THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Risk Assessment of Hygrothermal Performance
- Building Envelope Retrofit

SIMON PALLIN

Department of Civil and Environmental Engineering
Division of Building Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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SIMON PALLIN
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Department of Civil and Environmental Engineering
Division of Building Technology
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Telephone: + 46 (0)31-772 1000

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Abstract

A risk assessment of the hygrothermal performance for a building envelope retrofit investigates possible variations in energy performance, indoor environment quality and moisture safety and elaborates on the risks of exceeding defined acceptance criteria. These risks can be properly determined if including the variability of, by the investigated retrofit, most influencing parameters. As a result, the risks can also be presented with a variability, which subsequently can serve as a realistic and credible basis of judgment for risk tolerability decisions.

In general today, the risks of exceeding defined performance criteria are assessed based on the results of a deterministic hygrothermal calculation tool; an evaluation, in which the influencing parameters, such as material properties, indoor and outdoor climates are provided with fixed values. The result of such deterministic analysis will represent a single best-estimate of the future hygrothermal performance of the building. Consequently, the performance of the retrofitting measure, as a result of a deterministic simulation, will likely be underestimated or overestimated, since such analysis provides no expected variation of the hygrothermal performance. Actually, the result of a deterministic analysis represents an average hygrothermal performance; it takes no consideration, what so ever, to the expected deviations from that specific performance or the probability of occurrence.

However, the proposed risk assessment of a retrofitting measure will include the variability of the influencing parameters; thus, generating results which provides an expected deviation from the best-estimate and proper decisions can be made on the risks of exceeding acceptable performance levels. In addition, a risk assessment includes result, sensitivity and uncertainty analyses which enable an appropriate and credible evaluation of the retrofit, help to better understand the performance of the retrofit design and enable improvements of the design, if needed.

This thesis thoroughly describes a hygrothermal risk assessment procedure, including both a qualitative and quantitative risk analysis, and provides concrete examples of practice through several case studies.

Keywords: Risk, hygrothermal, retrofit, residential, energy savings, mold, simulations.

List of Publications

This thesis is arranged as an extended thesis by publications and consists of papers and manuscripts presented or accepted at international peer reviewed conferences and scientific journals; in exception of Paper II, which is an internal report of IEA Annex 55 RAP-RETRO.

Appended:

I. Pallin, S., Johansson, P., Shahriari, M. (2011). *Development of a Risk Assessment Procedure Applied on Building Physics: Part Two; an Applicability Study*. Proceedings of the 12th International Conference on Building Materials and Components, April 12-15, Porto, Portugal.

II. Pallin, S. (2011). Evaluation of Framework for Probabilistic Assessment - External Wall Retrofit with Interior Additional Insulation. IEA Annex 55 RAP-RETRO, San Antonio meeting, October 24-26.

III. Pallin, S., Johansson, P., & Hagentoft, C.-E. (2011). *Stochastic modeling of moisture supply in dwellings based on moisture production and moisture buffering capacity*. Paper presented at the IBPSA - Building simulation 2011, November 14-17, Sydney, Australia.

IV. Pallin, S., & Kehrer, M. (2012). *Hygrothermal Simulations of Foundations: Part 1 - Soil Material Properties*. Journal of Building Physics, published online 13 December 2012.

V. Pallin, S., & Kehrer, M. (2013). *Condensation Risk of Mechanically Attached Roof Systems in Cold Climate Zones*. Paper presented at the RCI 28th International Convention & Trade Show March 14-19, 2013, Orlando, Florida.

VI. Pallin, S., Kehrer, M., & Milller, W. A. (2013). *A Hygrothermal Risk Analysis Applied on Residential Unvented Attics*. Paper accepted to the Thermal Performance of Exterior Envelopes of Whole Buildings XII International Conference, December 1-5, Clearwater, Florida.

Other publications related to the work of the thesis:

Pallin, S. (2012). *Probabilistic Risk Assessment of Energy Efficient Retrofitting Techniques - Focus on Multi-family Dwellings and the Effects of Changing Air Movements*. Licentiate, Chalmers University, Gothenburg, Sweden.

Paper I is the second part of two papers, in which the writing and research of the appended Paper I was almost exclusively made by Simon Pallin. The work of Paper III was equally divided between Simon Pallin and Pär Johansson, and under the supervision of Carl-Eric Hagentoft. As for Paper IV to V, most of the work, research and measurements were made by Simon Pallin. In Paper VI, Manfred Kehrer has contributed with technical assistance in the simulation model and W.A. Miller has provided essential input data for the simulation model.

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Preface

The work of this thesis has been carried out at the Division of Building Technology, Department of Civil and Environmental Engineering at Chalmers University of Technology in Gothenburg in Sweden. This research project has been financially supported by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) of which I am very grateful.

First, I would like express my appreciation for my two brilliant supervisors; Professor Carl-Eric Hagentoft and Professor Angela Sasic Kalagasidis. They both are very professional and successfully complement each other. Thank you Angela, for opening my eyes into Buildings Physics, back in 2009. You are the reason why I applied to the PhD-position. Thank you Carl-Eric, for being a role model and for always seeing the opportunities.

A special thanks to the head of division and senior lecturer, Paula Wahlgren. You are the right person at the right position by being thorough, fair and caring. Thanks to the rest of my colleagues at the division, for contributing to a desirable working environment. Thank you Pär Johansson for all the work we achieved together and to Professor Mohammad Shahriari for your knowledge and enthusiasm, which has improved my way of thinking *Risk*.

I also want to express my gratitude to Manfred Kehrer, at the Oak Ridge National Laboratory, who is an extremely creative and humble scientist and also a person which I consider a good friend. Thanks to the rest of the colleagues at the lab in Tennessee.

Finally, I would like to thank Sara, my wife and very best friend. Thank you for your good advices and your never ending support. Without you, this would never have happened!

Simon Pallin

Gothenburg, May 2013

Abbreviations and Symbols

c	Specific heat capacity	(J/Kg,K)
C	Volumetric heat capacity	(J/m^3,K)
C	Air leakage coefficient	(m^3/s,Pa)
d	Material thickness	(m)
D	Liquid diffusivity	(m^2/s)
g	Moisture flux	(kg/m^2,s)
G	Moisture generation/flow rate	(kg/s)
I_i	Importance index	(-)
n	Air leakage pressure exponent	(-)
n	Porosity	(%)
O_{sens}	One-at-a-time sensitivity measure	(Dependent)
p	Definition of Probability in risk analyses	(%)
P	Pressure	(Pa)
q	Heat flux	(J/m^2,s)
q	Air leakage rate, related to building envelope area	(l/s,m^2)
Q	Heat flow rate	(W or J/s)
Q_{50}	Air leakage rate at 50 Pa pressure difference	(m^3/s)
R	Definition of Risk	(%)
s	Definition of Scenario in risk analyses	(-)
S_i	Sensitivity index	(-)
t	Time	(s)
T	Temperature	(°C or K)
v	Air humidity by volume	(kg/m^3)
w	Moisture content, mass by volume	(kg/m^3)
x	Definition of Consequence in risk analyses	(-)
α	Surface heat transfer coefficient	(W/m^2,K)
δ	Vapor permeability	(m^2/s)
λ	Thermal conductivity	(W/m,K)
μ	Water vapor diffusion resistance factor	(-)
ρ	Material density	(kg/m^3)
ρ_b	Dry bulk density	(kg/m^3)
ρ_s	Particle density	(kg/m^3)
φ	Relative humidity	(%)

ACH	Air Changes per Hour, (h^{-1})
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
cdf	Cumulative density function
ETA	Event Tree Analysis
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
HAM	Heat, Air and Moisture
HAZOP	HAZard and OPerability analysis
HVAC	Heating, Ventilation and Air-Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environment Quality
IBP	Fraunhofer Institute for Building Physics
IEA	International Energy Agency
m	Mold growth potential
MC	Moisture Content in percentage of saturation
MGI	Mold Growth Index
ORNL	Oak Ridge National Laboratory
OSB	Oriented Strand Board
pdf	Probability density function
PP	Payback Period
QlRA	Qualitative Risk Analysis
QRA	Quantitative Risk Analysis
RAP-RETRO	IEA Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost
SPF	Spray Polyurethane Foam
VAT	Value Added Tax
VMEA	Variation Mode and Effect Analysis
WRC	Water Retention Curve

1. Introduction

1.1. Background

A retrofitting measure of a building or a building component can be referred as an improved construction of the initial design; an enhancement which purpose usually is to decrease the net energy demand of the building and to improve occupants' perceived comfort.

There is a large need of residential retrofitting measures in many countries (RAP-RETRO, 2011), and Sweden is not an exception. About 30% of the Swedish residential building stock has a deteriorated hygrothermal performance which affects the indoor environment quality (IEQ) (Boverket, 2009b). However, there are specific risks, in terms of the future hygrothermal performance, that must be taken into account when planning for an efficient and durable retrofit. Therefore, throughout the planning of a retrofitting measure, it is crucial to discuss what consequences that may occur, directly or in the future. The risks must be investigated both on component level but also with a holistic view. In Sweden, assumingly 17 000 to 27 000 buildings was constructed with a certain type of external thermal insulation composite wall system (ETICS) up until 2007 (Samuelson & Jansson, 2009). Unfortunately, the wall assembly is now proven sensitive to moisture and possesses a high risk of developing intermediate mold; actually, about 55% of the buildings constructed with the wall system are damaged from moisture in at least one of the exterior walls (Jansson, 2011). As a consequence, an estimated total net cost (VAT excluded) of repairing the damaged wall is roughly 2,5 to 2,9 billion EUR (Samuelson & Jansson, 2009). The main reason why the wall system wasn't found risky is that the design was not comprehensively considered. Professionals, which analyzed the hygrothermal performance of the wall system prior to the construction, did only focus on the component level; meaning, the wall was only considered as a single element and not with consideration to the interface between the wall and other building components. Unfortunately, water intrusion proved to arise through interface details, and since water was not allowed to be drained off (as part of the design), materials, sensitive to high levels of moisture, such as wood, started to develop mold and rot (Boverket, 2009a).

A risk assessment of the hygrothermal performance (hygrothermal risk assessment) of a retrofitting measure enables both a qualitative and quantitative risk analysis of the expected building performance post-retrofit. Generally, the hygrothermal and technical performances of a building are evaluated based on a best-estimate; a single deterministic value of an investigated performance (Pietrzyk & Hagentoft, 2008). In reality however, the hygrothermal performance will vary from case to case; hence an analysis which includes the variability and uncertainty is more likely to represent the reality, thus more credible and therefore expected far more coveted by the decision makers. The difference between the result of a probabilistic and deterministic retrofit analysis is exemplified in Figure 1, in which the net energy consumption of a building has been estimated, presented as an annual net energy demand for a residential building post construction. The deterministic approach provides one single value, though the probabilistic approach includes an expected variation of the exemplified net energy consumption. Obviously, a probabilistic analysis enables a more thoroughly evaluation of the result and risk tolerability decisions.

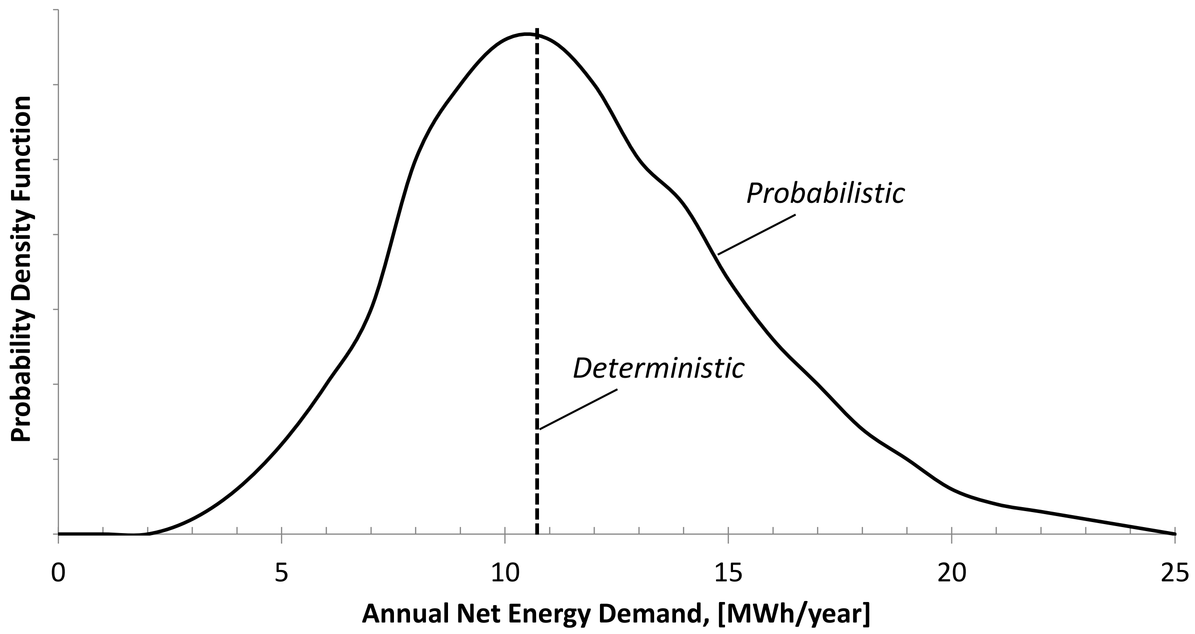


Figure 1 The difference between the result of a traditional deterministic analysis and a probabilistic hygrothermal risk assessment is illustrated as the annual net energy demand for a residential building post-retrofit. The deterministic approach presents one single value, in this case 10,7 MWh/year. A probabilistic risk assessment presents a result which may include both the expected variability and the uncertainty of the result. Obviously, there is a great difference between the two different approaches.

A probabilistic risk assessment also enables the sensitivity analysis of the influencing parameters of the hygrothermal building performance, from which the most decisive parameters can be defined. Consequently, this helps to understand the function of the retrofit and also helps to improve the retrofit design, in case the results of the risk assessment are considered unsatisfying.

Despite the large need of retrofitting measures in existing buildings, many retrofitting projects may stumble upon the lack of financial resources. Hence if the retrofit is realized, it is important that the invested money results in a durable and satisfying retrofitting measure; a design which both fulfills the purpose of the retrofit but also ensures low risks on the future hygrothermal performance.

1.2. Hypothesis

It is possible to identify the most reliable or risky retrofitting measure, in terms of the hygrothermal performance, using a probabilistic risk assessment. Stochastically varying input parameters in simulations generate realistic results, which both facilitate the evaluation process of a retrofit and make the results more credible. Therefore, hygrothermal risk assessment is a powerful practice to ensure an efficient and reliable design of a retrofitting measure and with the most suitable materials and technical solutions.

