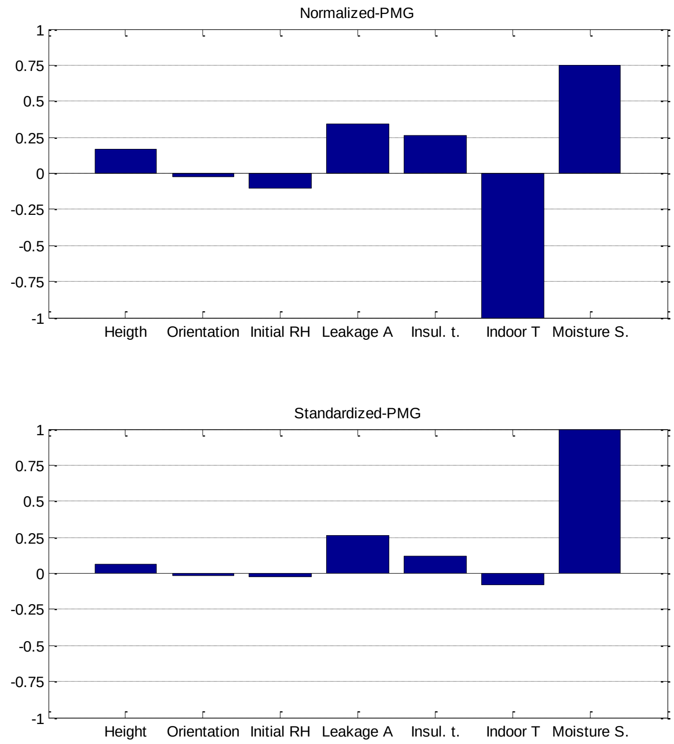

Figure 23 Case 4

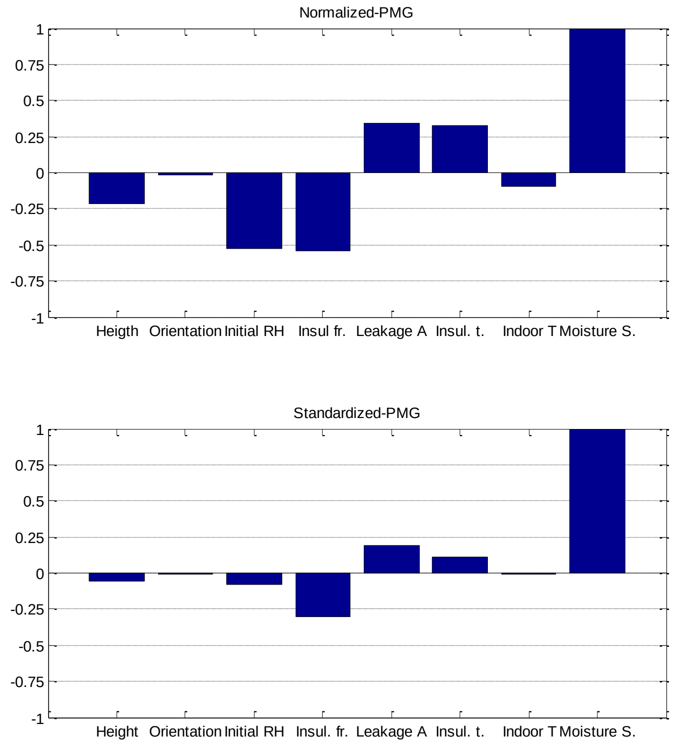

Figure 24 Case 5

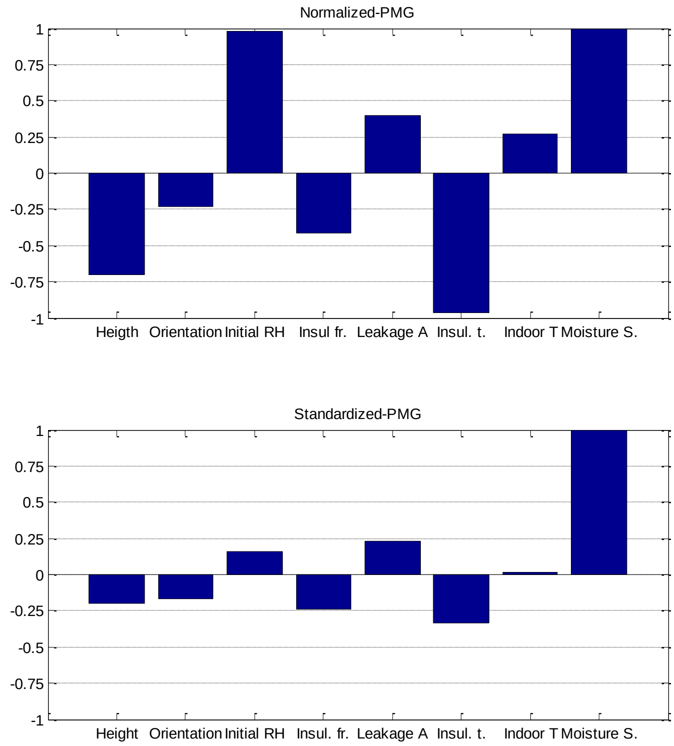

Figure 25 Case 6

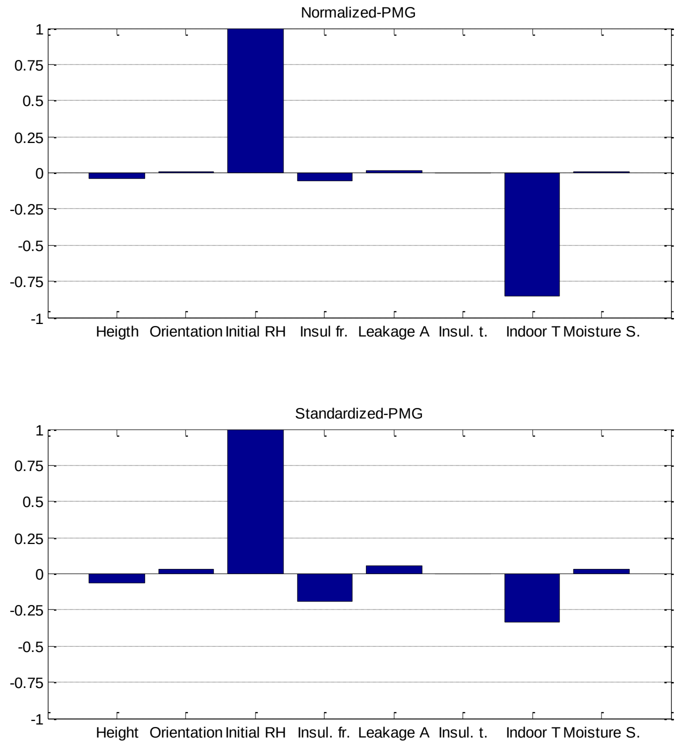

Figure 26 Case 7

Due to the low relative residual for the PMG regression, the data is also visually inspected by means of scatter-plots. As an example, PMG-values for case 4 and 7 are given by Figure 27 and Figure 28. The wood ceiling with higher leakage area is considered in case 4. For this construction the moisture supply and leakage area are the two most sensitive parameters according to Figure 23. Visually, by looking at the scatter-pots, we can confirm that this construction is sensitive to high moisture supply and a larger leakage area.

Construction 7 yields a different behaviour. The leakage area is much lower with the concrete ceiling. Hence, the tighter ceiling makes the moisture supply and leakage area insensitive parameters according to Figure 26. Construction 7 also has reduced ventilation in the attic; hence, the start RH in the wooden roof becomes the most sensitive parameter. This is clearly seen in the scatter-plot, see Figure 28.