The hygrothermal performance of a building or a building component is influenced by a large number of varying parameters, which are possible to identify. An appropriate qualitative risk analysis takes into account these parameters and investigates their influences and correlations in the studied retrofitting measure. Consequently, the likeliness increases of including all important parameters into the risk assessment of a retrofit and to apply them correctly.

Simulation of the hygrothermal performance is a good approach to estimate the expected future performance of a retrofit. The vast number of stochastically varying input parameters aggravates measurements as the solely assessment criteria for the retrofit design. Instead, a probabilistic simulation enables the study of a retrofit in multiple indoor and outdoor climates and with varying parameters such as material and technical properties; indoor heat and moisture production; and occupants' user behavior and level of comfort.

1.3. Scope of the Thesis

This thesis aims to present clarify a hygrothermal risk assessment procedure when performing retrofitting measures of residential buildings or building components. An existing risk assessment procedure is adapted to the thesis which is evaluated and adjusted to better fit the purpose. Further, several methods for the analytical part of the risk assessment is investigated from which a selection is recommended. The tool prerequisites, to perform probabilistic risk analyses with stochastically varying parameters, are also studied. Moreover, sensitivity and uncertainty analyses ensure a proper evaluation of the results. The risk assessment procedure is clarified with case studies of existing, plausible and/or recommended solutions of design for retrofitting measures of building components. Consequently, the thesis provides guidelines and examples on how to perform a successful hygrothermal risk assessment and retrofit design of residential buildings.

1.4. Limitations and Assumptions

This thesis is limited to the risk assessment of Heat, Air and Moisture (HAM) transfer through the building envelope, thus an evaluation of the hygrothermal performance of a building. Transport mechanisms as a result of structural or technical failures of the building envelope and the buildings technical performance system are not taken into account e.g. a water pipe rupture. Focus lies on the performance indicators of HAM transfer in buildings, such as energy demand, moisture safety etc., from which possible unwanted events and consequences of risks are defined.

A probabilistic risk assessment, in general, consists of several varying parameters with a range of uncertainty. The quality of the risk assessment depends on the accuracy of these parameters and shall be defined as precisely as possible. Basically, the varying parameters of this work are obtained from measurements, literature, statistical data, simulations, national and international standards and if necessary, qualified assumptions.

The simulation models, created for the work of the thesis, are both based on developed numerical models and existing mathematical and hygrothermal tools. The accuracy and correctness of the result given by the developed simulation models have, if possible, been compared with measurements or verified with existing studies. The existing tools have not been verified per se.

Further limitations and assumption will be explained throughout the text for a better understanding.

1.5. Method

A risk assessment procedure is presented, including both qualitative and quantitative risk analyses. Evaluation methods and sensitivity and uncertainty analyses are used, both from existing literature as well as specifically developed for the work related to the thesis.

The simulation models, used in various sections and case studies throughout the thesis, have been developed to represent HAM transfer through a building or a building component. The models have been designed with both existing and verified tools, as well as with tools specifically designed for the work of the thesis. If required, the models have been adjusted to enable multiple simulation runs, preferably probabilistic; thus with, if possible, stochastically varying input parameters.

Finally, the risk assessment procedure is verified with several case studies of retrofitting measures, which has been selected based on research, field investigations and discussions with stakeholders, decision makers and manufacturers.

2. **Risk and Reliability Assessment in Retrofitting**

There is a lack of tools to perform a complete risk and reliability assessment procedures on the future hygrothermal performance of residential buildings, despite that it is highly appreciated and asked for by practitioners (RAP-RETRO, 2011). A risk assessment, as part of the design phase of a building project will, if including the variability of the influencing hygrothermal properties, increase the likeliness of detecting unwanted consequences and economical events. Unfortunately, there are prerequisites which likewise aggravate the perfection of a hygrothermal risk assessment, such as the presence of stochastically varying parameters and the hygrothermal inertia of a building. Typically, the varying parameters in terms of the hygrothermal performance of a building are the outdoor climate; indoor heat and moisture production; material and surface properties; airtightness, ventilation rate and occupants' level of comfort. Consequently, these parameters, including their variability and uncertainty, must be implemented into a hygrothermal risk assessment, if realistic and reliable results are to be expected.

In general, a full risk assessment procedure consists of two steps; a risk analysis and a risk evaluation, in which the latter also include recommendations for improvements and decisions of acceptance (Ljungquist, 2005). Further, there are two fundamental types of risk analyses; the qualitative and the quantitative. A qualitative risk analysis (QlRA) is a relative measure of risk in which all the influencing parameters are defined and their importance is ranked, but with no specific values of risk. In a QlRA of the hygrothermal performance of a retrofit, possible risks of unwanted consequences post-retrofit are determined, their approximate likeliness of occurrence and also the determination of the most influential parameters. Experience, expertise and competence are usually important qualities of someone conducting a credible QlRA, hence tools and predefined procedures are helpful to aid the analysis.

A quantitative risk analysis (QRA) should preferably be able to generate a number of possible scenarios i.e. plausible configurations of values of the expected varying parameters. Hence QRA should account for every possible value that each influencing parameter could take and weighting each possible scenario with the probability of occurrence (Vose, 2008). Basically, the result of a QRA should include and respond to the *set of triplets idea*, which is based on the three questions: What can go wrong; how likely is it and what are the consequences (Kaplan & Garrick, 1981). A QRA should yield a quantitative insight into the possible range and likelihood of the result from the analysis (Cullen C & Frey C, 1999), thus possible variability and uncertainty distributions of the analysis outcome (Vose, 2008).

The main difference between a deterministic analysis and the above described scenario-based QRA, is that the deterministic analysis represents only one possible scenario. The purpose of a deterministic analysis is to point-estimate the prediction of a quantity; consequently, to obtain one single value which represents a best-guess of a performance and can be used in comparisons with other assessments (Cullen C & Frey C, 1999). A typical energy or hygrothermal calculation tool such as EnergyPlus, and WUFI can be classified as a deterministic analysis tool since the input parameters are fixed and the outcome of the analysis results in one single time-dependent distribution of an output parameter.

A combination of performing both a qualitative and a quantitative risk analysis can be quite powerful. The QlRA provides a detailed description of the influencing parameters on the predefined performance criteria and unwanted consequences and events can be identified from the defined parameters. In addition, correlations, flows of events or causes of failure may be described. Therefore, the outcome of a QlRA may simplify the development and completion of a QRA, since the most influential parameters already have been identified. A risk assessment algorithm including both a QlRA and a QRA is presented in Section 2.2 and serves as the investigated risk assessment procedure of this thesis.

2.1. Definitions of Risks

The variability describes the characteristics of a parameter, such as the mean value, standard deviation and range (Vose, 2008), whereas the uncertainty characterizes the lack of knowledge (ISO Guide 73, 2009). Both variability and uncertainty exist to some degree in all parameters of a probabilistic risk assessment, though the variability cannot be changed, the uncertainty can be reduced with better knowledge. Depending on the characteristics and relations between the influencing parameter of a risk assessment, the variability and the uncertainty will also affect the result, as seen in Figure 2.

Risk may be discussed without its context i.e. without specifically defining the risk of a consequence. However, in order to complete a successful risk assessment, the risks of specific events and consequences must be stated. By definition, the *risk*, R, is the *probability*, p, of a *consequence*, x, at a defined *scenario*, s (Kaplan & Garrick, 1981; Shahriari, 2011). A *consequence* may be referred as an unwanted outcome and the *scenario* is a plausible configuration of the influencing variables i.e. the input parameters of a QRA. Apparently, a *probability* must be related to a *consequence* and the *risk* depends on the defined circumstances i.e. the *scenarios*.

$$R = f(p, x, s). \qquad [1]$$

Reliability is also commonly used to define the dependability of a studied risk object. It is complimentary to R and therefore representing the probability of a satisfying outcome; a result which is considered to be safe. One might say that, risk is to failure as reliability is to safe. Consequently, reliability is the probability of a process with a successful outcome and risk is a measure of the probability of failure (Haldar & Mahadevan, 2000). The relation between p, x and R, as seen in Equation [1], is illustrated in Figure 2, in which the impact of the variability and uncertainty of the input parameters on the exemplified performance criterion is illustrated. In Figure 2, both the parameters, and the analyzed risk assessment performance criteria, are defined with probability density functions (pdf); one representing the variability and two representing the variability including lower or upper levels of uncertainty. The pdf of the variability is placed on top of the pdfs which include the uncertainties (color rendered). In the lower illustration of Figure 2, R is defined by the distinction between safe and failure, meaning where p as a function of x is defined. Everything above the level of risk is considered as a failure; everything below is considered as the reliability, thus safe. In Figure 2, a pdf of a performance indicator is the final outcome of combining all the parameters in a scenario-based QRA.

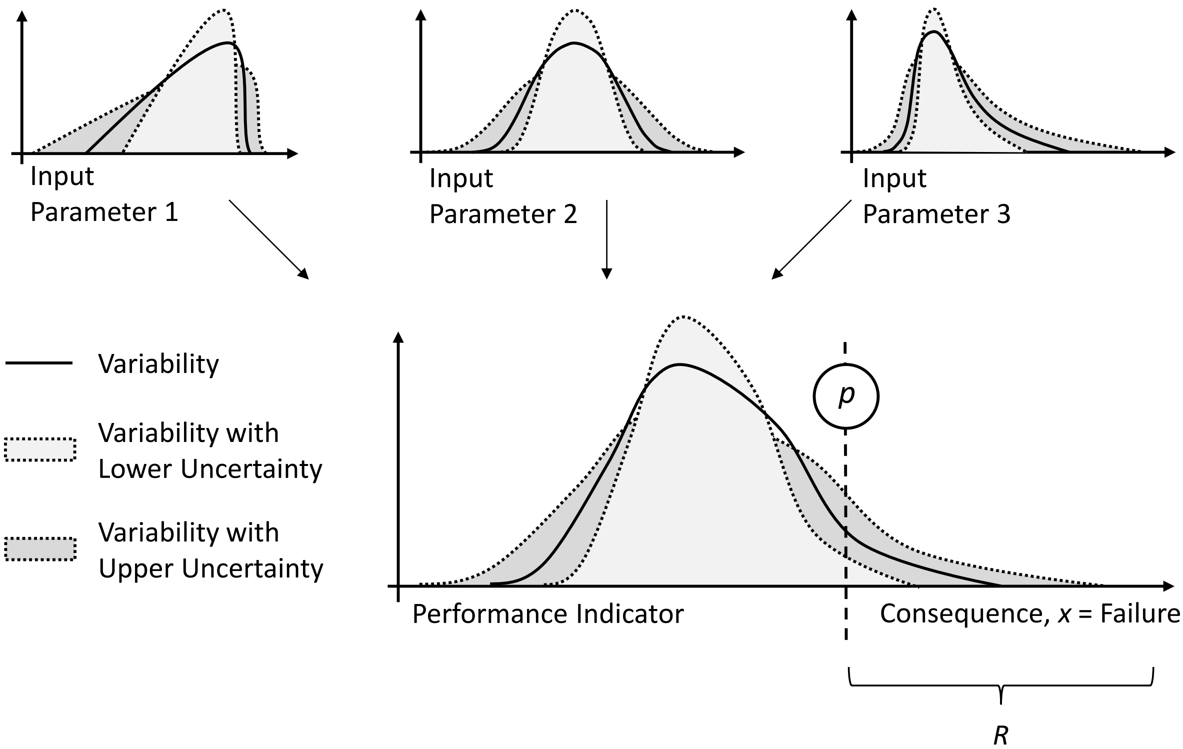


Figure 2 An illustration of the relations between the input parameters and the resulting performance indicator of a risk assessment. The variability and the combination of the variability, with either lower or upper uncertainties, are presented as probability density functions (pdfs) for the three parameters and for the scenario-based QRA performance indicator. The dashed line separates safe from failure in the studied indicator.

2.2. Risk Assessment Approach

This thesis presents a hygrothermal risk assessment approach for the evaluation of a building retrofit design. The assessment approach is based on existing algorithms (Ljungquist, 2005; Sasic Kalagasidis & Rode, 2011; Vose, 2008), though adjusted and improved to better fit the purposes of a retrofit risk assessment. However, the risk assessment algorithm presented in this thesis can equally apply in the energy and moisture safety design of new building constructions.

The risk assessment algorithm is presented as a step by step approach in Figure 3. The section of *SCOPE* consists of *System Formulation*, *Targets and Concerns*, *Existing Conditions* and *Strategy Identification*. The *System Formulation* intends to describe the purpose of the retrofitting project, formulating boundaries of limitations, the scale of the analysis and to overall describe what is meant to be considered in the risk assessment. The gathering of knowledge and experience from similar projects is also included in this initial step of the risk assessment. *Targets and Concerns* aims to formulate the performance criteria of the risk assessment; the concerns, total cost of the project, and/or costs of operations. It may also include the prediction of what the consequences might be if the targets are not fulfilled. The targets may be based on values of energy efficiency, moisture durability, occupants' expected level of comfort and the indoor air quality (IAQ). *Existing Conditions* describes valuable and available information of the building status and suggests on further information if such is needed. Further, information is provided on damaged building materials, status of technical equipment, occupants' comfort issues and other information needed for the retrofit design. The *Strategy Identification* presents the chosen retrofitting strategies based on the above given information. The decisions are well defended in which the reasons behind the proposed designs are explained and verified.

The section of *QUALITATIVE RISK ANALYSIS* consists of two analysis segments; the *Risks Identification* and the definition of *Influential Parameters, Uncertainties and Correlations*. The first step includes to identify possible unwanted events or consequences which are decisive on the hygrothermal performance of the retrofit or will have a great influence on whether the prescribed targets of the risk assessment are fulfilled or not. Based on the specified unwanted consequences and events, the influencing parameters are defined and possible correlations are discussed. The purpose is to gather an in-depth understanding of the interaction between the influencing parameters and the performance criteria of the risk assessment.