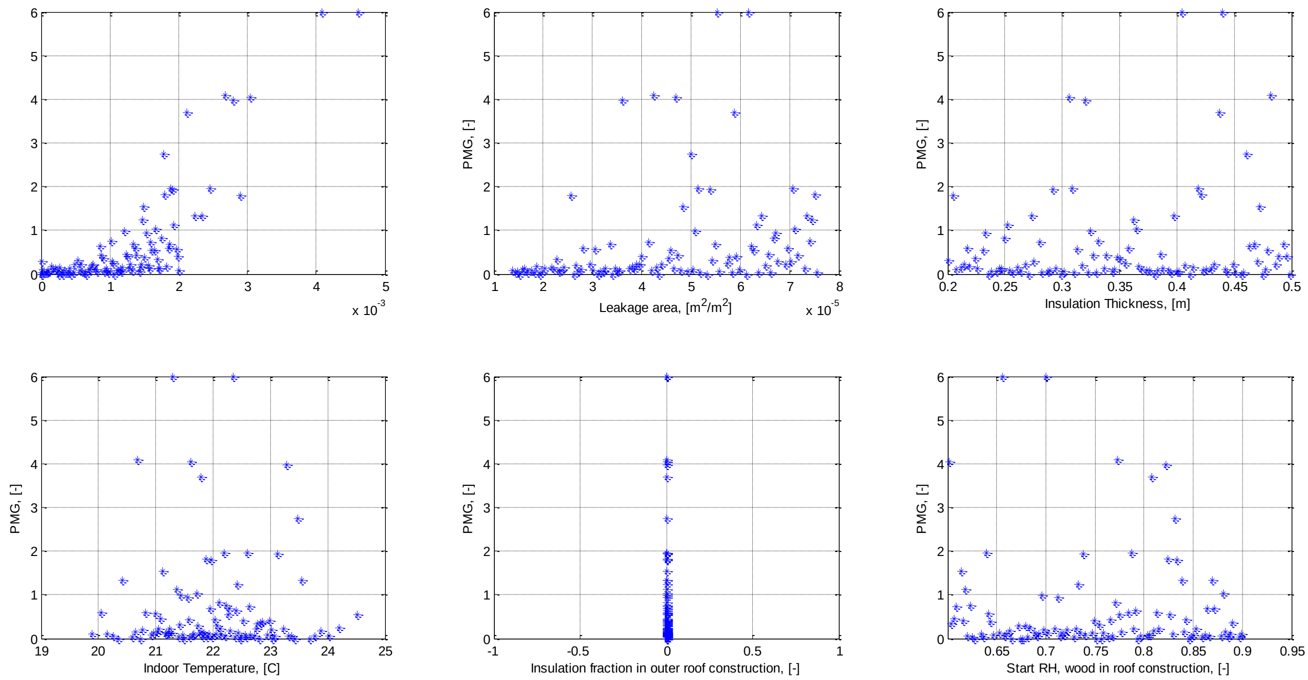

Figure 27 Scatter-plot PMG-values for case 4

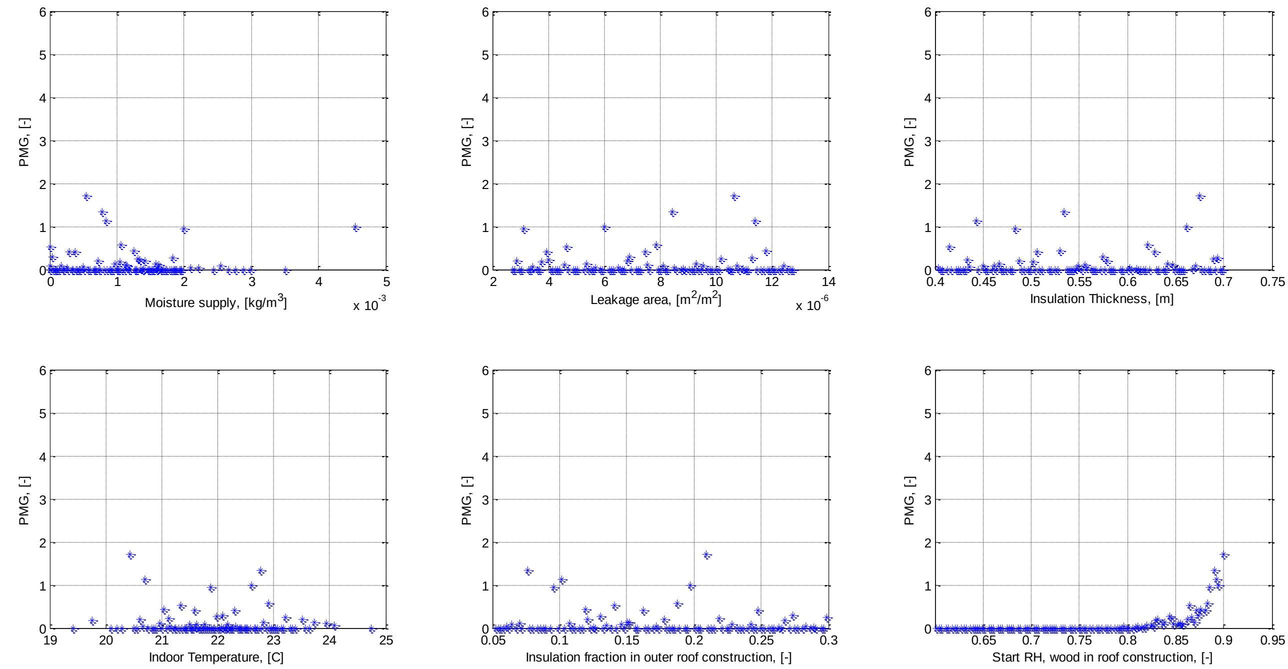

Figure 28 Scatter-plot PMG-values for case 7

Solution C

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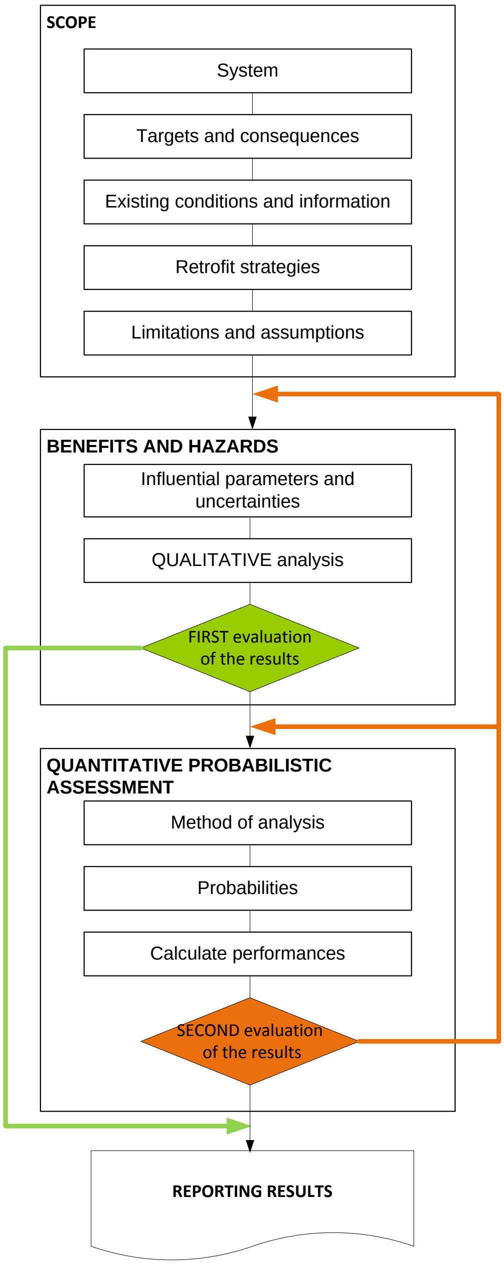
C1 INTRODUCTION

The purpose of this exercise is to evaluate the Framework for probabilistic assessment of hygrothermal performance of buildings that has been suggested in Annex 55, Subtask 3. The evaluation involves testing of the Framework on a hypothetical retrofitting case. The inspiration for Common exercise 2 of Subtask 3 is a renovation of the attics in a residential area Sigtuna, in Sweden. Several retrofitting alternatives have been suggested in the task in conformity with an accepted practice of retrofitting attics in Sweden, or what is believed is a good retrofit. The tasks in Common exercise 2 are to rank the suggested retrofitting alternatives according to identified risks and to report the entire procedure of the risk assessment by following the steps the Framework. For the former, a probabilistic modelling tool is provided together with supplementary input data. The purpose of the latter is to show if there is a need for additional clarifications or steps in the Framework, in which case a revision of the Framework may be suggested.

In a previous evaluation of the Framework, which is performed by the colleagues from the Danish Technical University (Just Johnston and Juhl, 2012), a substantial revision of the Framework has been suggested and motivated by the needs of consulting engineers. Besides a rewording of academic terms into a more common language, Just Johnston and Juhl suggested to expand the qualitative analysis section to "…allow smaller businesses to do extensive parts of the preliminary work before handing the assignment over to more specialised groups and thereby reducing their costs. Also, if professionals can use the tool without having to go through quantitative analysis, the tool could fairly be expected to be used more often. This additional use and the inherent extra awareness could be hypothesised to have a positive impact on the quality of building designs." The revised Framework is shown together with the original one in the figure that follows.

Inspired by these compelling motives for the revision of the Framework, the solution to Common exercise 2 is presented here in accordance with the structure of the revised Framework. As it will be seen, the revised Framework has facilitated well the risk evaluation procedure. A short summary of more specific findings about using the revised Framework is presented at the end of the report.



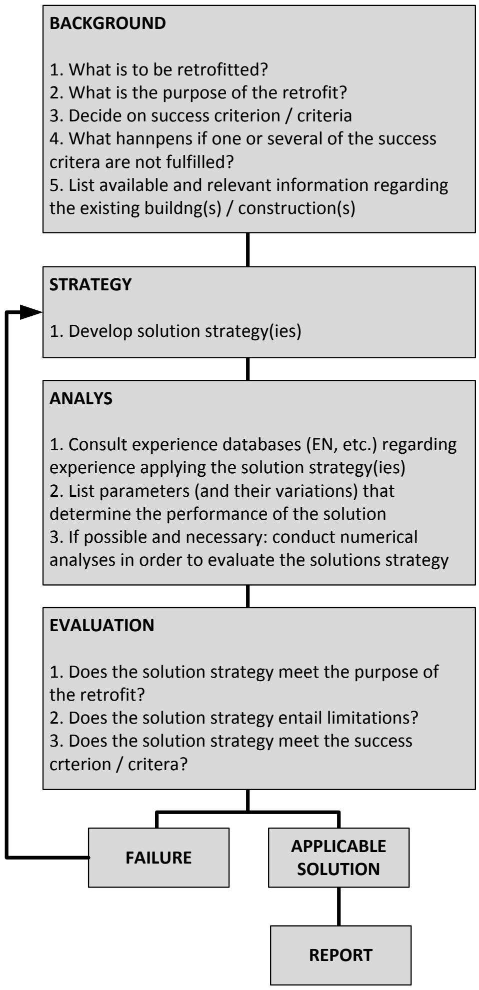


Figure 29 To the left: the Framework suggested in Subtask 3. To the right: the revised Framework by Just Johnston and Juhl.

C2 BACKGROUND

C2.1 What is to be retrofitted?

Sigtuna is a residential area near Stockholm, in Sweden, with a number of two-storey apartment buildings from early 1970s. The buildings were considered for retrofitting in order to comply with national targets on low energy use in buildings.

A preliminary energy analysis provided by Harderup and Stein (2010) shows that additional insulation of the building envelopes is necessary in order to meet desired energy targets for the buildings in Sigtuna.

This includes also the reduction of heat losses through the ceiling towards the attic, which can be done by adding an additional insulation layer on the existing attic floor. There are some considerations of adding extensions, i.e. additional storeys on top of the existing buildings. In such a case, the existing attics would be replaced by new attics of the same appearance and with well-insulated floors.