The QlRA is followed by a first evaluation of the analysis, in which the result of the first analysis is presented together with decisions on the necessity for further analyses. A *Qualitative Risk Evaluation* gathers and analyzes the results of the QlRA. As a suggestion, the influence of the parameters is ranked for a better comparison and further decisions making. There are certain methods which are helpful when conducting a QlRA; a collection of these methods are presented in Section 3.1. A QRA doesn't necessarily follow the evaluation of the QlRA; the risk assessment can come to a halt depending on the outcome of the evaluation. If the proposed retrofitting measure and object of the risk assessment is considered safe and with a high credibility of the QlRA, a QRA is not needed. Consequently, in such an event, the analyzed retrofitting measure is recommended and acceptable based on the prescribed targets and concerns. Further, the risk assessment can come to a halt if crucial information is missing or if the credibility of the QlRA is low; as a consequence, the risk assessment is redirected back to the start of the QlRA, or if necessary, back to the section of the Scope. In addition, such measures are also taken if the studied retrofit is considered to fail based on the defined targets and concerns. The risk assessment algorithm continues to the section of the QRA, if the analyzed retrofit is still considered to be applicable and if more detailed investigations are requested.

The section of the *QUANTITATIVE RISK ANALYSIS* consists of defining *Method and Performance Indicators*, *Input Values and Probability Distributions,* determine the *Design and Run Simulation Model* and making *Result, Sensitivity and Uncertainty Analyses* of the results. In *Method and Performance Indicators,* the type of simulation method for the analysis is determined and the availability of existing models is investigated. In addition, the type of sampling method for the simulation model shall be defined e.g. Monte Carlo or Latin Hypercube sampling methods, further described in Section 4.2. Performance indicators are defined to enable the result, sensitivity and uncertainty analyses of the risk assessment. The values of the input parameters must be established and their variability, uncertainty and correlations, to ensure realistic and reliable simulation results. Once all the information needed is implemented into the model, the simulations can get started. The number of iterations of simulations depends on the prescribed convergence criteria, the nature of the input parameter variability and uncertainty and also on the defined performance criteria. The simulation results enable a sensitivity and uncertainty analysis which may be conducted for several reasons; to determine which of the input parameters require additional research in order to reduce the output uncertainty, which input parameters are insignificant and can be neglected in the risk assessment model; which of the varying parameters contribute the most and how are they correlated (Hamby, 1994).

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

In *DOCUMENTATION*, the products of the risk analysis are presented in a *Risk Analysis Report*. The values of risk are compared with the performance indicators and the predefined concerns. Discussions on *Options and Recommendations* and on further analyses are made and suggestions on possible alternatives for improvement of the studying object. The documentation of the risk assessment serves as the foundation on which the decision makers should make *Risk Tolerability Decisions*. In this section, the studying object of the risk assessment can also be compared with existing risk analysis reports.

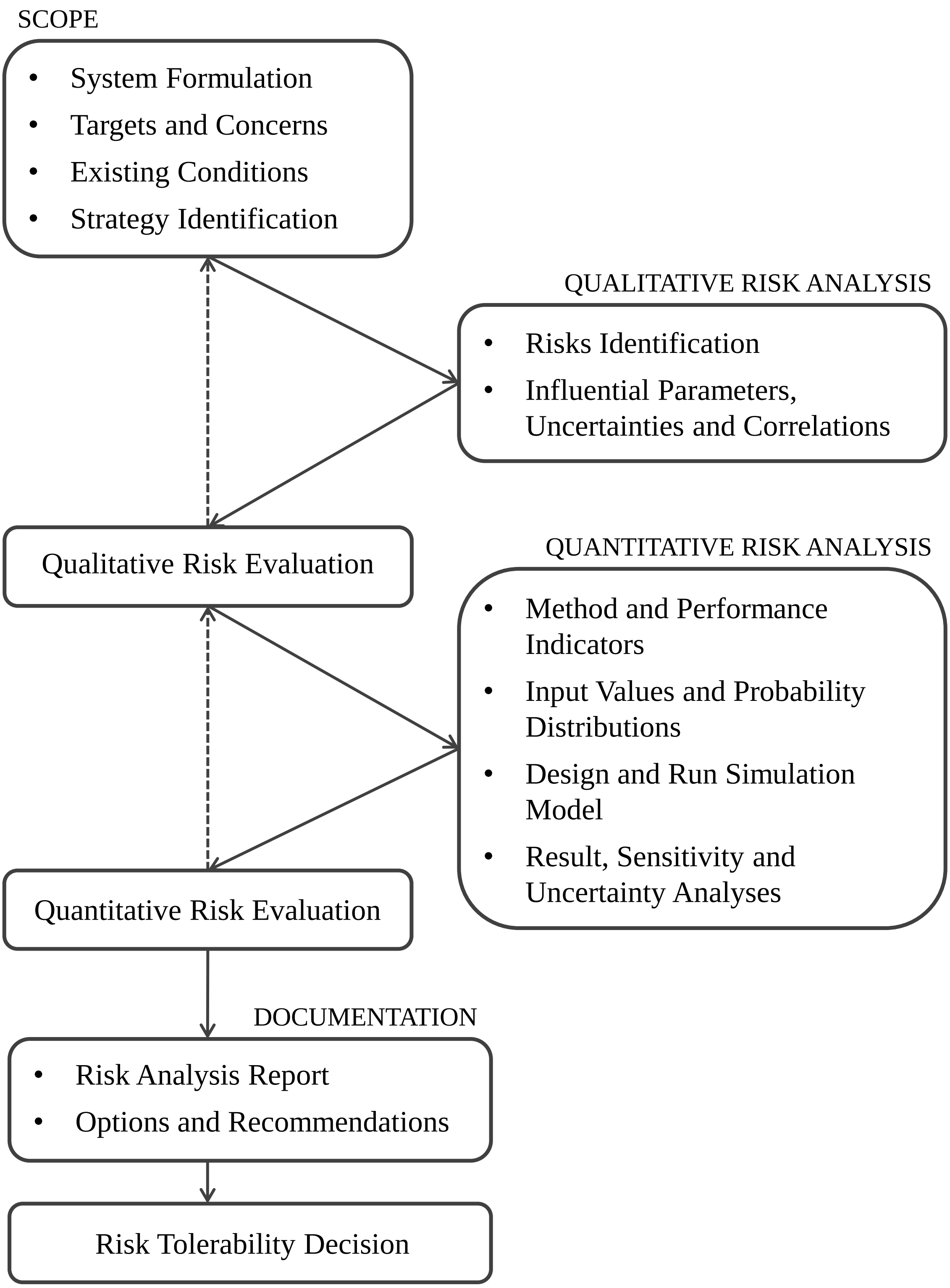


Figure 3 A hygrothermal risk assessment algorithm, developed to facilitate the evaluation of energy efficiency and moisture safety in the design phase of a retrofitting residential buildings. The algorithm is based on existing risk assessment approaches (Ljungquist, 2005; Sasic Kalagasidis & Rode, 2011; Vose, 2008), though adjusted and improved to better fit the purposes of a retrofit risk assessment. The presented risk assessment algorithm can equally apply in the energy and moisture safety design of new building constructions. The dashed lines with arrows indicate possible redirections, based on the decisions made during the risk assessment process.

3. Identification of Influencing Parameters

A hygrothermal calculation tool is a well-recognized approach to assess the future energy efficiency and moisture performance of a building. These tools allow realistic numerical calculations of the coupled heat and mass transfer in building components over time. The number of input data needed to perform hygrothermal simulations is many; therefore, equally many distributions of variability and uncertainty must be expected to influence the calculation results. Generally, these stochastic variations are not taken into account when estimating the performance of a building or a building component; hence the result of these deterministic analyses ought to be presented with variability and uncertainty. The importance of the parameter variability depends fully on the object which is simulated, though commonly, a few can be referred as most decisive on the future hygrothermal performance.

Typically, the most influential input parameters in a hygrothermal simulation model can be obtained from the list below, in which the variability and uncertainty of the most decisive ought to be implemented into a QRA, to ensure credible results.

- Outdoor Climate and the Buildings Level of Exposure
- Indoor Heat and Moisture Production
- Air Distribution System
- Occupants' Level of Comfort
- Occupants' User Behavior
- Airtightness
- Material and Surface Properties
- Workmanship Upon Construction
- Accuracy of Intended Design
- Technical Equipment

In addition to the above stochastically varying parameters, the durability of materials and the geometrical properties of the building will influence the future performance. The maintenance will also affect the expected service life of the building and the building components. In conclusion, the presented decisive input parameters are assumed to possess both a variability and a level of uncertainty, which depends on existing knowledge of their probability distributions.

3.1. Identification Procedures

Risks identification procedures can be used for two purposes; either to identify unknown risks or events based on known influencing parameters; or to identify parameters which can result in specified consequences. There are a number of tools to aid the identification process and some of the most common are Fault Tree and Event Tree Analyses, FMEA, VMEA and HAZOP (Shahriari, 2011).

A **Fault Tree Analysis** (FTA) works in a backward order, starting with a top event, which is the considered system failure (Bedford & Cooke, 2001). The potential causes of the event are systematically illustrated through the correlation of intermediate events using Boolean operators (Or, And, Not, …). A Fault Tree branches downwards to the basic events, which obviously are the main causes of the resulting failure. An **Event Tree Analysis** (ETA) works in a forward logic and begins with an initiating event from which subsequent events are identified, usually with a Yes or No criterion. Both the FTA and the ETA can be combined with values of probability. Therefore, the likeliness can be defined of an event to occur in an ETA or the probability of an event to cause a failure in a FTA.

The HAZard and OPerability study (**HAZOP)**, is a scenario-based qualitative risk analysis method. HAZOP initiates with a studied function or parameter from which deviation of design and operating conditions are defined. Further, consequences due to potential deviations are defined and recommendations for preventative actions. The HAZOP usually requires many hours of work by a group of experts, which consequently is a drawback of the method (Shahriari, 2011).

The Failure Modes and Effects Analysis (**FMEA)**, intends to recognize single system failures, identify the subsequent effects and present actions of improvement to reduce the risks of failures (Nielsen, 2002). There are no connections between specific failures of a FMEA since they are considered as independent events, no matter if it is true or not. A more stochastic approach, in comparison with FMEA, is to apply the Variation Mode and Effect Analysis (**VMEA)**. This analysis method locates and rank noise factors (e.g. parameters with variability) that influence the variability of the final product. Further, risk priority numbers are given for each noise factor, to determine which of the parameter that has the highest influence on the outcome (Chakhunashvili et al., 2004).

Either method for the risks identification process are applicable for a hygrothermal risk assessment, though it is highly recommended not to use more complex methods than necessary. Preferably, an ETA, FTA or a VMEA should be applied, since these methods, not only brought upon knowledge of the influencing parameters and the risks of consequences, but also may provide specific values of risks. An additional advantage with a FTA and VMEA is that they include correlations between the influencing parameters.

3.2. Lack of Input Data

Naturally, there are a number of parameters that, due to insufficient knowledge of their natural variability, possesses a large uncertainty. However, the uncertainty can be reduced through further measurements and studies (Vose, 2008). In some cases, the only alternative is to apply a best-guess of the variability and uncertainty ranges; hence the result of the analysis becomes less credible.

This section describes the process of increasing the knowledge of the natural variations of two potentially important input parameters in a hygrothermal risk assessment; the excess of indoor moisture and the hygrothermal properties of soils.

3.2.1. Indoor moisture production

The results and conclusions presented in this section summarize the appended Papers I and III.

The excess of indoor moisture is usually a very significant parameter in concerns of the hygrothermal performance, IAQ, durability and service-life a building. Due to the fact that the indoor air humidity is one of the most important parameters when designing a building envelope, it is essential to apply realistic design values (TenWolde & Pilon, 2007); still, the indoor moisture production or moisture supply is usually defined with international standards (ASHRAE 160-2009, 2011; EN-ISO 13788, 2011). Since there is a lack of knowledge of the indoor moisture production variability, a great uncertainty must be expected; hence further studies of the stochastic variation of this parameters is justified.

Table 1 Expected ranges of moisture generation from common residential moisture sources.

Indoor Moisture Sources			
	[kg/Event]		*[kg/Event]*
Bathing	0,06 - 0,16	Food Preparation - Lunch	0,25 - 1,75
Showering	0,20 - 0,40	Food Preparation - Dinner	0,47 - 3,86
Sauna Bathing	0 - 1,28	Hand Dishwashing	0,10 - 0,60
Whirlpools	0,12 - 0,32	Dishwashing Machine	0,20 - 0,40
Tumble Dryer	0 - 0,70		*[kg/day]*
Unvented Drying	1,25 - 3,50	Humans	0,50 - 2,00
Ironing	0 - 0,60	Pets	0,10 - 1,20
Floor Mopping	0,30 - 5,00	Aquarium	0,40 - 1,40
Food Preparation - Breakfast	0,13 - 0,52	Plants	0,10 - 0,50

In hygrothermal simulation models, the indoor moisture production can either be presented as a production rate, G, or together with the ventilation rate, as an indoor moisture supply, Δv. The essential differences between the two ways of definition will be further explained shortly. In order to predict G or Δv, the moisture generations from various moisture sources, also referred as moisture loads, are needed (Yik et al., 2004).

Further, the user behavior of the occupants must be established to estimate the total daily moisture load (Christian & Trechsel, 1994). The occupants' behavior basically affects two important parameters; the duration of the moisture generative activity and the time of initiating the activity. Consequently, there are three parameters which will influence the resulting moisture load; time, duration and rate of moisture generation. The most common moisture generative activities in residential households are presented in Table 1, together with expected ranges of moisture production loads.

In order to simulate the variability of the indoor moisture supply, a probabilistic model has been developed to combine the variability of all the moisture generative activities in Table 1, and the user behavior of the occupants. Statistical information has been implemented into the created scenario-based simulation model, which subsequently provides data of expected occupant-household compositions in correlation with type of dwelling. Further, the data has been correlated with the incidence of certain moisture generative household appliances. These first steps of the simulation procedure define the scenarios and conclude the upper section of the flow chart, as seen in Figure 4.

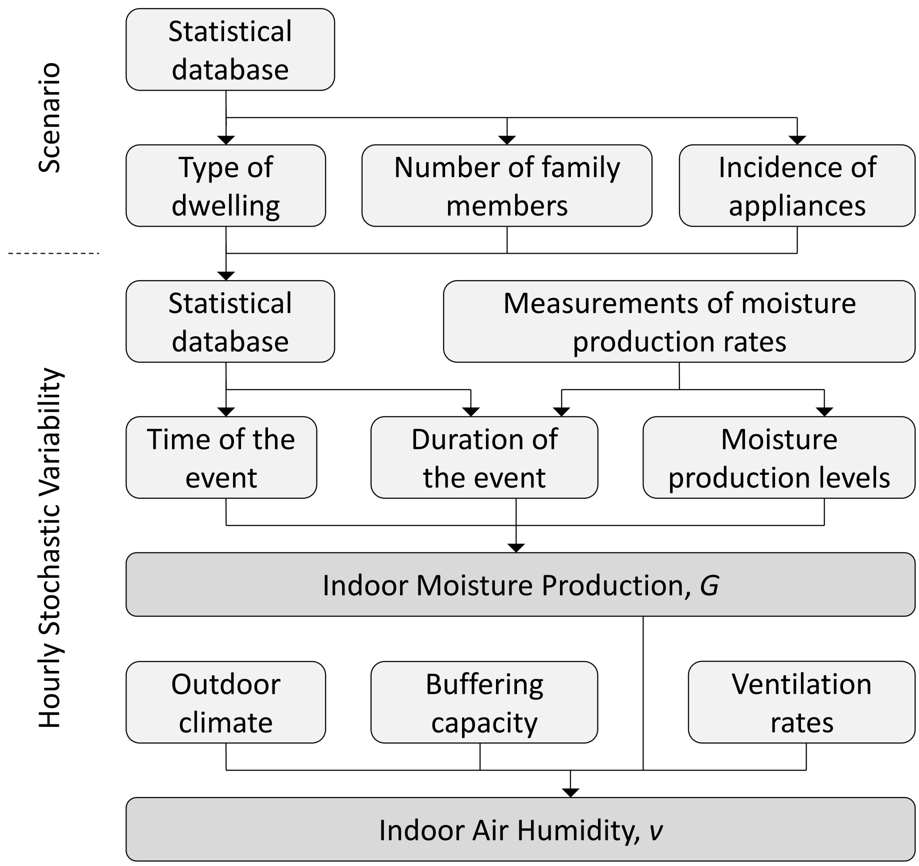


Figure 4 The composition of family members and household appliances in a plausible Swedish household is defined based on statistics. The resulting scenario is then combined with statistical information on the occupants' activity patterns and the levels of moisture generation; resulting in an indoor moisture production rate. Further, the moisture production, outdoor climate, buffering capacity in materials and ventilation rate are applied to determine the indoor air humidity.

The simulated scenario defines, not only the simulated number of household members and their ages, but also defines whether a moisture source is present or not. For example, if a scenario is defined without a bathtub, consequently the activity of bathing will not exist. Once a scenario is defined, the expected occupants' user behavior and the expected durations and levels of moisture production rate can be estimated, based on statistical data and measurements. The final outcome, from combining the occupants' activity patterns and the levels of moisture generation from the activities, is the hourly variation of the indoor moisture production rate. Naturally, the production rate can also be displayed as a daily average, which is the case of Figure 5 and Figure 6, in which the daily moisture production rates for multi-family and single-family dwellings are illustrated. Figure 5 and Figure 6 compares the simulated moisture production rates with two major studies, conducted in Sweden in 1992 and 2008 (Boverket, 2010b; Norlén & Andersson, 1993). The measured and simulated daily averages of indoor moisture production are presented as discrete probability distributions.

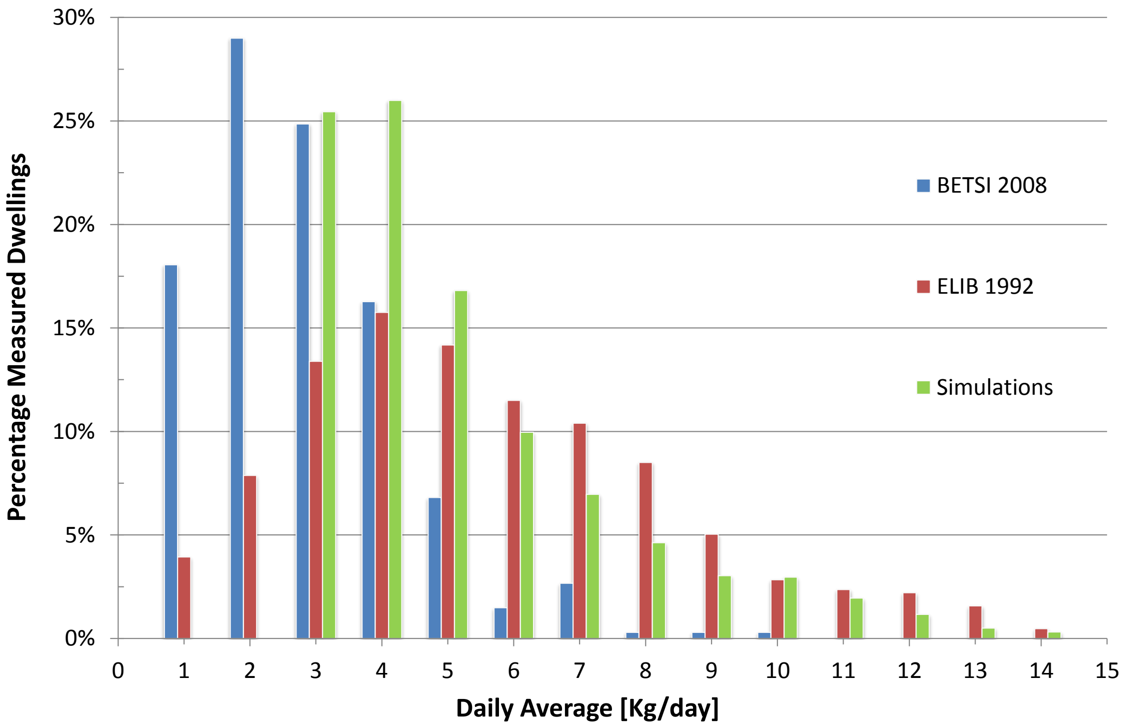


Figure 5 Discrete probability distributions of daily averages of indoor moisture production rates in Swedish multi-family dwellings. The three different probability distributions represent two Swedish measurement studies and the simulated moisture production of this work.

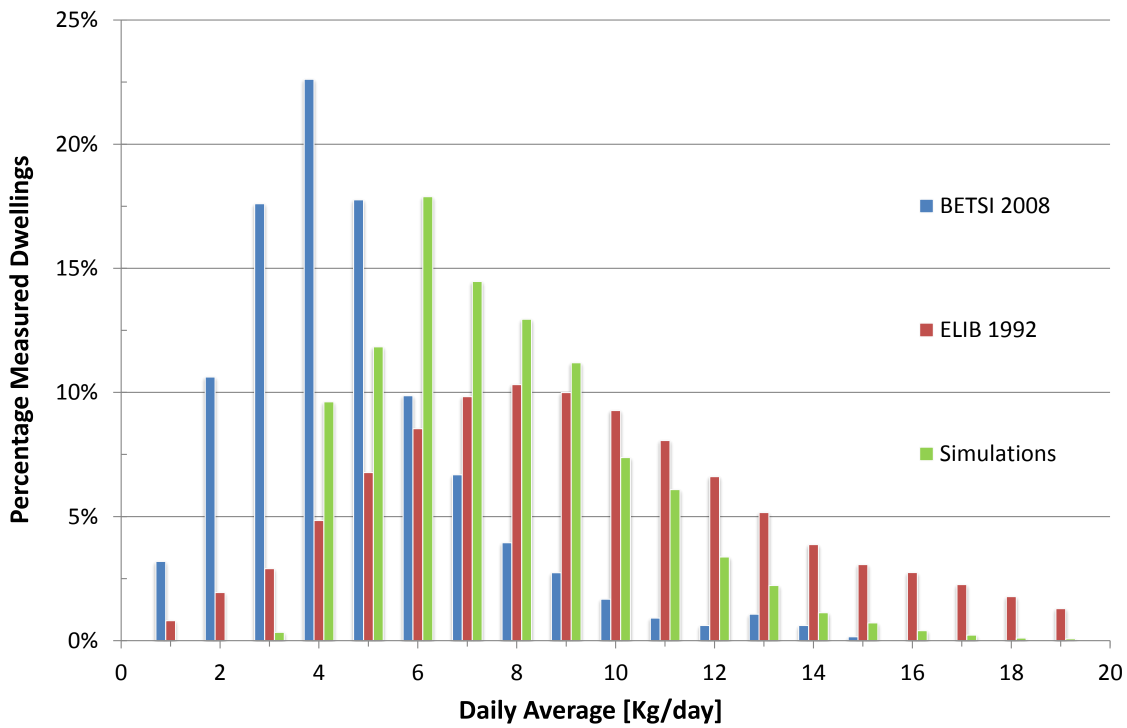


Figure 6 Discrete probability distributions of daily averages of indoor moisture production rates in Swedish single-family dwellings. The three different probability distributions represent two Swedish measurement studies and the simulated moisture production of this work.

The simulations of this work agree mostly with the study made in 1992. An important aspect to consider for the comparisons, both for single and multi-family dwellings, is that the simulated daily average actually is the yearly daily average. This is the reason why the simulated distributions in Figure 5 and Figure 6 have few low values and rather abruptly initiates with a high probability in the lower range of the distributions.

A notable feature of simulating the indoor moisture production is that the created scenarios can be defined based on known properties of the retrofit object. If the household is equipped with a tumble dryer, a dishwashing machine or an aquarium, then the scenarios will be created based on these characteristics, thus decreasing the variability and therefore target-orienting the indoor moisture production rate. This feature of a scenario-based simulation model is a great advantage in comparison with the application of standardized design values or arbitrary measurements data.

The most influencing moisture sources in Swedish households are presented in Table 2 as annual averages of hourly moisture production rates and regardless of type of dwelling. The values in Table 2 shows that unvented drying of clothing and human perspiration and respiration is by far the most influencing moisture productive activity inside the dwelling.

Table 2 The most decisive moisture sources in Swedish households, if present and regardless of type of dwelling. The values are based on annual averages of 10 000 simulated Swedish households.

Moisture Production Rate - Top Five Most Critical [g/h, year]		
1	Unvented Drying	78,4
2	Humans	72,0
3	Showering	42,1
4	Food Preparation – Dinner	38,3
5	Aquarium	35,1

In Figure 7, the average diurnal variation of the simulated indoor moisture production rate is illustrated, together with lower and upper 10th and 90th percentiles. Apparently, the stochastically variability of the indoor moisture production is large; hence great variations of the production rate can be expected. This further implies that simulating the indoor moisture production has great advantages in comparison with standardized design values.

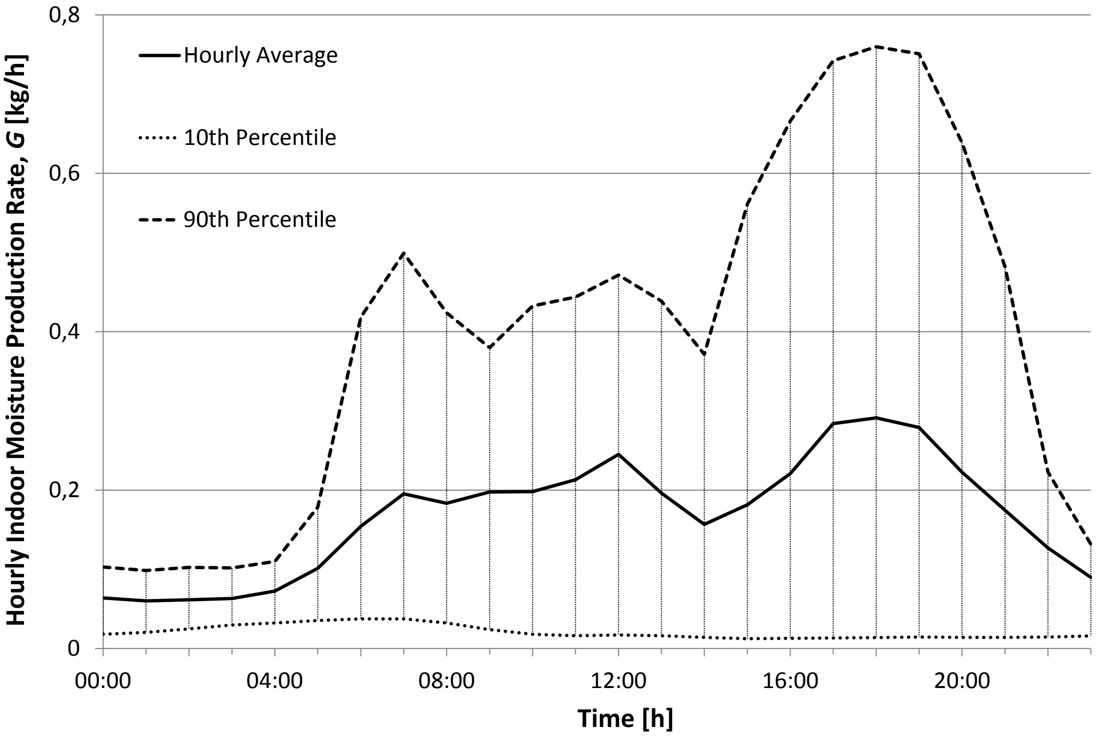


Figure 7 Diurnal variations of the simulated indoor moisture production in Swedish multi-family dwellings. The lower and upper 10th and 90th percentiles illustrate the great variability of the production rate.

As seen in Figure 4, the indoor air humidity can be determined based on the indoor moisture production, the outdoor moisture content, the moisture buffering capacity of the interior materials and the ventilation rate of the air distribution system. A multi-family dwelling unit have been simulated in the climate of Gothenburg (oceanic climate), with a simulated moisture production and with statistical data of ventilation rates from measurements in an existing study, comprehending over 400 dwellings (Boverket, 2010b). Subsequently, the moisture buffering capacity has been taken into account for indoor materials made of wood, gypsum and textiles. The results from simulating the indoor air humidity, both with and without the influence of moisture buffering materials, are presented as an indoor moisture supply, Δv, in Figure 8. The diurnal variations of the two cases reveal great correlations though a much higher fluctuation is expected when not considering the moisture buffering capacity. Naturally, the daily averages of the indoor moisture supply for the two distributions are equal, both 1,6 (g/m^3).