The analysis presented here is focused solely on risks related to the retrofitting of the existing attics or to the building of new attics of higher energy standard.

Figure 30: Apartment buildings in Sigtuna

C2.2 Purpose of the retrofit

The overall purpose of retrofitting is to reduce the current specific annual energy demand of 170 kWh per m² of heated floor area by about 50 %.

Besides, the retrofit should be cost-effective and durable, allowing problem-free renting of the apartments in the next 40 years.

C2.3 The success criteria

From a preliminary energy analysis shown in Figure 31 it follows that, by combining different retrofitting measures such as additional insulation of the building envelope and renovation of the ventilation system, the existing specific energy use in the buildings could be reduced to 89 kWh/m²/year. To achieve this energy target, the thermal transmittance through the ceiling should be reduced from current 0.22 W/m²K to 0.12 W/m²K, and that the overall air tightness of the building should be improved from 1.2 l/m²s to 0.65 l/m²s[4].

[4] At 50 Pa pressure difference

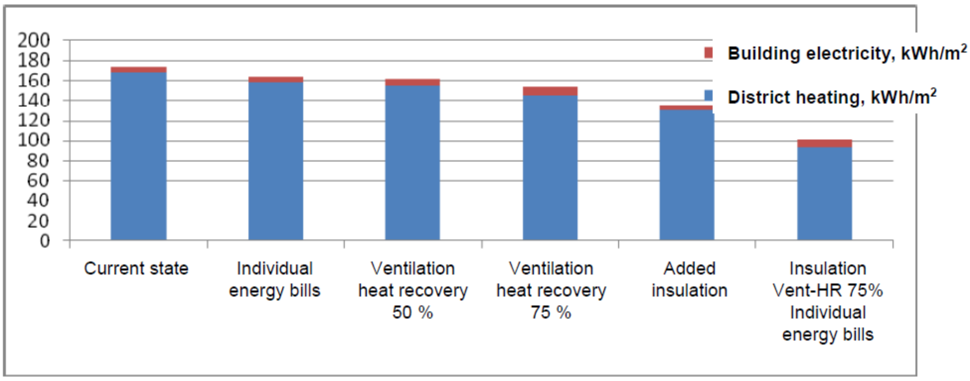


Figure 31 Specific energy use in the buildings in Sigtuna in relation to different retrofitting measures. From Harderup and Stein (2010).

A durable retrofitting of the attics means a cost-free operation of the attics over the buildings' lifetime. According to statistics (Boverket, 2010), common failures in attics' performance are due to water leakages through the roof or due to mould growth on the wooden roof underlay. The first could be prevented by a correct (water-tight) building of the attic roof. As for the latter, a remedy should be decided based on the attic construction, geographic location, operating conditions, as discussed in Hagentoft and Sasic (2012).

The success criteria in summary:

1. the total heat loss through the attic floor after retrofitting should be reduced by about 50 %. The total heat loss consists of a heat loss by transmission through the ceiling, and of a heat loss by air leakages from the dwellings to the attics.
2. Therefore, there should not be risk of mould growth in the attic. In other words, the mould growth index MGI for the roof underlay, as defined by Hukka and Viitanen (1999), should be less than 1.

C2.4 What happens if one or several of the success criteria are not fulfilled?

At the time of the report of Harderup and Stein (2010), the energy target 89 kWh/m²/year was much below a past limit for energy use in residential buildings, i.e. 110 kWh/m²/year (BBR 2010). The current limit is 90 kWh/m²/year[5], (BBR 2011:26), which is just slightly above the targeted value. If the suggested renovations would fail to reduce the current energy demand in the buildings below the values expressed in the current building regulations, the buildings would be classified in a worse "ene rgy" category. This could have various consequences for the house owners, and one could be a loss of reputation. In case of an increased price for energy delivered by district heating systems, the renting could be more expensive to compensate for higher energy demands.

From the energy savings point of view, the renovation of attics is the cheapest retrofitting measure, as shown in Table 6, and the easiest to apply. From the moisture safety point of view, the measure can trigger a mould growth on the wooden roof underlay. In such a case, the reparation of the attics would lead to additional costs.

Table 6 Cost of energy saving measures (from Mata, 2011)

[5] for the multi-residential dwellings in the same climate zone and where the heat is delivered by district heating

Measure	Interest rate	Lifetime	Maintenance cost	Specific cost per surface of basement	Specific cost per surface of facade	Specific cost per surface of roof	Specific cost per surface of window	Unitary cost
	%	years	SEK/y	SEK/m2	SEK/m2	SEK/m2	SEK/m2	SEK/Unit
Change of U-value of ellar/basement	4	40	0	1306	0	0	0	0
Change of U-value of facades (different types)	4	40	0	0	1508	0	0	0
Change of U-value of attics/roofs (different types)	4	40	0	0	0	410	0	0
Replacement of windows	4	40	7	0	0	0	2629	0
Upgrade of ventilation systems with heat recovery, for apartment buildings (MFD)	4	20	1000	0	0	0	0	44652

C2.5 Available and relevant information regarding the existing building construction

The buildings in Sigtuna are lamellar houses, arranged parallel to each other by longer sides, as shown in Figure 30. The houses are covered by shed roofs in northwest or southeast directions.

A vertical cross-section of the house is shown in Figure 32. The height of the house is 5 m, and approximately 7 m at the top roof edge. The width of the house is 11 m. The roof is pitched at 10 degrees.

The attic floor is made of 180 mm prefabricated concrete. The roof construction is (from outside to inside): a water and vapour tight layer (asphalt sheet) on top of a roof underlay, which is traditionally made of bare wooden boards of thickness 22 mm. .

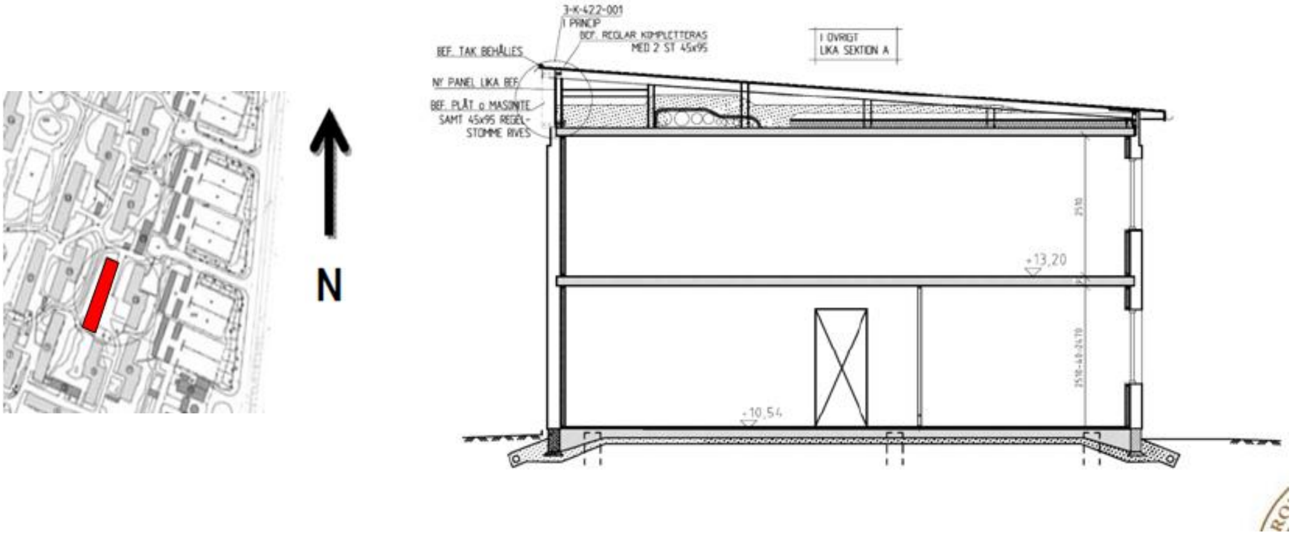


Figure 32: Left: Spatial plan of the buildings in Sigtuna. Right: Vertical cross-section through the attic before retrofitting

The condition of the attic in the current state is not known, though some information can be deducted from a photo and the plans of the apartments provided in Harderup and Stein (2010). The roof underlay and the roof trusses are free from visible mold spots. A possible moisture damaged part can be seen on the photo in Figure 33. As the damage seems localized, it could be due to some old water leakage in the roof. The existing insulation on the attic floor is uneven and there are cables (or just trash).

A mechanical exhaust only ventilation system is used for the ventilation of the houses. The exhaust air is collected in the bathrooms and kitchens. A system of air ducts that are placed in the attic, on the attic floor, takes away the exhaust air out of the houses. The mechanical exhaust only ventilation system is beneficial as it creates an under pressure in the apartments in relation to the attic, preventing thus air leakages to the attic. It is very likely that it will be replaced by an exhaust-supply ventilation system, in which case the pressure difference between the attic and the apartments will decrease.

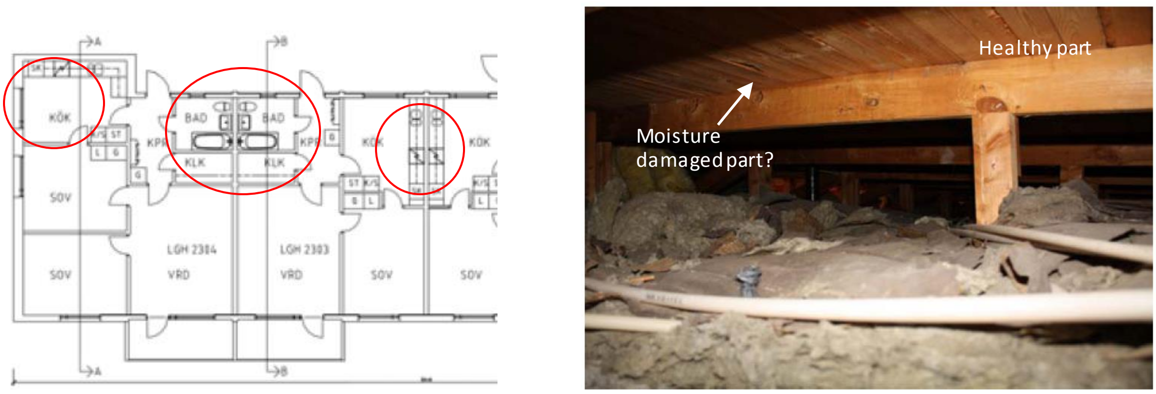


Figure 33: Left: Plan of the apartments. Right: photo from the attic in the current state (Harderup and Stein, 2010).