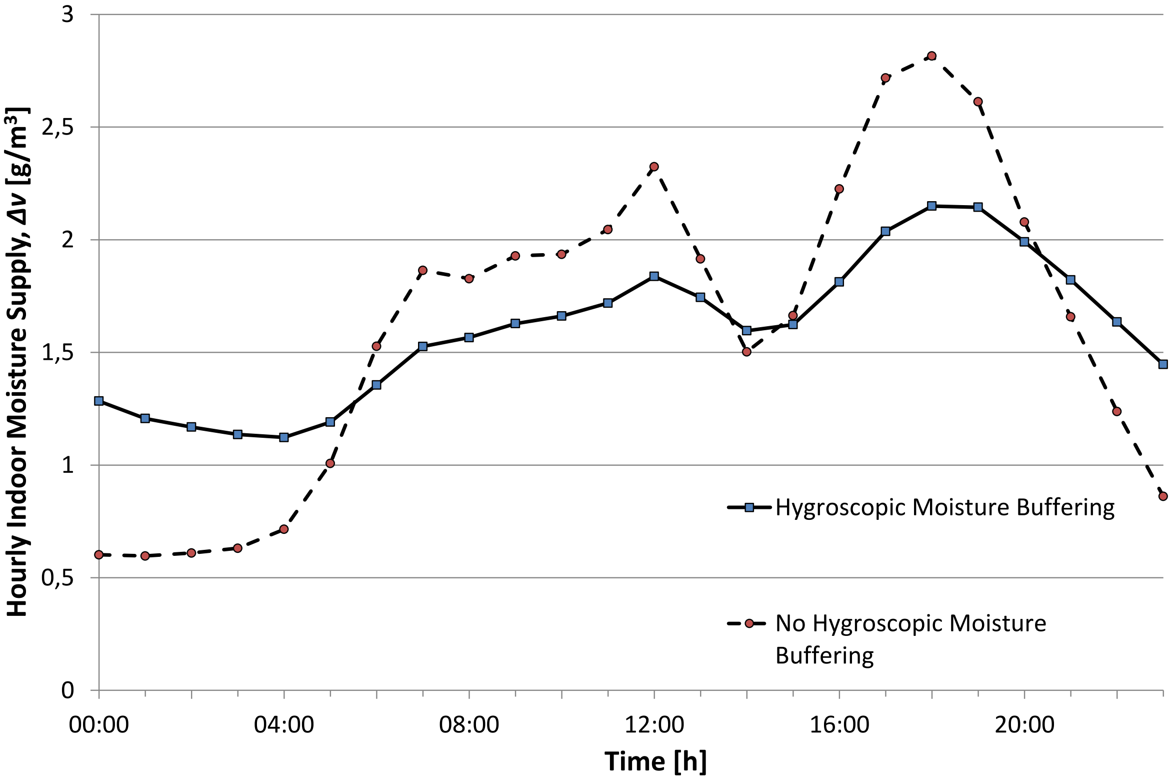


Figure 8 Diurnal variations of the simulated indoor moisture supply in multi-family dwellings located in Gothenburg, Sweden. Two variations are presented, with and without the influence of moisture buffering materials. The indoor moisture supply is a combination of the indoor moisture production presented in Figure 7, the ventilation rates from measurements (Boverket, 2010b), climate data from a reference year of Gothenburg (Meteotest, 1999) and the moisture buffering capacity of interior materials made of wood, gypsum and textiles.

3.2.2. Hygrothermal properties of soils

The results and conclusions presented in this section summarize the appended Paper IV.

Accurate and reliable material properties are essential for the credibility of the hygrothermal performance design. Soil is one material parameter which usually is defined with identical features, despite the type of soil that is to be represented in the hygrothermal simulation model. The hygrothermal properties of soil are important when analyzing and designing both new buildings and retrofits, for which the outer boundary of the building enclosure consists of soil. Typical types of building construction that are greatly influenced by soils are basements, crawl spaces, and slabs on grade. Soil can be differentiated into 12 classes of soil textures on the basis of three soil components; Clay, Sand, and Silt (USDA, 2008), as seen in Figure 9. The hygrothermal properties of these soil textures will vary and must therefore be defined separately.

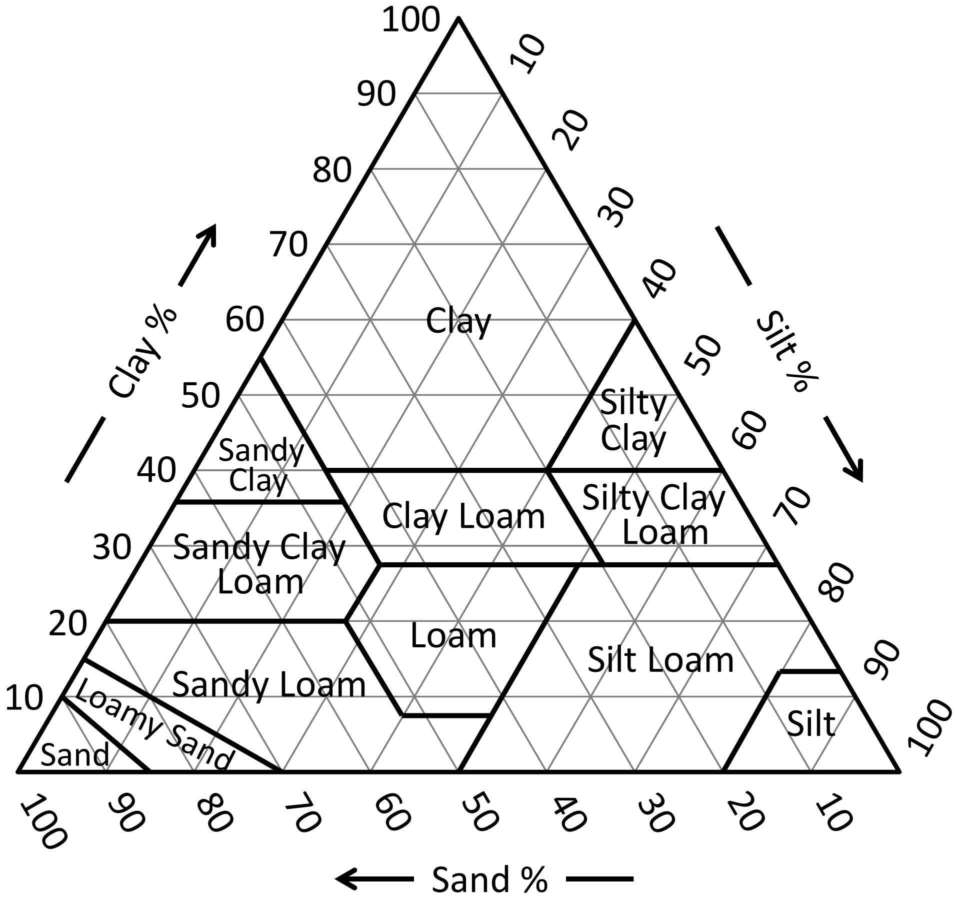


Figure 9 The soil texture triangle in which soils are differentiated into 12 classes of textures on the basis of three soil components; Clay, Sand, and Silt (USDA, 2008)

The hygrothermal properties, which are chosen to be defined for the 12 soil textures and are essential for the hygrothermal performance of the soil, are presented below.

- Moisture Storage Function
- Liquid Water Transfer
- Vapor Diffusion Resistance Factor
- Dry Bulk and Particle Density
- Porosity
- Thermal Conductivity
- Specific Heat Capacity

The moisture storage function, also known as the sorption isotherm, describes the relation between the moisture content, w, and the relative humidity, φ. This relation has been obtained by converting the van Genuchten expression (the soil water retention curve, WRC), which defines the relationship between the volumetric water content of the soil as a function of the suction pressure, expressed as an equivalent soil pressure head (van Genuchten, 1980). The advantage of applying the van Genuchten is that all necessary data is provided for all 12 texture classes, hence the moisture storage function for each soil can be obtained. The result from converting the existing data from van Genuchten into a sorption isotherm is illustrated in Figure 10.

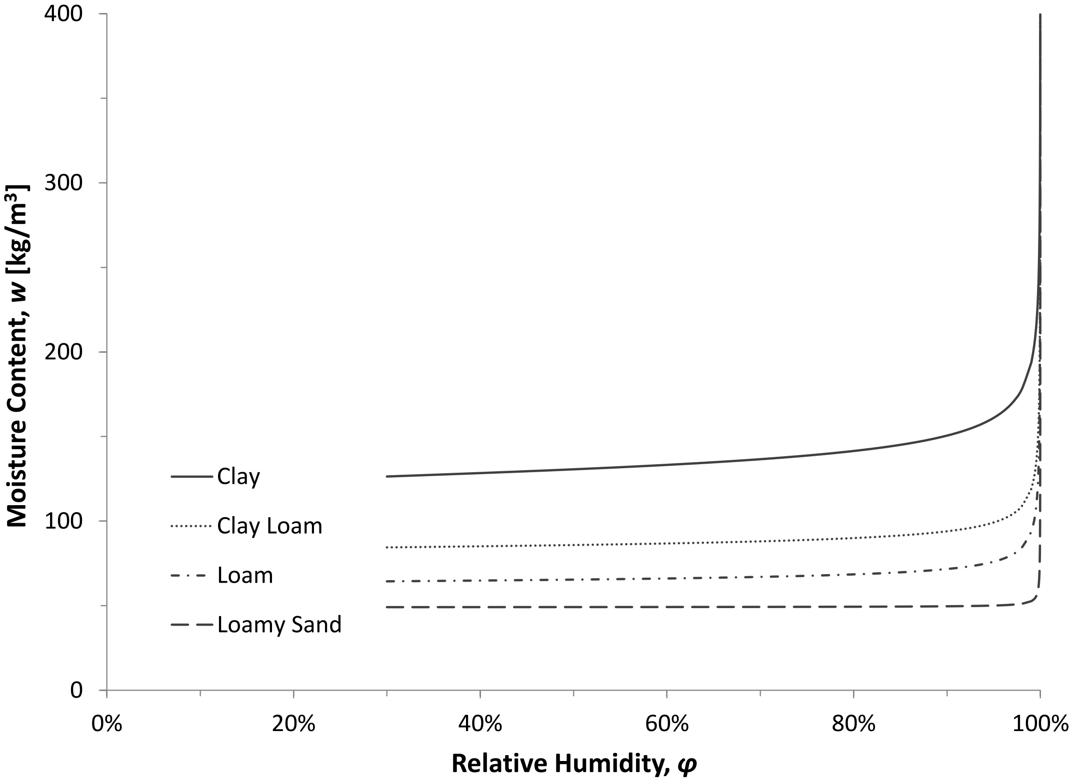


Figure 10 Sorption isotherm of four soil texture classes; Clay, Clay Loam, Loam and Loamy Sand. The relation between the moisture content, w, and the relative humidity, φ, is obtained from converting the van Genuchten expression (van Genuchten, 1980).

The liquid water transfer, also referred as liquid transport coefficient or liquid diffusivity, D, describes the flux of liquid water in the soil. D is dependent on the water content, w, of the soil hence a relation between D and w is necessary. The variation of the liquid diffusivity for four different textures of soil is presented in Figure 11. In addition, the value of D varies according to whether the soil is being dried or wetted i.e. an effect of hysteresis. The liquid diffusivity for a soil that is being dried is referred to as drying or drainage diffusivity, D_{dry}, whereas a soil which is being wetted is referred to as wetting or absorption diffusivity, D_{wet}. However, the hysteresis will not be as important as the disparity in D between the different soil textures, as seen in Figure 12.

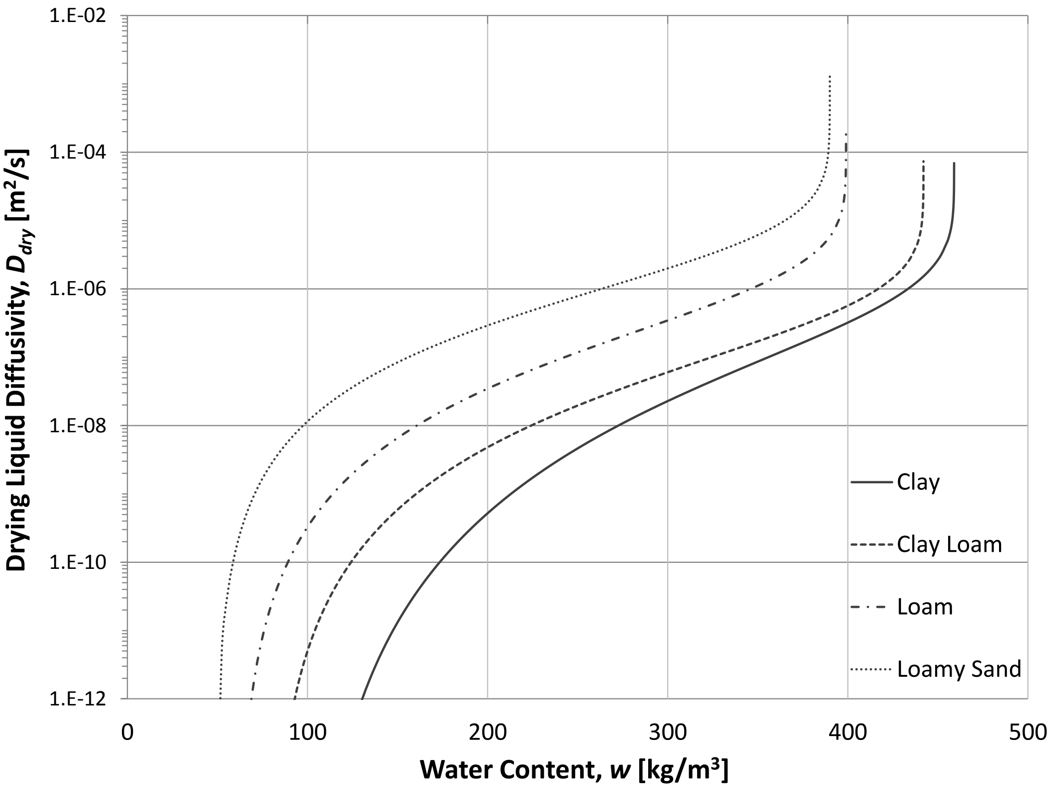


Figure 11 The drying liquid diffusivity, D_{dry} describes the flux of liquid water in the soil and varies in accordance with the moisture content, w. The variation of D_{dry} is presented for the soil textures of Clay, Clay Loam, Loam and Loamy Sand.