C3 RETROFIT STRATEGY

C3.1 Developing solution strategies

Major means for the reduction of heat losses through the ceiling are good insulation of the attic floor (400 mm or more) and a better airtightness of the ceiling. Although the latter normally constitutes a minor part in the total heat loss through the ceiling[6], it is important to include it into the analysis because of its great impact on the moisture performance of the attic. Namely, a reduced air infiltration from the dwelling to the attic reduces a moisture excess in the attic and, thereby, the risk for moisture accumulation in the roof underlay.

An airtight attic floor is a necessary but not the sufficient condition for preventing moisture accumulation in the roof underlay. In certain circumstances, the moisture in the outdoor air, which is used for ventilation of the attic, can condensate on the roof. This occurs when the attic becomes colder[7] than the outdoor air, which is typically due to night-time cooling from the sky. Roof and the roof underlay, as the most exposed parts of the attic to the sky are also the most susceptible area for the moisture condensation. In these conditions, moisture condensation occurs even in attics with perfectly airtight attic floor.

Insulation of the roof and a reduced ventilation of the attic are further measures that may decrease a moisture condensation at the roof underlay. The first prevents sub-cooling of the roof by sky radiation, while the latter reduces moisture condensation at the roof underlay when the roof is colder than the outdoor air. Each 1cm of insulation on the roof increases the temperature of the roof by approximately 0.25 °C during sub-cooling. The same measure decreases the temperature of the roof correspondingly during sunny hours, which makes the attic colder and susceptible to moisture accumulation. The final outcome of this measure depends on the balance between cold and warm periods, and on the presence of moisture sources in the attic. The reduced ventilation is effective when the ventilation by outdoor air is a dominant cause for a moisture condensation at the roof underlay. Otherwise, it can worsen the conditions inside the attic by reducing moisture removal from other moisture sources in the attic, such as built-in moisture or moisture due to air infiltration from the dwelling.

All above mentioned measures can be applied separately or in combination. Thus, six different solutions for the retrofitted attics are identified, as summarized in Table 7 and illustrated in Figure 34. As it can be seen, the major grouping of the cases is done in respect to the airtightness of the attic floor.

Table 7 Retrofit measures for the attic

Retrofit cases	Good airtightness of the ceiling			Poor airtightness of the ceiling		
	A1	A2	A3	A4	A5	A6
Insulated floor (at least 400 mm)	X	X	X	X	X	X
Insulated roof (optional)		X	X		X	X
Normal ventilation of the attic[8]	X	X		X	X	
Reduced ventilation of the attic[9]			X			X

[6] In Sweden

[7] Below a dew point temperature for the outdoor air

[8] Through 20 mm wide openings along roof edges, on both sides

[9] Through gable vents. App. 10-20 times less airflow rate than through 20 mm wide openings along roof eaves

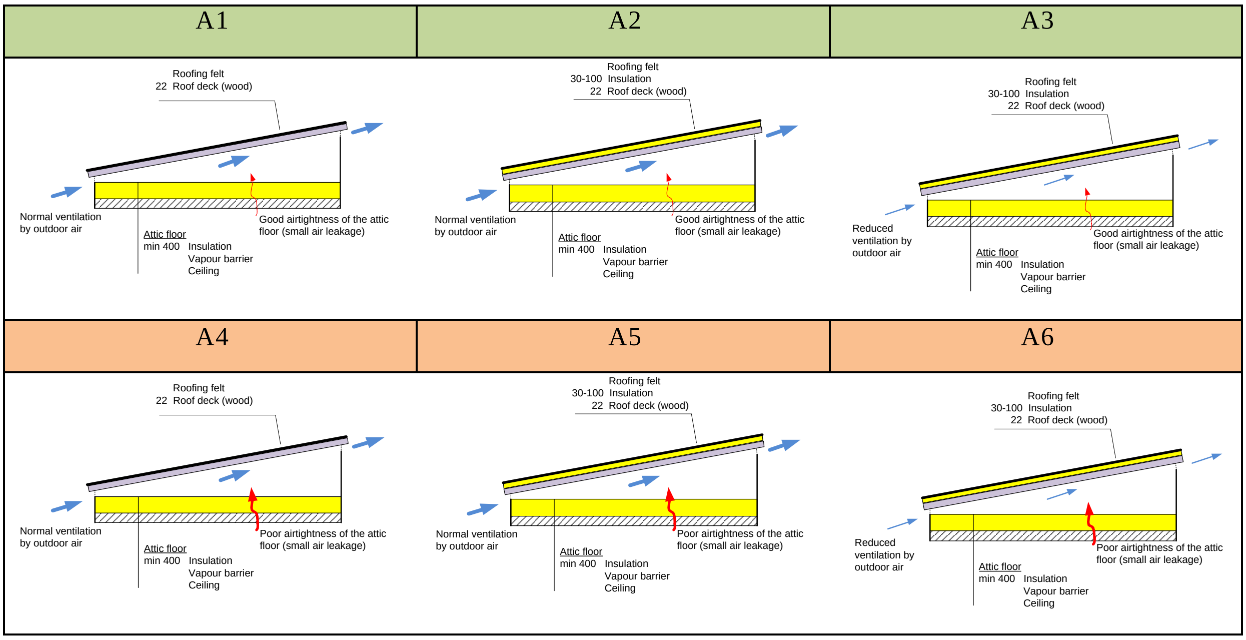


Figure 34: Alternative constructions of the new attic

C3.2 Assumptions and limitations

This analysis applies only on cold attics. It is assumed that the slope of roof does not change with the retrofitting. It is further assumed that there are no water leakages through the roof or through the service pipes inside the attic. Finally, there are no any air leakages from the service pipes.

C4 ANALYSIS

C4.1 Existing knowledge about the chosen retrofit strategies

About 88 % of the buildings in the Swedish building stock have a roof construction with a cold attic (of type A1 or A4, with normal or reduced ventilation) and mould is visible in about 15 % of them (Hagentoft and Sasic, 2012). Hence, cold attics are regarded as risk constructions. The mould problem is present in both old and new constructions. There is a certain correlation between the occurrence of mould in attics and the following conditions:

- Naturally ventilated buildings and mechanical ventilation systems that creates a positive indoor pressure
- Heating system, not using combustion
- A large moisture production indoors (moisture supply), in combination with air leaky
- ceiling / attic floor
- Roof underlay consisting of wooden board such as plywood
- Increased thickness of the attic ceiling insulation
- Air leakage through the attic floor
- The ventilation of attics in cold and maritime climates

Attics of types A2-A3 and A5-A6 are rare and thus there is no reliable statistics about their hygrothermal performance.

Many of the above indicated conditions could be valid for the buildings in Sigtuna. As concluded in Hagentoft and Sasic (2012), a proper retrofit strategy for the attics should be decided based on the attic construction, geographic location, operating conditions.

C4.2 Parameters that determine the outcome of the retrofit

In the Common Exercise number four of Subtask 2 (ST2 CE4), fifteen different parameters have been identified as potentially influential on the outcome of the retrofit. For the sake of clarity, these parameters are grouped here in several categories together with their default values.

Geometry of the building

- Height of the building: 5 m
- Length of the building (eave side): 20 m
- Area of ceiling and roof: 20·11=220 m^2
- Orientation of one of eave side: W
- Thickness of the wooden underlay: 0.022 m

Hygrothermal properties of the wooden underlay

- Vapour diffusion coefficient of wood: $1\cdot10^{-6}$ m^2/s
- Initial relative humidity of the wooden underlay: 70 %
- Thermal conductivity of wood: 0.13 W/mK

Insulation of the attic floor and the roof

Thermal transmittance of the attic floor U_c: 0.2/0.1/0.07 W/m^2K corresponding to 200/400/600 mm of insulation on the attic floor

$$U_c \approx \frac{0.04}{x}$$

where 0.04 W/mK is the thermal conductivity of insulation and *x* is the insulation thickness on the attic floor

Resistance of the roof insulation: 0.8/1.25/2.5 m^2K/W corresponding to 0.02/0.050/0.1 m of insulation in the roof

$$R_r \approx \frac{y}{0.04}$$

where 0.04 W/mK is the thermal conductivity of insulation and *y* is the insulation thickness of the roof

Ventilation and air infiltration in the attic

- Venting area per meter eave: 0.02/0.001 m^2/m, where the first corresponds to the venting area of a traditional attic construction, i.e. 20 mm wide opening along the roof edge, while the latter corresponds to venting through gable vents.
- Leakage area per area of the attic floor: $6.4\cdot10^{-6}$ / $3.8\cdot10^{-5}$ m^2/m^2, where the first corresponds to an attic floor with GOOD airtightness ($n_{50\_ceiling}$=0.05 1/h when n_{50_house}=2.5 1/h), and the latter to an attic floor with POOR airtightness (n_{50}=0.3 1/h when n_{50_house}=2.5 1/h). According to Hens et al. (2003), the good value of airtightness can be expected in heavy-weight compact roofs with a polyethylene (PE) vapour and airflow retarder with open overlaps, and the poor in lightweight compact roofs without vapour and airflow retarder.