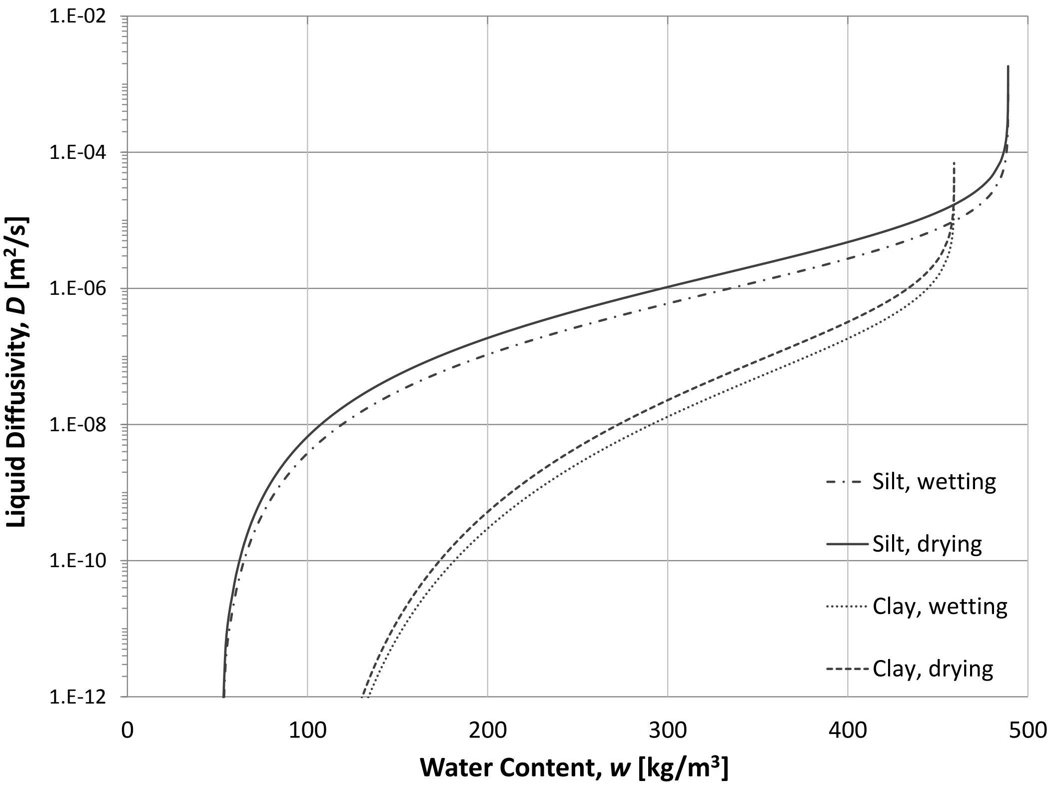


Figure 12 The drying and wetting liquid diffusivity, D_{dry} and D_{wet}, for Clay and Silt. Apparently, the difference in D between the soils is more significant than the effect of hysteresis.

The bulk density of soil is the combined weight of the soil solids, water, and air divided by the bulk volume. The dry bulk density, ρ_b, (kg/m^3) is the bulk density for a completely dry soil.

The particle density, ρ_s, (kg/m^3) in soils is defined as the mass of the solids divided by the volume of the solids, consequently, without considering the volume of the pores or the mass of liquid and gas inside the pores. The particle density can be used to determine the porosity, n, in relation with the dry bulk density:

$$n = \left(1 - \frac{\rho_b}{\rho_s}\right). \qquad [2]$$

The ρ_s is typically assumed to be 2650 (kg/m^3) in soils and earth materials (Blanco-Canqui et al., 2006; Eshel et al., 2004), though variation exists between 2400 and 2900 (kg/m^3) depending on the composition of minerals and organic components (Rühlmann et al., 2006). An existing study presents the particle densities from 176 experimental sites (Keller & Håkansson, 2010) which include nine of the 12 defined soil textures; the remaining three textures are assumed to equal 2650 (kg/m^3). In Table 3; ρ_b, ρ_s and n are presented for the 12 soil textures.

Table 3 The dry bulk density, particle density, and porosity for the 12 soil textures, of which the bulk and particle density are obtained from averages of 560 soil samples at 176 experimental sites (Keller & Håkansson, 2010).

Soil Texture	**Dry bulk density, ρ_b** *[kg/m^3]*	**Particle density, ρ_s** *[kg/m^3]*	**Porosity, n** *[%]*
Clay	1270	2620	52
Clay Loam	1360	2600	48
Loam	1290	2600	50
Loamy Sand	1510	2640	43
Sand	1580	2650	40
Sandy Clay	1400	2650	47
Sandy Clay Loam	1520	2620	42
Sandy Loam	1550	2580	40
Silt	1390	2650	49
Silty Clay	1400	2610	48
Silty Clay Loam	1280	2590	50
Silt Loam	1440	2600	45

The water vapor diffusion resistance factor, μ, is the rate of vapor diffusion through a material in comparison with stagnant air, and is typically assumed to be 50 for soils (EN-12524, 2000), regardless of the type of soil texture.

The thermal conductivity of soils, λ_{soil}, increases with the moisture content (Abu-Hamdeh, 2003). Other factors that influence the conductivity, though slightly, are mineral composition, temperature, type of soil texture, and time (Becker & Fricke, 1997). An empirical solution of λ_{soil} has been defined on the basis of the available data collected from the study of three different soil textures: Sand, Silt, and Clay (Becker & Fricke, 1997), though, converted to a function of *w,* as seen in Figure 13.

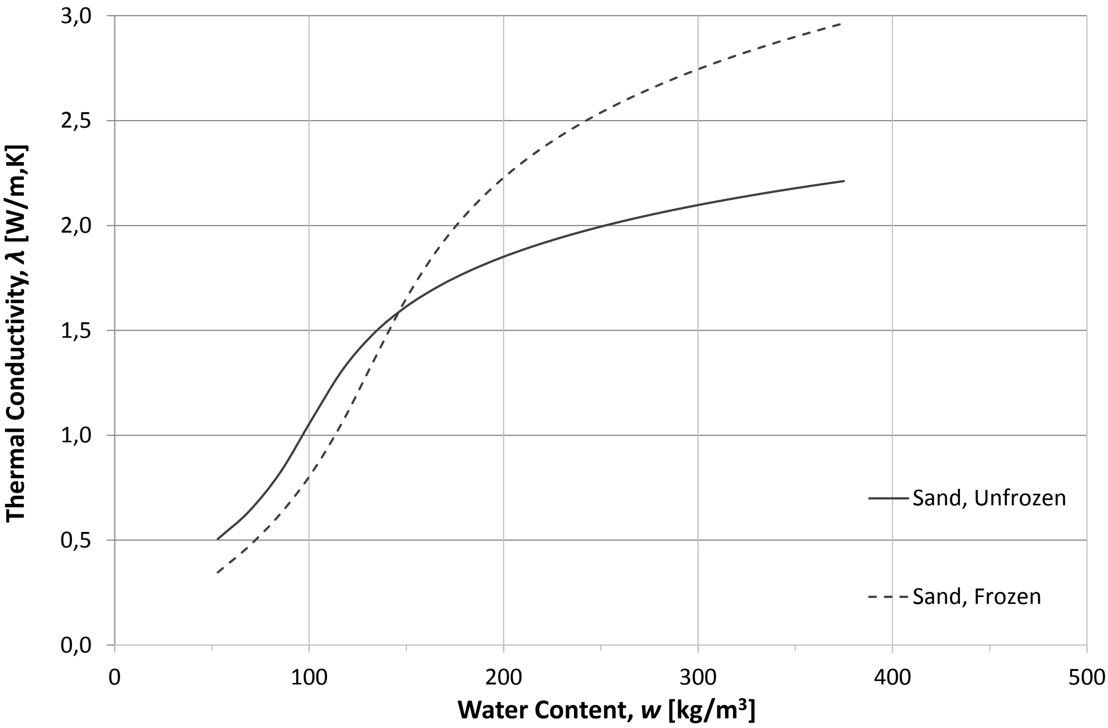


Figure 13 Thermal conductivity of sand as a function of the water content, w. The thermal conductivity, λ, varies also slightly, whether the soil is in a frozen or unfrozen state.

The specific heat capacity of dry soils, c_{dry}, can vary from 710 to 1550 (J/kg,K) (Olchev et al., 2009), though most commonly c_{dry} is assumed 850 (J/kg,K) (Acs et al., 1990; Kung & Steenhuis, 1986) where the actual volumetric heat capacity of the soil, C, increases linearly with the soil moisture content:

$$C = \rho_b \cdot c_{dry} + w \cdot c_w. \quad [3]$$

where c_w is the specific heat capacity of water.

In conclusion, the hygrothermal properties of soils vary depending on soil texture. The expected effect and variation on the hygrothermal performance is investigated in the case study of a retrofitting measure applied on a below-grade wall, as seen in Section 0.

4. Simulation and Analysis Methods

Hygrothermal simulations are suitable for a QRA, though with some prerequisites on the tools which are used. The simulation tool must enable the implementation of the parameter variability i.e. the values of the input parameters must be able to be changed. Further, in a QRA, the simulation tool should enable multiple simulation runs, preferably without interference. A perfect hygrothermal simulation tool allows implementing the variability of the input parameters and most importantly, offers to stochastically vary these parameters or by a specified randomness. Alternatively, this sampling process can be made outside the simulation tool but with the interaction of an additional tool which possesses these features. This section discusses the three major phases of a successful QRA; the preparatory work, running the simulations and suitable approaches for post simulations and result analysis methods.

4.1. Hygrothermal Performance Indicators

The definition of performance indicators, P_{ind}s, is an essential step of a QRA since they will be part of the evaluation criteria in the forthcoming risk tolerability decisions. Preferably, P_{ind} is a value of a performance, a state of failure or financial key ratios. Common P_{ind}s for the application in a hygrothermal risk assessment are presented below. Since the aim of a risk assessment is to estimate the future hygrothermal conditions of a building, the indicators are related to either energy or moisture performances. In addition, several of the presented P_{ind}s below, are suitable for pre and post-comparisons.

Domestic Energy Consumption, Q_{dom}: The amount of energy for heating and cooling is a very useful indicator to evaluate a retrofitting measure. Naturally, the heating demand can be defined over a specific time and in relation with the residential floor area (kWh/year·m^2 or MWh/year). Alternatively, the energy consumption can be described as a cost, though together with a consumer price index, if making comparisons for longer periods of time.

Airtightness, q_l: Sealing leaks in the building envelope or sealing a leaky air distribution duct system is a potential energy saving approach; hence leakage rates are suitable indicators of the building or duct airtightness. The leakage rate is usually described in relation with the area of the building envelope (l/s·m^2) or as an interior air volume based Air Changes per Hour (ACH); both at a specific pressure difference, ΔP, of 50 Pa.

Relative Humidity, φ: The risk of mold can be roughly estimated with relative humidity levels. However, the risks also depend on the temperature since a critical relative humidity φ_{crit} can be defined for a given temperature. The relation between the actual φ and φ_{crit} can be defined as a **Mold Growth Potential**, m, in which values over 1 indicates favorable conditions for mold growth (C-E. Hagentoft et al., 2008). In addition to φ

and temperature, the risk of mold depends on the type of exposed material, time and fluctuation of φ; since an empirical model has been formulated, referred to as a **Mold Growth Index** (MGI) (Hukka & Viitanen, 1999).

Moisture Content, w: The risk of rot in wood-based materials is commonly evaluated with w (kg/m^3) or as a percentage of saturated moisture content (MC) (Straube et al., 2010). Values of 20-25% for MC are usually taken as a critical upper limit to prevent decay in wood-based materials (DIN 68800-2 (2012-02), 2012).

Payback Period (PP*)*; A financial indicator which is useful to estimate the time required to return the investment of the retrofit. The payback period is also practical in the comparison with different retrofitting measures.

Naturally, there is a vast range of optional P_{ind}s such as; the expected Service-Life, IAQ, Occupants' Comfort Levels and Environmental Indicators.

Another important aspect which is worth to bring up for discussion, is the lack of variability acceptance for the P_{ind}s. Since the future performance of a building or a building component is evaluated based deterministic values of the P_{ind}s, an uncertainty range must be expected. Assumingly, this typically applies to P_{ind}s such as φ, m, MGI, w and MC under which specific levels of failure are assumed. In reality, the risks associated with these indicators could exist even if the criteria are not fulfilled and as well, they may not exist even if the criteria are exceeded.

4.2. Preparations and Pre-Simulations

In hygrothermal simulations, the influential parameters must be taken into consideration to obtain truthful and acceptable results, though the implementation of the variability of all input parameters is usually not necessary. In case the distinction of the most decisive parameters has not been made, pre-simulations can identify those with the highest influence on the performance. A pre-simulation could consist of gradually varying the extreme values or with specified upper and lower percentile of each parameter, whilst holding the other parameters fixed. Consequently, the importance of each parameter variability can be estimated and the least influencing parameters can subsequently be excluded from the forthcoming simulations. A great weakness with multiple simulation runs, which according to the author is usually required for a QRA, is the time demand. Therefore, reducing the number of parameters, with a defined variability but with a low influence, will optimize the time required for the simulations, but will still ensure credible simulation results.

Once the variability of the parameters has been defined, a sample method must be established. Both the sampling method of Monte Carlo and the Latin Hypercube are applicable in a QRA. The Monte Carlo method randomly chooses a value of a parameter, based on the defined variability. The purpose of the Monte Carlo sampling method is to produce values of a parameter which is equivalent with the probability distribution. However, a low number of parameter samples is likely to overrepresent segments of the parameter variability hence a larger number of samples is usually required for a better fit. An alternative sampling method to Monte Carlo is the Latin Hypercube, which doesn't over- and undersample the way the Monte Carlo method does. The Latin Hypercube, referred to as a stratified sampling technique (Bedford & Cooke, 2001), divides the probability distribution into k intervals with equal probability. Once sampling, the values are chosen from each defined interval. The intervals are then marked as have already been used until values from all intervals have been represented, at from which point the sampling process starts over (Vose, 2008). The Latin Hypercube sampling method is claimed to be more efficient than the Monte Carlo method (Janssen, 2013); however, the time required for preparations is larger for the Latin Hypercube due the required stratification of the parameter variability and the determination of the number of iterations. In addition, a highly irregular shape of the variability requires a large number of sampling intervals; hence, in such cases, the Monte Carlo method is equally applicable.

The last step, prior to initiating the simulations, is to choose the appropriate simulation model. Naturally, the decision depends on what is to be simulated, though the tool in which the model is designed, must possess certain qualities to successfully generate probabilistic results. First, it should be able to perform multiple runs of scenarios, in which the scenarios can be either pre-produced or generated inside the simulation model. For the latter case, the model must be able to implement the parameter variability and to stochastically, or by a specified randomness, vary these parameters to ensure the generation of probabilistic scenarios. Further, the chosen values of the varying parameters should be logged to enable the post-simulation analysis and the result of the risk analysis should preferably be automatically saved after completing each iteration of the simulation.