Indoor conditions in the apartment below the attic

- Indoor temperature: 22 °C
- Indoor moisture supply: 3 g/m^3

Outdoor weather conditions in Sigtuna (Stockholm)

- Year of climate data: 1975-2005

The above listed parameters are not equally important for the outcome of the retrofitting and it is desirable to classify them into important and less important. In the lack of other knowledge, the classification can be done by numerical simulations, where the values of the parameters are varying within expected ranges, one in a time or several at once, and by analysing how these changes affect the outcome of the retrofit. Reasonable guesses are also very helpful in the classification. These different approaches are demonstrated hereafter.

The buildings in Sigtuna were produced in a mass production and it could be expected that the geometry of the attics and the hygrothermal properties of the building materials used for the attics didn't vary significantly between the buildings. Hence, the parameters 1-8 can be fixed to default values throughout the whole analysis. Insulation of the attic floor and roof, ventilation of the attic and air leakage of the ceiling (the parameters 9-12) can be changed substantially during the renovation; it is necessary to carefully investigate how their variability affects the outcome of the retrofitting. A special attention should be paid to the variability of the ceiling airtightness (12), because it can be changed by the tenants after the retrofitting (user-made penetrations for lamps). The remaining parameters, i.e. indoor thermal comfort ant moisture excess (13-14) and the weather conditions at the time of the retrofitting (15) cannot be affected by the retrofitting but could have a large impact on it; therefore, they will be also varied in the analysis.

In summary, seven out of fifteen parameters need to be varied in the analysis, which would require a quite number of simulations. For example, if each parameter takes two values, i.e. the minimum and maximum, 2^7=128 is necessary to explore all possible combinations of these values. If three values are to be tested for each parameter, e.g. the minimum, middle and maximum, the number of simulations rises to 3^7=2187. It is thus highly recommended to develop a strategy for varying the influential parameters in the numerical simulations that will support a knowledge build-up about the risks associated with the retrofitting. A good simulation strategy will quickly identify the cases with high and low risks, which can be omitted from further analysis and thereby the total number of simulations can be decreased.

C4.3 Numerical analysis

Numerical simulations that are presented hereafter are performed by a Matlab script entitled Cold_Attic_5.m, which is provided together with ST3 CE2.

As a success criterion for energy performance of the attics after the retrofitting, the total heat loss through the ceiling during January, which is the coldest month in Sigtuna, is used. The total heat loss comprises both transmission and air leakage losses through the ceiling.

The risk of mould growth is estimated based on a maximum MGI that is found at the roof underlay during the first year after the retrofitting. The procedure is described below. There are several assumptions beside this success criterion. Firstly, it is assumed that attics are mould-free after the retrofitting (MGI=0). Secondly, the renovation of the attics is finished during summer, closer by the end of June. Thirdly, if the maximum MGI exceeds the value 1 during the first year after the retrofitting (see for example Figure 35), the attic is considered under a risk of mould growth. Finally, when several outcomes for a same attic construction are investigated, the risk of mould growth is found by dividing the number of cases with MGI>1 by the total number of investigated cases. Figure 36 shows 128 different outcomes for an attic of a certain construction, where the variations in the outcomes are obtained by varying the parameters 12-15. As it can be seen, in 17 out of 128 cases, MGI is larger than 1 and the risk of mould growth is estimated as 17/128=13%.

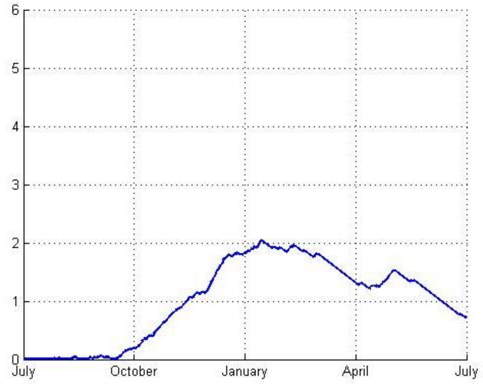


Figure 35 An example of a calculated MGI for a roof underlay in a retrofitted attic, during the first year after the retrofitting. Maximum MGI is 2.

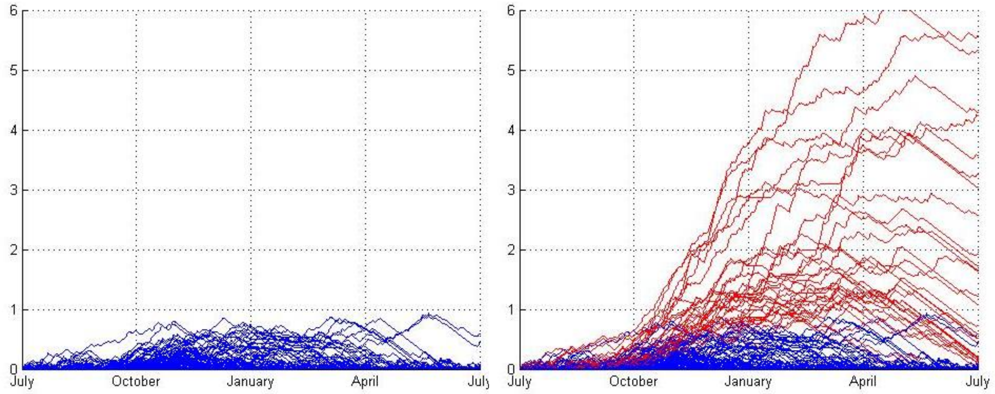


Figure 36 Assessment of mould growth risk for an attic. To the left, the mould free cases (111 in total). To the right: 111 mould free cases (in blue) together with 17 mould risk cases (in red, with MGI>1). Total number of cases is 128.

The investigation starts by analysing the outcome of the retrofitting due to increased insulation thickness on the attic floor. The insulation thickness is varied in a discreet manner, from 200 mm, to 400 mm and 600 mm. The existing attic construction is investigated, i.e. A1 and A4 with good and poor airtightness of the attic floor, respectively. Only the weather conditions are varied randomly. All other parameters are kept constant as shown in Table 8

.

Table 8 Preliminary analysis on air tightness of the attic floor

	Type of attic construction	A1			A4		
	Case	1	2	3	4	5	6
	Geometry of the building						
1	Height of the building, m	5	5	5	5	5	5
2	Length of the building (eave side), m	20	20	20	20	20	20
3	Area of ceiling and roof, m2	220	220	220	220	220	220
4	Orientation of the roof	W	W	W	W	W	W
5	Thickness of wooden underlay, mm	22	22	22	22	22	22
	Hygro-thermal properties of wood						
6	Thermal conductivity of wood, W/mK	0.13	0.13	0.13	0.13	0.13	0.13
7	Vapour diffusion coefficient of wood, m2/s	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06
8	Intial relative humidity of wood, %	70	70	70	70	70	70
	Insulation of the attic floor and the roof						
9	Insulation on the attic floor, mm	200	400	600	200	400	600
10	Insulation on the roof, mm	0	0	0	0	0	0
	Ventilation and air infiltration in the attic						
11	Venting area, opening mm	20	20	20	20	20	20
12	Airtightness of attic floor	good	good	good	poor	poor	poor
	Indoor conditions in the apartment						
13	Indoor temperature, oC	22	22	22	22	22	22
14	Indoor moisture production, g/m3	3	3	3	3	3	3
15	**Outdoor climate**	* random	random	random	random	random	random
	RESULTS						
	Mean energy loss in January, kWh/m2	3.89	1.98	1.26	3.97	2.04	1.22
	Mean max MGI	0.07	0.21	0.21	2.29	3.37	3.28
	Risk of MGI>1, %	0	0	0	100	100	77

* random means that the climate year is randomly selected in the interval 1975-2005

The results in Table 8 show that the most decisive parameter for the energy loss through the ceiling is the thickness of insulation. The heat loss can be halved when the insulation thickness is doubled. Adding more insulation, to 600 mm, additionally decreases the heat loss. A small difference between the heat losses in attics A1 and A4 is due to air leakage through the ceiling.

Based on these result, it follows that the air tightness of the attic floor is the most decisive parameter for mould growth risk. A sufficiently airtight attic floor will prevent the moisture infiltration to the attic and the risk of mould growth on the roof underlay during the first year after the construction of the attic. The risk of mould growth is very large if the attic floor is not air-tight, and due to this, the attic type A4 can be de-selected form further investigations. These findings are also summarized in the figure that follows.

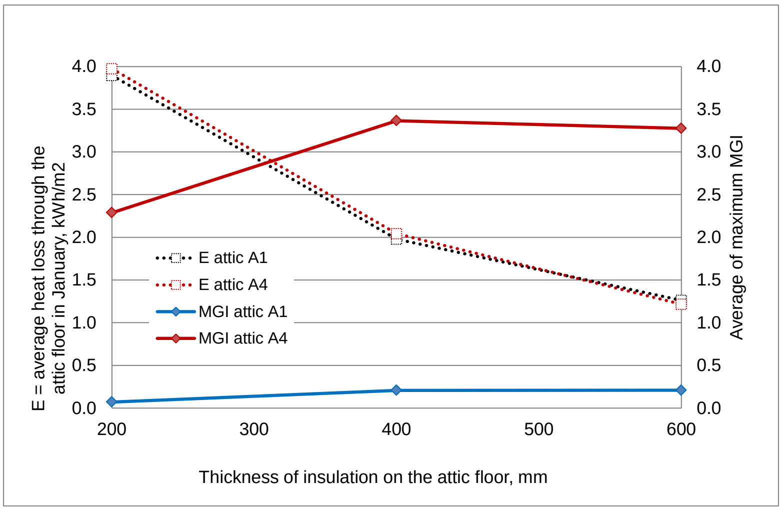


Figure 37 Summary of the results from Table 8.

Each calculated case 1-6 involves 30 different runs, where an outdoor climate is selected randomly. An example of a random selection of climate years is shown in Figure 38. As it can be seen, some climate years have been selected more times than the others, whereas some have not been selected at all. It would be preferable that each year is selected equal number of times as there is no any reason for prioritizing certain years. Because of this, all results are preliminary and serve as orientations for further investigations.

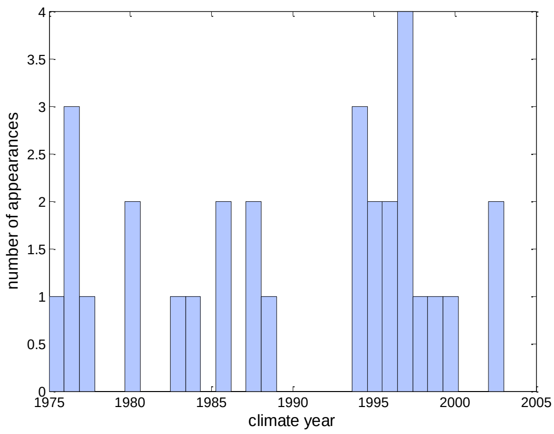


Figure 38 Randomly selected climate years for the case 1. The total number of cases is 30.

The investigation continues by varying the venting area and the insulation of the roof in attics with good airtightness of the attic floor, i.e. A1-A3, as shown in Table 9. The case 2 from Table 8 is used as a reference and the differences in respect to this case are marked with grey. Besides the differences in the attic construction, air tightness of the ceiling and indoor moisture production are also varied. The first is varied uniformly between the values $5 \cdot 10^{-6}$ to $9 \cdot 10^{-6}$ m^2/m^2, i.e. in a close vicinity of the reference value $6.4 \cdot 10^{-6}$ m^2/m^2. The latter is varied around the reference value of 3 g/m^3, and by following a normal distribution and with standard variation of 1 g/m^3. This is additionally illustrated in Figure 39.

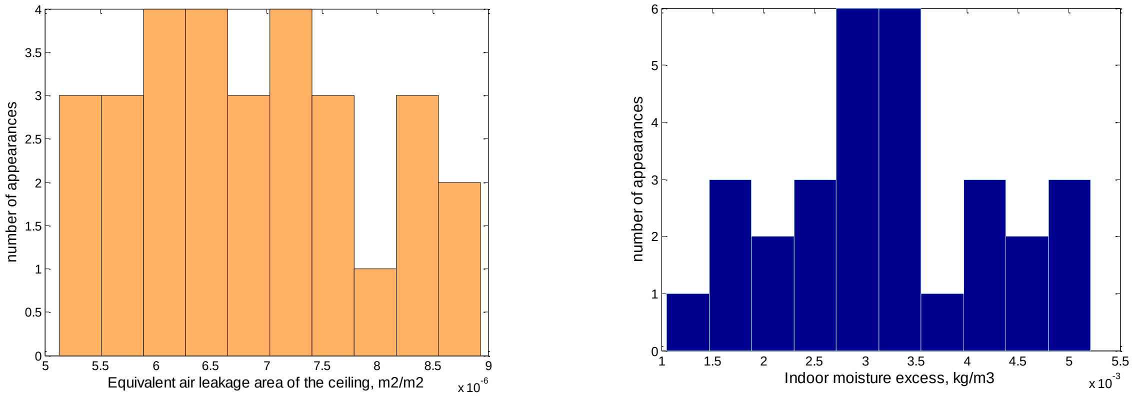


Figure 39 Randomly selected values of airtightness of the ceiling (to the left) and of indoor moisture excess (to the right). The total number of cases is 30 in each example.

The results in Table 9 show that a varying airtightness of the ceiling and a varying indoor moisture production (cases 21 and 25) do not affect significantly the results in comparison to the reference case, although a decrease in MGI can be observed. It is also shown that 30 mm of insulation on the roof decreases the energy loss through the attic floor by additional 10 %. Furthermore, the reduced ventilation through the attic contributes to somewhat lower MGI in the attic, though without a significant influence on the energy loss. Finally, the reduced ventilation and the insulation of the roof results in the lowest MGI in the attics.

Table 9 Impact of roof insulation and reduced ventilation of the attic on the outcome of the retrofit of an attic with good airtightness of the attic floor

	Type of attic construction	Reference	A1	A2	A3	
	Case	2	21	23	24	25
	Geometry of the building					
1	Height of the building, m	5	5	5	5	5
2	Length of the building (eave side), m	20	20	20	20	20
3	Area of ceiling and roof, m2	220	220	220	220	220
4	Orientation of the roof	W	W	W	W	W
5	Thickness of wooden underlay, mm	22	22	22	22	22
	Hygro-thermal properties of wood					
6	Thermal conductivity of wood, W/mK	0.13	0.13	0.13	0.13	0.13
7	Vapour diffusion coefficient of wood, m2/s	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06
8	Intial relative humidity of wood, %	70	70	70	70	70
	Insulation of the attic floor and the roof					
9	Insulation on the attic floor, mm	400	400	400	400	400
10	Insulation on the roof, mm	0	0	30	30	0
	Ventilation and air infiltration in the attic					
11	Venting area, opening mm	20	20	20	1	1
12	Airtightness of attic floor	good	* good ±	good ±	good ±	good ±
	Indoor conditions in the apartment					
13	Indoor temperature, oC	22	22	22	22	22
14	Indoor moisture production, g/m3	3	3	** 3 ± 1	3 ± 1	3 ± 1
15	**Outdoor climate**	random	random	random	random	random
	RESULTS					
	Mean energy loss in January, kWh/m2	1.98	1.98	1.77	1.78	1.97
	Mean max MGI	0.21	0.17	0.08	0.03	0.11
	Risk of MGI>1, %	0	0	0	0	0

* good ± means that the airtightness is varied uniformly in the interval (5-9)·10^{-6} m²/m²
** indoor moisture production 3 ± 1 is varied by a normal distribution, with a mean at 3 g/m3 and a standard deviation 1 g/m3

A similar analysis can be performed on attics with poor airtightness of the attic floor (A4-A6). Case 4 from Table 8 serves as a reference in this investigation and the differences in respect to the reference case are marked with grey (see Table 10). The results show that insulation on the roof decreases substantially the risk of mould growth from 100 % as in the reference case, to 17 % if 100 mm insulation is applied on the roof. At the same time the energy loss through the attic floor decreases by 23 %. Furthermore, it can be seen that a reduced ventilation of the attic (case 45) decreases somewhat but not enough the risk of mould growth in the attic in comparison to the reference case. Finally, the reduced ventilation should not be combined with the insulated roof (case 44) as it increases the risk of mould growth.

Table 10 Impact of roof insulation and reduced ventilation of the attic on the outcome of the retrofit of an attic with poor airtightness of the attic floor

	Type of attic construction	Reference	A4		A5			A6	
	Case	4	41	42	43	431	432	44	45
	Geometry of the building								
1	Height of the building, m	5	5	5	5	5	5	5	5
2	Length of the building (eave side), m	20	20	20	20	20	20	20	20
3	Area of ceiling and roof, m2	220	220	220	220	220	220	220	220
4	Orientation of the roof	W	W	W	W	W	W	W	W
5	Thickness of wooden underlay, mm	22	22	22	22	22	22	22	22
	Hygro-thermal properties of wood								
6	Thermal conductivity of wood, W/mK	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
7	Vapour diffusion coefficient of wood, m2/s	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06
8	Intial relative humidity of wood, %	70	70	70	70	70	70	70	70
	Insulation of the attic floor and the roof								
9	Insulation on the attic floor, mm	400	400	400	400	400	400	400	400
10	Insulation on the roof, mm	0	0	0	30	50	100	30	0
	Ventilation and air infiltration in the attic								
11	Venting area, opening mm	20	20	20	20	20	20	1	1
12	Airtightness of attic floor	poor	* poor ±	poor ±	poor ±	poor ±	poor ±	poor ±	poor ±
	Indoor conditions in the apartment								
13	Indoor temperature, oC	22	22	22	22	22	22	22	22
14	Indoor moisture production, g/m3	3	3	3 ± 1	3 ± 1	3 ± 1	3 ± 1	3 ± 1	3 ± 1
15	**Outdoor climate**	random	random	random	random	random	random	random	random
	RESULTS								
	Mean energy loss in January, kWh/m2	2.04	1.96	1.94	1.76	1.69	1.57	1.67	1.97
	Mean max MGI	3.37	2.91	2.6	1.47	1.14	0.52	4.45	3.73
	Risk of MGI>1, %	100	87	67	43	37	17	87	77

* poor ± means that the airtightness is varied uniformly in the interval (1-6)·10^{-5} m^2/m^2

C5 EVALUATION

C5.1 Does the solution strategy meet the purpose of the retrofit?

From a preliminary numerical analysis presented above, one can conclude that any of the retrofit strategies A1-A6 will reduce the energy loss through the ceiling. However, there are substantial differences between these attics in respect to the mould risk:

A1-A3 the risk is low, and these solutions are advised

A4 & A6 the risk is high risk and these strategies are not advised

A5 + 10 cm, the risk is around 20 %

C5.2 Does the solutions strategy entail limitations?

The absence of mould growth risk during the first year after the retrofitting does not mean that the risk can be avoided in the coming years. Based on the results, the most decisive parameter appears to be the airtightness of the ceiling. If it is worsen, an attic may fall in a risk category.

More varying parameters, a larger number of runs and a batter sampling technique for randomly selected values may provide somewhat different results of the mould risk assessment. By varying for example five out of eight parameters, which are sampled by a quasi-random technique entitled Sobol, and larger number of simulations, 300 instead of 30, the risk of mould growth in the attic of type A5 is found to be 12 %. Examples of sampling of the climate years and indoor moisture productions by the Sobol technique are given below. In comparison to pure random (Monte-Carlo) sampling on a fewer number of cases from Figure 34 and Figure 35, much better filling of the ranges is achieved and a more faithful presentation of the desired distributions.

Although the estimated risks differ largely in absolute values (20% and 12%), the risk of 12 % is too large as it means that roughly every 10th building will be under a risk of mould growth. Therefore, the renovation type A5 is not advised.