4.3. Running the Simulations

Prior to running the simulations, the criterion on when to halt the simulations shall be determined. Either a stopping criterion can be defined based on the sampling convergence i.e. when the number of scenarios and their parameter configurations are equivalent with expected probability ranges; or, the criterion of halting the simulation can be based on the results. In the latter criterion, the number of iterations can be assumed sufficient when the output of the simulations converges with any tolerance of deviation from the mean, standard deviation or any specified percentile. In the case of Latin Hypercube, the number of sample iterations is usually pre-determined (Janssen, 2013). Once, the convergence or halting criterion is defined, the simulation can be started.

4.4. Post Simulations

The information provided and discussed upon in this section is densely presented; hence the reader is advised to the case studies of Chapter 0 for further references, examples and explanations.

The post simulation phase consists of analyzing and presenting the results of the simulations in an understandable and useful manner. The simulation results can either be presented with illustrations, figures, graphs or values and should preferably be based on the defined P_{ind}s. Typical graphical presentations are probability density functions (pdf), cumulative density functions (cdf) or discrete probability distributions (Vose, 2008). The results can also be presented in values of the P_{ind} describing the mean, variance, spread, shape, percentiles or skewness of the probability distribution. If multiple P_{ind}s are used, a comparison between the indicators can be made with a ranking method. A recognized method is to apply the Spearman's ranking, which determines the correlation between the indicators based on their given ranking (Bedford & Cooke, 2001). To clarify, each simulated scenario can be ranked based on a specific P_{ind}; this procedure is repeated for each performance indicator; subsequently, each scenario is provided a ranking number for each P_{ind}. Further, the ranking numbers are compared, revealing which of the P_{ind}s that are most correlated. This procedure is powerful in the sense of revealing the trustiness of one P_{ind}, in comparison with the others.

Another important step of the post simulation phase is the sensitivity analysis. The main purpose of such analysis is to identify the key input parameters i.e. which parameters that will have the highest influence on the studied performances. The determination of the parameters with the highest impact is also valuable if measures of improvement are to be taken on the retrofit design. There is a large number of approaches for a sensitivity analysis; ranging from simple to complex methods. The decision makers in a retrofitting project have seldom explicit knowledge in risk assessment since the result, which is presented, should be comprehendible and trustworthy. In most cases, a simple method is therefore most suitable for analyzing the result of a hygrothermal risk analysis; since an analyzing method which is not fully understood by the observer, becomes less reliable and its purpose questionable.

Examples of methods for a sensitivity analysis are the *One-at-a-time sensitivity measure*, O_{sens}, the *Sensitivity index*, S_i, and the *Importance index*, I_i, (Hamby, 1994). The purpose of the first method is to repeatedly vary one parameter while holding the others fixed; therefore, this method determines the impact of the varying parameter on the performance indicators. O_{sens} can be defined as;

$$O_{sens,p} = MAX(P_{ind,p}) - MIN(P_{ind,p}), \qquad [4]$$

under the exclusive influence of the input parameter, p. Therefore, O_{sens} can be defined for each varying parameter of the sensitivity analysis. The parameter variability which results in the largest value of O_{sens} is subsequently the parameter with the largest influence on the evaluated P_{ind}.

The method of the *Sensitivity index* applies the result of O_{sens}, which is divided by the maximum value of the performance indicator under the influence of the parameter p, $MAX(P_{ind,p})$. Consequently, S_i is expressed as following;

$$S_{i,p} = \frac{O_{sens}}{MAX(P_{ind,p})} = \frac{MAX(P_{ind,p}) - MIN(P_{ind,p})}{MAX(P_{ind,p})}. \qquad [5]$$

S_i is a relative indicator of the influence, thus comparable for each varying parameter of the study. The parameter with the highest value of S_i has the highest influence.

The *Importance index*, I_i, evaluates the spread and irregularity of P_{ind} under the exclusive influence of each parameter variability. I_i is defined by the relation between the variance, σ^2, due to the variability of $P_{ind,p}$ and the variance due to the total variability of P_{ind}, thus;

$$I_{i,p} = \frac{\sigma^2_{P_{ind,p}}}{\sigma^2_{P_{ind}}}. \qquad [6]$$

The above presented methods of sensitivity analysis, additional and elaborated methods are exemplified in the case studies presented in Chapter 0.

5. Case Studies

This chapter presents four case studies of retrofitting measures, using the proposed procedure as illustrated in Figure 3. The four retrofits consist of two roof constructions, one exterior wall and one below-grade wall assembly. This chapter also serves to validate and verify the credibility and applicability of the proposed risk assessment procedure.

5.1. Case Study 1 – Residential Unvented Attic

The following case study is summarized by a hygrothermal risk assessment applied on a residential unvented attic, presented in the appended Paper VI.

A pitched roof is a very common residential building construction in which the attic, if vented with exterior air, can be converted into an unvented and conditioned space. The main reasons for such retrofitting measure are to improve the energy efficiency and to create a better environment for the HVAC system (which is located inside the attic space). A leaky air distribution system results in less energy losses compared to an air distribution system located in a ventilated attic (Rudd, 2005). Further, air leakages from the indoor environment or the duct system may lead to mold growth on the interior surface of the roof (C-E. Hagentoft et al., 2008) or result in ice dam creation (Lstiburek, 2006). Consequently, there are advantages with an unvented compared with an exterior vented attic, at least in terms of energy efficiency. In concerns of moisture safety, the performance of an unvented attic is not too well investigated; hence a hygrothermal risk assessment is valuable.

- SCOPE ***CASE STUDY - 1***

System Formulation

The unvented attic is considered part of the conditioned space though not intended to be inhabited by the occupants; therefore, the environment in the attic is similar to the indoor climate. In a building with an unvented attic, the HVAC system is preferably located inside the attic space and will therefore have an impact on the attic environment, depending on the features of the HVAC unit and the duct system. Naturally, also the outdoor climate and material properties plays a significant role in the expected hygrothermal performance of an unvented attic. In conclusion, the unvented attic is influenced by a large number of parameters and must therefore be evaluated as a complete system with correlated boundary conditions. The attic, the roof and the inside of the building together with expected fluxes of heat, air and moisture between these spaces of an unvented attic are illustrated in Figure 14.

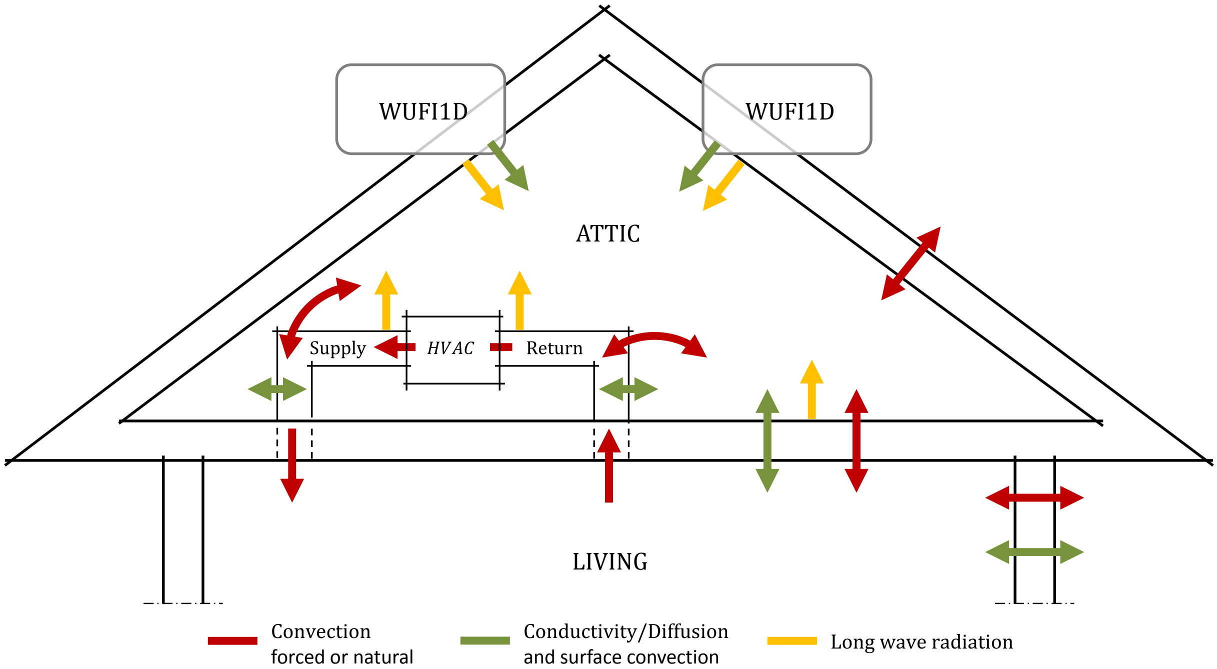


Figure 14 The unvented attic, hosting a HVAC system, must be considered as a very complex hygrothermal system with a large number of interacting mechanisms. The arrows depict the location and direction of both the heat and water vapor transfer of convection, conductivity/diffusion and long wave radiation. The model also illustrates the structure of the latter presented simulation model, in which the hygrothermal calculation tool WUFI1D is used to simulate the two roof components.

Targets and Concerns

The intention of the retrofitting measure is to improve the energy efficiency, the service-life of the HVAC system and to still ensure a moisture safe roof construction. There is large amount of wood-based materials in a residential attic, both rafters, ceiling joists and roof deck sheathing, which unfortunately is a favorable environment for mold growth depending on available nutrients, the present air humidity and temperature (Hukka & Viitanen, 1999). It is of great concern to prevent critical levels of relative humidity, φ, inside the attic; which also is a potential for moisture build up in the wood materials, especially the roof sheathing (Straube et al., 2010).

Existing Conditions

The existing materials are considered to be in acceptable and good conditions.

Strategy Identification

An exterior ventilated attic is converted into an unvented conditioned space. Spray polyurethane foam (SPF) is applied between the roof rafters and the openings at the soffits are sealed to ensure an air tight roof construction. The existing insulation material in the ceiling floor is removed to ensure an attic environment equivalent with the indoor conditions.

Risks identification

The vapor permeability of SPF can either be referred to as open or closed and there are risks associated with the application of them both. A vapor open SPF enables moisture from the attic air to penetrate the foam insulation and to the reach the upper OSB roof sheathing. Therefore, there is a risk of critical levels of moisture content (MC) in the OSB sheathing. The application of a closed SPF is also associated with a major risk. A roof covering of shingles or similar vapor tight material will together with the closed SPF create a double layer of vapor resistance with intermediate organic materials. In case moisture penetrates in between the double layer, the drying potential is very low; hence moisture problems may arise.

An additional risk is associated with the assumption of an air tight roof construction. What happens if the application of the SPF is improperly applied and makes air move through created leakage channels in the roof construction? Hence intermediate condensation is an obvious risk due to exfiltration or intrusion of the humid attic air.

Influential Parameters, Uncertainties and Correlations

An unvented attic, hosting a HVAC system, must be considered as a very complex hygrothermal system. The future performance and expected service-life of the roof construction will depend on a number of influencing parameters. These parameters are important to include when analyzing the future conditions of an unvented attic, in terms of energy efficiency, moisture safety and durability. A range of influencing parameters in an unvented attic is given below:

- Indoor Heat and Moisture Production
- Hygrothermal Material Properties
- Natural and Driven Air Leakages
- Features of the HVAC System i.e. Dehumidifying/Humidifying Effect, Air Flow Rate etc.
- Geometrical Variations of the Building Components
- Outdoor Climate
- Orientation and Location of the Building and Slope of the Roof
- Workmanship
- User Behavior i.e. HVAC Set-Point Temperatures, Airing, Maintenance etc.

There is a clear correlation between the cycling of the HVAC unit, the characteristics of the air distribution system, the indoor and attic climate and the outdoor environment. In addition, the flow and directions of forced and natural air movements are influenced by all the above. Since the correlations are complex, these are best predicted through advanced hygrothermal simulations.

- RISK EVALUATION *CASE STUDY - 1*

The hygrothermal performance of the unvented attic is influenced by a large number of parameters with a high variability. In addition, many of the parameters are closely correlated and also complicated to rank based on the expected roof and attic performances. Assumingly, parameters such as the vapor permeance of the SPF, the indoor moisture supply, the thermostat set-point temperatures and the outdoor climate are all highly influential on the energy and moisture performances of the roof and attic. The attic, as a system, has a complex nature and therefore specific values or ranges of risks cannot be estimated; hence the hygrothermal performance of the unvented attic is far too complex to be analyzed solely with a QlRA. A full QRA is therefore recommended and obviously necessary to enable the inclusion of the most influencing parameter variabilities in the risk assessment.

- QUANTITATIVE RISK ANALYSIS *CASE STUDY - 1*

Method and Performance Indicators

A simulation model of the unvented attic is developed using a numerical model created in MATLAB® and in interaction with WUFI-1D, which is a validated hygrothermal calculation tool (Künzel, 1995). The numerical MATLAB® model is designed to calculate the heat and water vapor transfer through the building components and intermediate air volumes, in exception of the outer roof construction which is calculated in WUFI-1D. The numerical tool is designed to simulate the performance of the complete building envelope and inner environment except for the roof construction. WUFI-1D is a one-dimensional hygrothermal tool hence the complete attic model requires two WUFI-models; one left and one right roof construction. This approach requires an iterative process between the two WUFI-1D models and the mathematical MATLAB® model, as seen in Figure 14. An iterative simulation process is essential to enable the two WUFI-models and the mathematical model to represent a complete and realistic system of the attic space and the adjacent roof construction; therefore, the interaction enables the coupling of the simulated elements of WUFI and the attic environment.

The consequences of interest are the risk of rot in the wood-based roof sheathing and the risk of mold on the surfaces of roof rafters and ceiling joists. In addition, the impact due to the parameter variability on the energy demand of the air distribution system is of interest. Subsequently, the P_{ind}s of this case study are the moisture content, MC, of the OSB, the attic air relative humidity, φ_{attic}, and the energy demand of the HVAC unit, Q_{HVAC}. Commonly, a MC of 20-25% is usually considered as a critical upper limit to prevent decay of wooden materials (DIN 68800-2 (2012-02), 2012). The Mold Growth Index (MGI) is also a useful indicator to estimate the development of mold on a wooden surface (Ojanen et al., 2011). In this case study, the MGI is investigated on the surfaces of roof rafters and ceiling joists.

Input Values and Probability Distributions

There is an extensive amount of essential information of the input parameters which is needed if expecting realistic results from the simulation of the unvented attic. The input parameters for the simulation model are either defined with deterministic values or with a variability. This section briefly presents the varying input parameters of this case study. For further information regarding the deterministic input parameters, the reader is referred to the appended Paper VI.