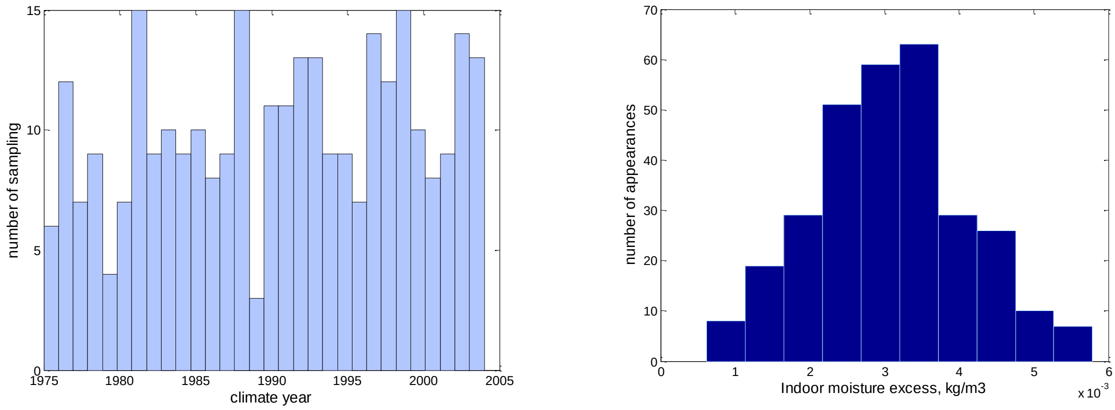


Figure 40 Quasi-randomly selected values of the climate year (to the left) and of indoor moisture excess (to the right) by using Sobol technique. The total number of cases is 300 in each example.

C5.3 Does the solution strategy meet the success criteria?

In order to meet the success criteria, the retrofit strategies A1-A3 should include at least 400 mm insulation on the attic floor.

C6 APPLICABLE SOLUTIONS

Applicable solutions are A1-A3, while A4-A6 will lead to very large or a significant failure.

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Solution D

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The goal of the study is to reduce the heat loss through the new attic floor by at least 50% in comparison to the present state (?) and overall air tightness of the building should be improved from 1.2 L/sm2 to 0.65 L/sm2.

Mission: "For the buildings in Sigtuna, the builders should choose, among six alternatives, an attic construction with the satisfactory energy performance and the lowest risk for mould growth on the roof underlay. Of course, the price also plays a role."

We have analyzed the thermal performance and mould growth risk by running stochastic simulations for each six alternatives. Total of 900 runs were carried out for each set.

The alternatives for the new attics are presented in Table 1 with the varied parameters and their ranges.

Table 11 Parameters used in the simulations. (U=uniformly distributed values)

Alternative Feature	1	2	3	4	5	6
Concrete floor	X	X	X			
Timber framed floor				X	X	X
Insulated floor (U-value)	0.1-0.2 U	0.1-0.2 U	0.1-0.2 U	0.1-0.2 U	0.1-0.2 U	0.1-0.2 U
Insulated roof (R-value)	0	0-2 U	0-2 U	0	0-2 U	0-2 U
Ventilation at eaves	0.01-0.03 U	0.01-0.03 U	0	0.01-0.03 U	0.01-0.03 U	0
Ventilation at gable ends	0	0	0.001-0.003 U	0	0	0.001-0.003 U
Ceiling leakage (m^2/m^2)	$1\cdot10^{-6}$-$1\cdot10^{-5}$ U	$1\cdot10^{-6}$-$1\cdot10^{-5}$ U	$1\cdot10^{-6}$-$1\cdot10^{-5}$ U	$1\cdot10^{-5}$-$5\cdot10^{-5}$ U	$1\cdot10^{-5}$-$5\cdot10^{-5}$ U	$1\cdot10^{-5}$-$5\cdot10^{-5}$ U
Ti (°C)	22 std 1	22 std 1	22 std 1	22 std 1	22 std 1	22 std 1
MS (g/m^3)	1.2 std 0.8	1.2 std 0.8	1.2 std 0.8	1.2 std 0.8	1.2 std 0.8	1.2 std 0.8
Constants						
Height, m	5					
Area, m^2	220					
d, m	0.022					
Deltav, m^2/s	$1\cdot10^{-6}$					
StartRH	0.7					
Lambda, W/mK	0.13					

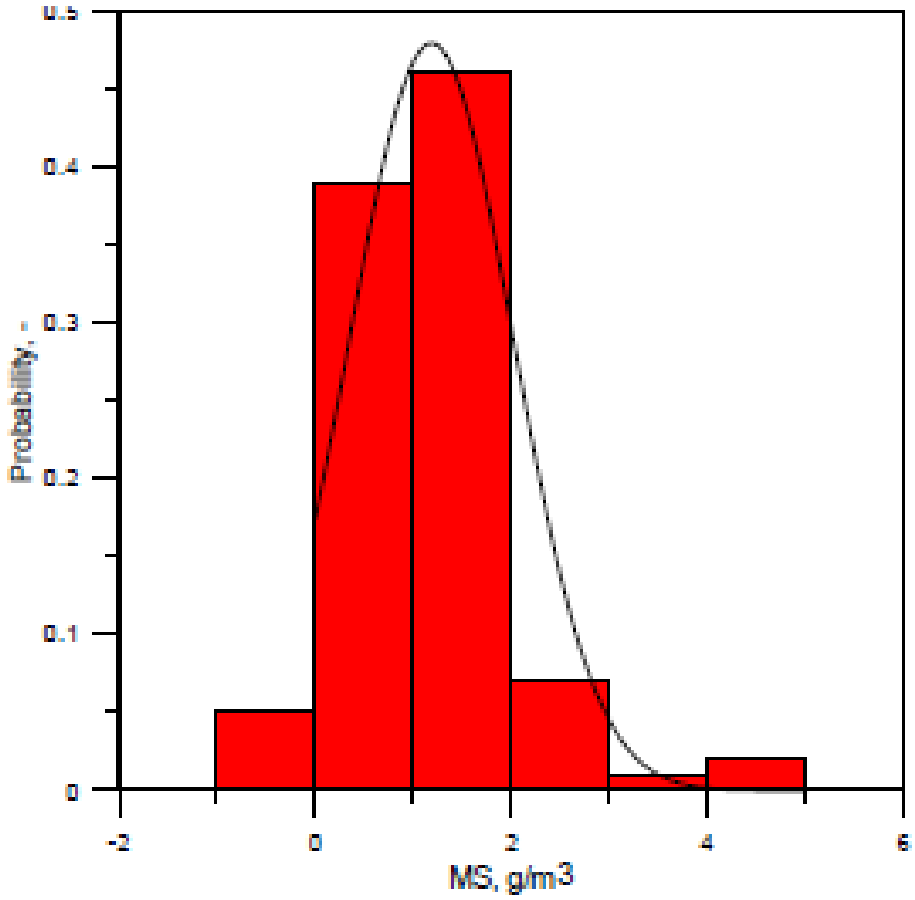

Figure 41 Indoor moisture loads applied to the simulations.

D1 Process of selecting the solution

We have selected the best alternative by going through a series of analyses. First we have looked at the thermal performance and second we have confirmed that the subset based on thermal performance has adequate and acceptable moisture performance. Cost values were not given and we won't analyze the costs versus savings (i.e., payback period).

The results presented in the following have been simulated with the weather data for the east orientation.

Thermal performance

First the set of alternatives were simulated with a fixed climate to look at the best thermal alternatives.

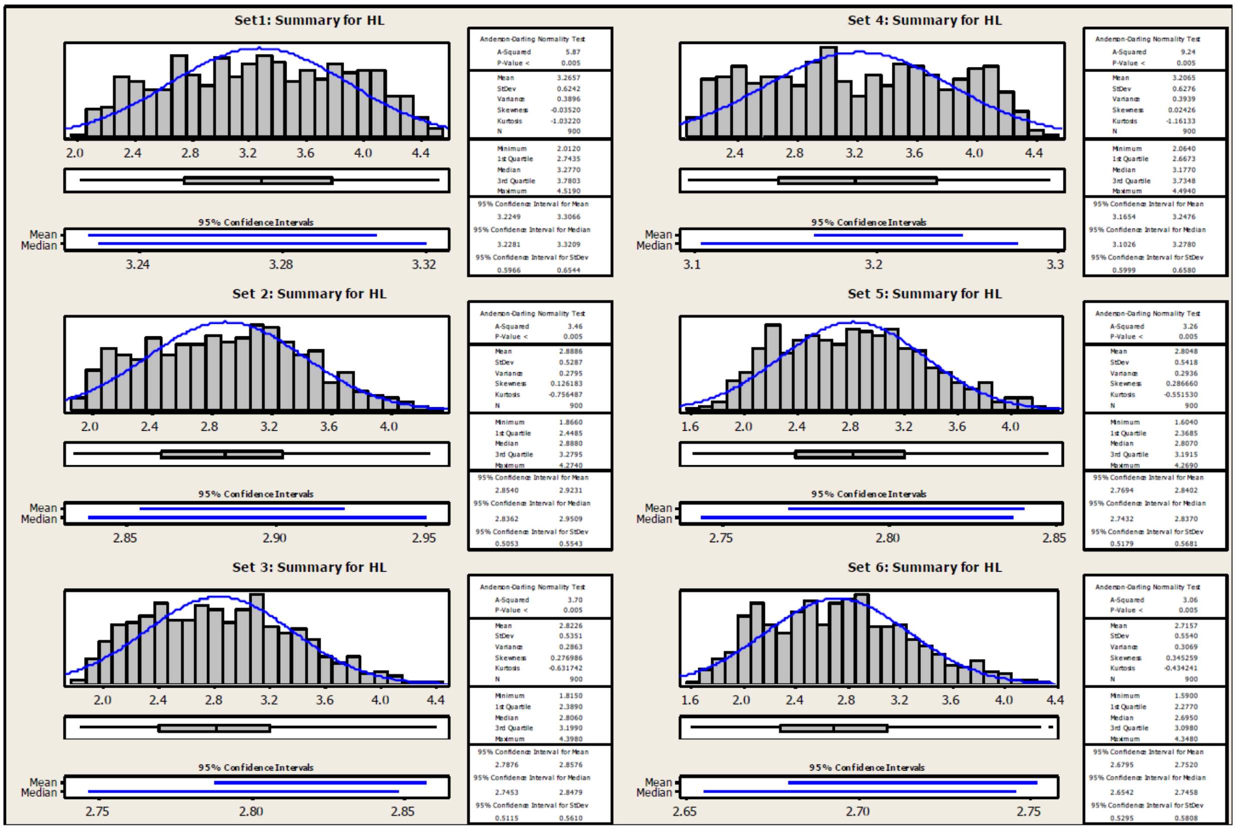

Figure 42 Summary results for Heat Loss with a fixed weather year (5, East). Alternative sets are shown in titles. The left column is for the concrete attic floor and the right column for the wood frame attic floor.

Table 12 Cumulative Heat Loss in January for the six alternatives.

Alternative	Heat Loss, average (min, max)
1	3.27 (2.01, 4.52)
2	2.89 (1.87, 4.27)
3	2.82 (1.82, 4.40)
4	3.21 (2.06, 4.49)
5	2.80 (1.60, 4.27)
6	2.72 (1.59, 4.35)

In comparison, the present roof system (concrete, 200mm insulation) has a heat loss of about 4.2 kWh/m2 in January.

The lowest heat loss in January is used as the criterion to select the best system in terms of thermal performance. The heat loss includes only conduction through the ceiling – the air leakage is not included in the heat loss (this was not included in the output).

The attic ventilation has a negative effect (increased heat loss) on the thermal performance of the attic in the analyzed climate. The heat loss in January is larger in alternatives 2 and 5 (ventilation at eaves) than in alternatives 3 and 6 (gable end ventilation) for concrete and timber framed floor systems, respectively.

The best set of these six alternatives is chosen based on the mean heat loss in January. The best set of the six alternatives has the following features:

- Insulated roof

- Less attic ventilation

- Higher leakage in the ceiling (indoor air warming up the attic).

These features are included in the alternative 6 with the timber framed floor. We can argue that both the concrete and the timber framed floor systems would be equally good if the energy loss due to the air leakage was taken into account in the overall heat loss. Therefore, based on the thermal performance alone we select alternatives 3 and 6 as the potential candidates.

D2 MOISTURE PERFORMANCE

The mold growth risk is analyzed by calculating the attic thermal and moisture performance with 30 years weather data. All of the systems show low mold growth risk on average. However, the timber framed attics have a higher probability (albeit small) for higher risk (see example: Set 4, maximum mold index 4.7).

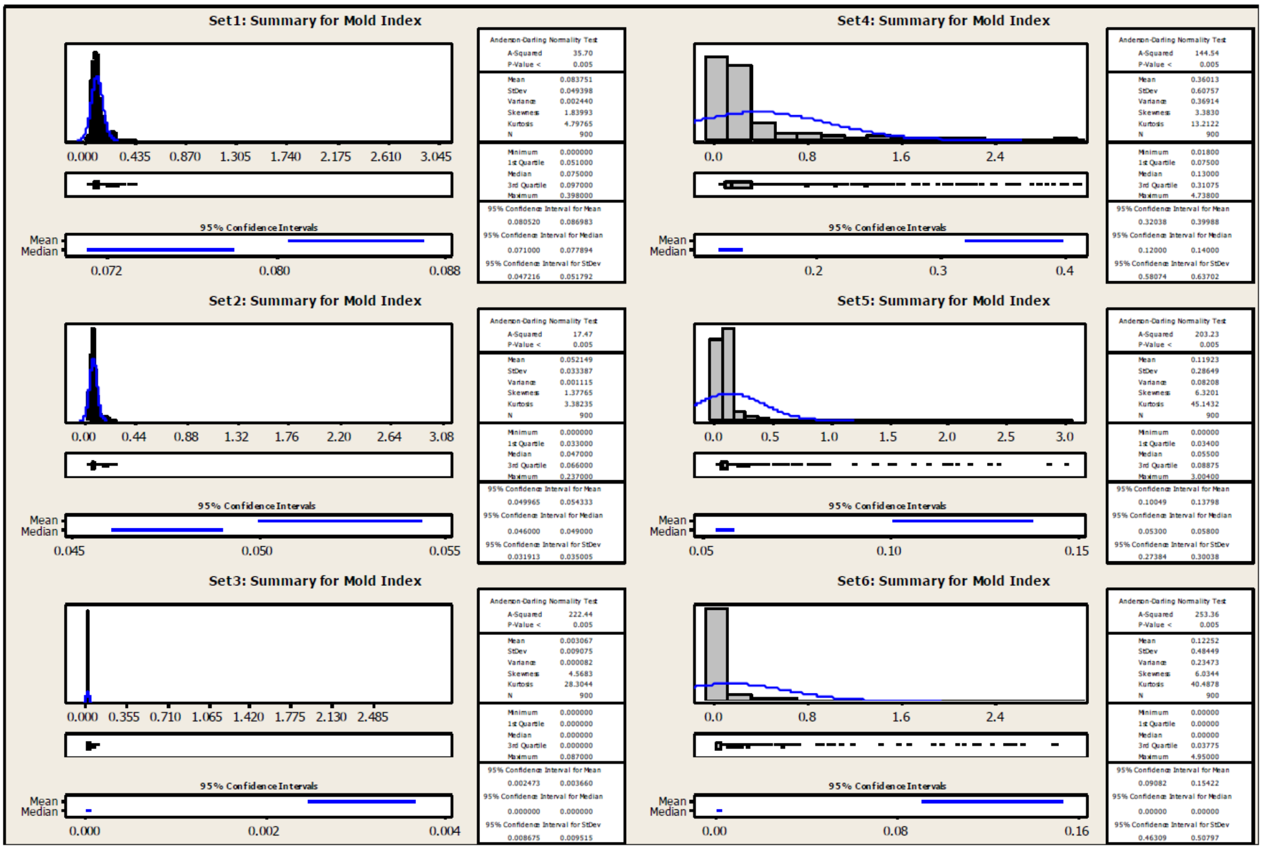

Figure 3. Summary results for Mold Index with multiple weather years (East). Alternative sets are shown in titles. The left column is for the concrete attic floor and the right column for the wood frame attic floor. Minimum and maximum scales are the same for all the plots.

Table 3. Mold Index for the six alternatives.

Alternative	Mold Index, average (min, max)
1	0.08 (0.00, 0.40)
2	0.05 (0.00, 0.24)
3	0.00 (0.00, 0.09)
4	0.36 (0.02, 4.74)
5	0.12 (0.00, 3.00)

6	0.12 (0.00, 4.95)

The timber framed floor system has a slightly higher potential for mold growth. In the simulation model the only difference between the timber framed and the concrete floor systems is in the air leakage from indoors. However, with the assumed moisture production rates the probability of visible mold growth (Mold Index >3) is very small even in the attics with concrete or timber framed floor systems.

The concrete floor system is better in terms of moisture performance (less mold growth potential in the roof sheathing). Adding roof insulation further reduces the possibility of mold growth.

The alternatives were further analyzed by including the starting relative humidity in the varied parameters.

Top ten best cases in the alternative set 3 (concrete floor with roof insulation and gable ends ventilation) are:

Ae, m^2/m	Rr, m^2K/W	Ac, m^2/m^2	Uc, W/m^2K	Ti, C	MS, g/m^3	MI, -	CHL, kWh/m^2
0.0011	1.93	3.36E-06	0.111	19.67	0.00103	0	1.815
0.0014	1.96	8.61E-06	0.104	21.81	0.00235	0	1.819
0.0019	1.86	7.91E-06	0.103	21.84	0.00012	0	1.832
0.0017	1.70	4.84E-06	0.102	21.58	0.00010	0	1.838
0.0016	1.78	9.94E-06	0.104	22.00	0.00118	0	1.854
0.0021	1.27	8.12E-06	0.102	20.87	0.00067	0	1.859
0.0022	1.91	7.65E-06	0.110	20.71	0.00124	0	1.860
0.0016	1.85	5.25E-06	0.110	20.51	0.00116	0	1.863
0.0021	1.79	3.96E-06	0.105	21.47	0.00120	0	1.869
0.0027	1.61	1.54E-06	0.103	21.26	0.00210	0	1.872

D3 Discussion about moisture performance

The roofs did not have any water leaks in the models and the tolerance of the two differing systems to recover from moisture leaks can only be analyzed by using higher initial relative humidity in the roof sheathing. Ideally from the thermal stand point we would get the best performing system by eliminating the attic ventilation and from the moisture stand point we would want to eliminate the air leaks from indoors to the attic. However, since the ceiling has a vapor barrier, the roof would have poor ability to tolerate and dry out any water leaks without any ventilation (even by air leaks). The effect of attic ventilation can be seen by comparing the results for mold index with varying initial relative humidity. The attic with eave vents has higher attic ventilation rates resulting in lower mold index than in the attic with gable end vents and lower ventilation rates.

D4 Discussion about the cost effect

Without any cost data available for the different systems we can only give directional guidance to choosing the most cost effective system with the required thermal and moisture performance. Insulating the attic floor is (typically) lower in cost than insulating the roof – therefore increasing the floor insulation even more would be cheaper than adding roof insulation. The risk for mold growth is small with the low air leakage from indoors to the attics even without the roof insulation (Set 1).

Combining all the results including thermal, moisture and cost analysis we recommend Set 1 with thick pink blown-in insulation on the concrete attic floor and attic ventilation with eave vents.