Except for the climate, the varying parameters is sampled based on an *importance sampling* (Vose, 2008), in which the chosen values represent the extreme tail of the parameters variability. Six different input parameters are selected to vary in the simulation model due to their expected high influence on the hygrothermal performance of the attic and roof construction. The varying parameters of this study are the following:

- Thermostat Set-Point Temperatures
- Outdoor Climate
- Vapor Permeance of the Rigid Spray Foam Insulation
- Air Leakage Rate From Supply and Return Ducts
- Airtightness of the Ceiling Floor
- Indoor Moisture Production

The thermostat set-point temperatures for cooling and heating vary between 21,1/23,3°C and 20/25,6°C, thus representing an assumed small and wide range of, by the occupants considered, comfortable indoor temperatures. Practically, the simulation model determines the HVAC cycling based on 21,1/23,3°C and then applies the same supply air flow rate on 20/25,6°C set-points. This approach will determine the impact on the hygrothermal performance of the unvented attic due to the occupants desired comfort temperatures.

The outdoor climates, applied to the simulation model, represents U.S. climate zone 1 to 7, ranging from Miami, FL, in the south to Fargo, ND, in the north. The thermal resistance of the roof consists of either open or closed cell SPF. A 4% leakage of the supply and return air flow rate, from and to the air distribution system, is assumed as a low leakage rate; a high rate is considered as 20%.

A leaky ceiling floor will enable air to exchange between the attic and the living space. The potential air movements are induced by air pressure differences and the flow of air and direction depends on temperatures, ventilation system and wind forces. In this study, two conditions are assumed for the ceiling airtightness along the ceiling floor area; a low value is set to 2,0 ($l/s{\cdot}m^2$)and high value is considered 10,0 ($l/s{\cdot}m^2$).

The generation of moisture inside the building varies between either the daily average of residential moisture load, presented in Section 3.2.1, or the standard design value of a four-bedroom living (ASHRAE 160-2009, 2011). The daily averages are weighted according to a human activity pattern (ANSI/ASHRAE 90.2-2007, 2007).

Design and Run Simulation Model

The air distribution system, applied to the simulation model, is designed as a whole house air distribution, with intermittent supply and with an exterior air intake on the return side of the HVAC system. The cycling of the HVAC system depends on the indoor temperature and the set-point temperatures of the thermostat. The simulation model is designed to optimize the HVAC unit to a 50% on and off cycle and at a small span of set-point temperatures, 21,1/23,3°C.

In order to determine the attic temperature, the indoor temperature and the cycling of the HVAC system must be estimated. The indoor thermal conditions will mainly depend on thermostat set-point temperatures, outdoor temperature together with the U-value of the building envelope; further, the indoor thermal inertia, the fenestration area coupled with incident solar radiation and the indoor thermal load. In concerns of water vapor transfer, the moisture buffering capacity of the materials inside the attic and the indoor space are equivalent with the defined materials with heat capacity (ANSI/ASHRAE 90.2-2007, 2007). All other material properties are provided from the WUFI material database.

Combining all the varying parameters results in 224 (2x7x2x2x2x2) different scenarios of the unvented attic, where each scenario requires an iterative simulation run with the numerical MATLAB® model and the two WUFI-1D models. Each scenario is simulated for one consecutive year until convergence criteria are fulfilled. The required convergences are 0.1% for the attic temperature (in Kelvin) and 1% for the vapor content (g/m^3) of the attic air, in comparison with previous iteration. In order to fulfill the convergences and finish the simulation, the deviation between any previous and present iteration, at a specific time step, shall not exceed the criteria.

Further details regarding the simulation model is given in the appended Paper VI.

Result, Sensitivity and Uncertainty Analyses

After completing the simulations of the 224 different scenarios of an unvented attic, the following P_{ind}s were taken into consideration; the MC in the OSB roof sheathing, the energy demand of the air distribution system, Q_{HVAC}, and the relative humidity in the attic, φ_{attic}. Part of the result analysis was also to list the most reliable and the most risky assemblies of the varying parameters.

The configuration of the parameters, for the most reliable and the most risky roof construction due to critical levels of MC, are presented in Table 4. The different scenarios are presented for U.S. climate zone 1 to 7. There are some distinguished conclusions to make out of Table 4; every best performed unvented attic roof is always constructed with a closed SPF and with a low indoor moisture supply. The opposite is valid for the most risky roof. In all cases, except for climate zone 4, a high duct leakage has a positive effect on the MC of the OSB; most likely due to the dehumidifying effect of the HVAC cooling coils, which, by a higher rate of air leakage, will have a higher influence on the vapor content of the attic air during the operating cooling mode. In concerns of moisture safety, there are no clear pattern for the varying parameters of the thermostat set-point temperatures or the ceiling airtightness. A detailed illustration of the annual development of the MC is presented in Figure 15 for climate zone 1 and 3, for the simulated best and worst scenarios according to Table 4.

Table 4 The Configurations of the varying parameters with lowest and highest risk of critical levels of MC in the OSB, presented for U.S. climate zone 1 to 7. The set-point temperatures are referred to as a small span (21,1/23,3°C) or large span (20/25,6°C). The reason why the best configurations all have a maximum MC of 16% is that this value was set as a starting value of the MC in the OSB and obviously, these best-performed configurations never exceed this value.

Rank	Climate Zone	Direction	Set-Point	SPF	Duct Leakage	Ceiling Leakage	Moisture Production	MC max
Best	1	South	Small	Closed	20%	2@50	Normal	16%
Worst		North	Large	Open	4%	10@50	High	38%
Best	2	South	Small	Closed	20%	2@50	Normal	16%
Worst		North	Small	Open	4%	10@50	High	43%
Best	3	South	Small	Closed	20%	2@50	Normal	16%
Worst		North	Large	Open	4%	10@50	High	45%
Best	4	South	Large	Closed	4%	10@50	Normal	16%
Worst		North	Large	Open	4%	10@50	High	54%
Best	5	South	Small	Closed	20%	2@50	Normal	16%
Worst		North	Large	Open	4%	10@50	High	47%
Best	6	South	Small	Closed	20%	2@50	Normal	16%
Worst		North	Large	Open	4%	10@50	High	45%
Best	7	South	Large	Closed	20%	2@50	Normal	16%
Worst		North	Large	Open	4%	10@50	High	37%

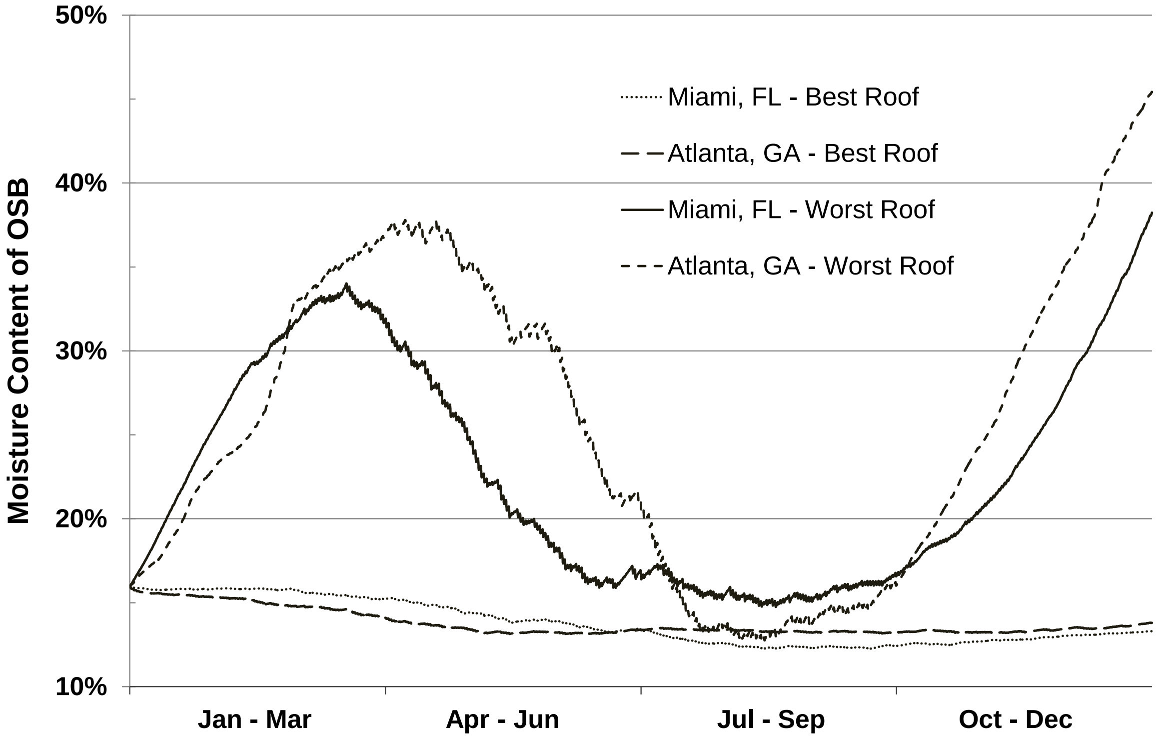


Figure 15 The annual development of the MC in the OSB sheathing, for the simulated best and worst scenarios of U.S. climate zone 1 and 3; Miami, FL and Atlanta, GA.

In this QRA, the importance of the different varying parameters is estimated by measuring the average deviation of a varying parameter, when remaining all parameters but one fixed. Repeatedly, the disparity in annual maximum of MC is compared when changing only the value of the investigated parameter. The average disparity of the parameter (in this study the MC) is referred as D_p and expressed as:

$$D_p = \frac{1}{n/2} \sum_{i=1}^{n/2} \left| X_{i,p}^{A} - X_{i,p}^{B} \right|, \qquad [7]$$

where

D_p = The average disparity of one varying parameter, p (p=1:6),

X = The indicator or the analysis (in this case the maximum MC [%]),

n = Total number of scenarios i.e. sets of different values of X (n=224).

Further, D_p for each varying parameter is weighted with the parameter with the highest value, referred to as D_p^{max}; hence an relative disparity, D_p^{rel}, can be defined for each parameter as:

$$D_p^{rel} = \frac{D_p}{D_p^{max}}. \qquad [8]$$

Consequently, the parameter with the highest D_p^{rel} obtains a relative value of 1,0. All other parameters receive a D_p^{rel} of either 1,0 or lower. This method enables to compare the influence of the varying parameters on the studied P_{ind}. In this QRA, the annual maximum of MC in the OSB sheathing is one of the P_{ind} and the result of the importance analysis is presented in Figure 16. According to the result of the sensitivity analysis, the vapor permeance of the SPF is the most important parameter on the MC of the OSB; meaning, whether the SPF is closed or open, will have the largest impact on the estimated conditions of the OSB sheathing in the roof construction. Other important parameters are the outdoor climate and the indoor moisture production.

According to Figure 16, the thermostat set-point temperatures and duct leakages have low influences on the annual maximum MC of the OSB; however, the duct leakage seems to have some influence according to Table 4. Obviously, the thermostat set-point temperatures govern the cycling of the HVAC and therefore the amount of energy required. Figure 17 illustrates the required amount of energy, as a factor of reduction, F_{red}, from the HVAC unit if changing the set-point temperatures from 21,1/23.3°C to 20/25.6°C. The analysis does not take the efficiency of the HVAC unit into consideration nor the differences in efficiency between heating and cooling.

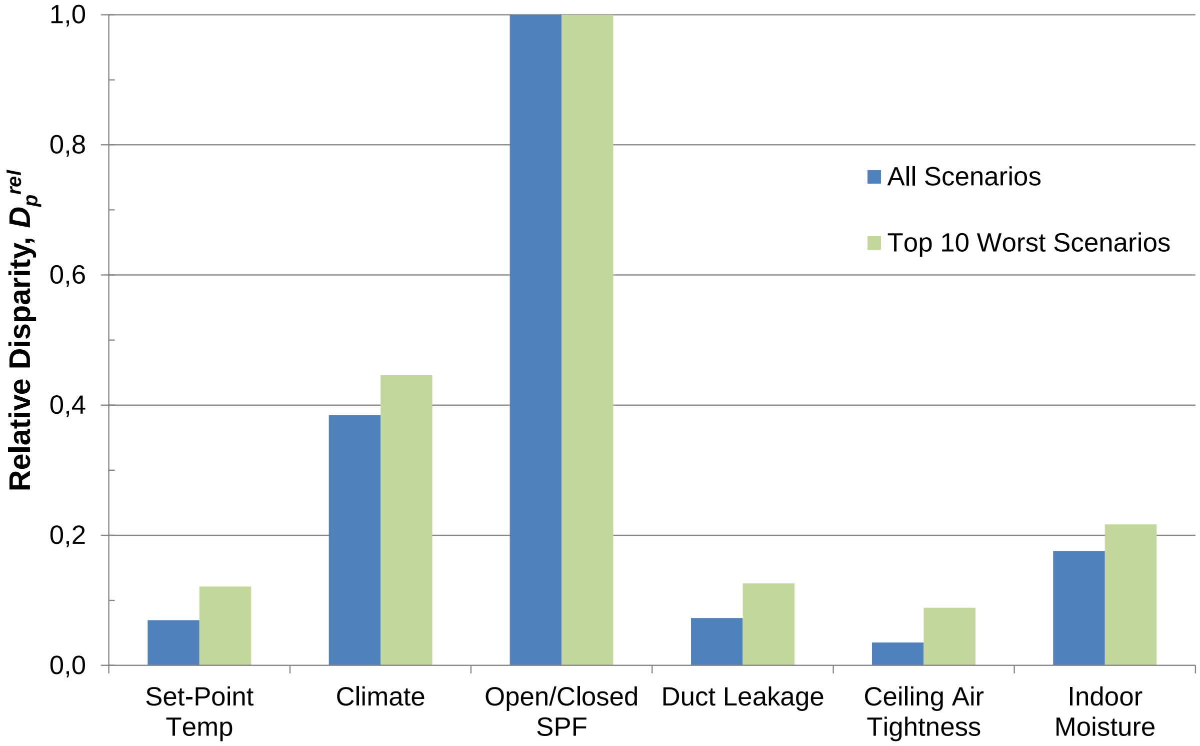


Figure 16 The relative disparity, D_p^{rel}, for the varying parameters of this study. According to the analysis, the simulated maximum MC of the OSB will vary mostly depending on weather the SPF is vapor closed or open. Both the outdoor climate and the indoor moisture production will have a rather high influence on the maximum MC as well.

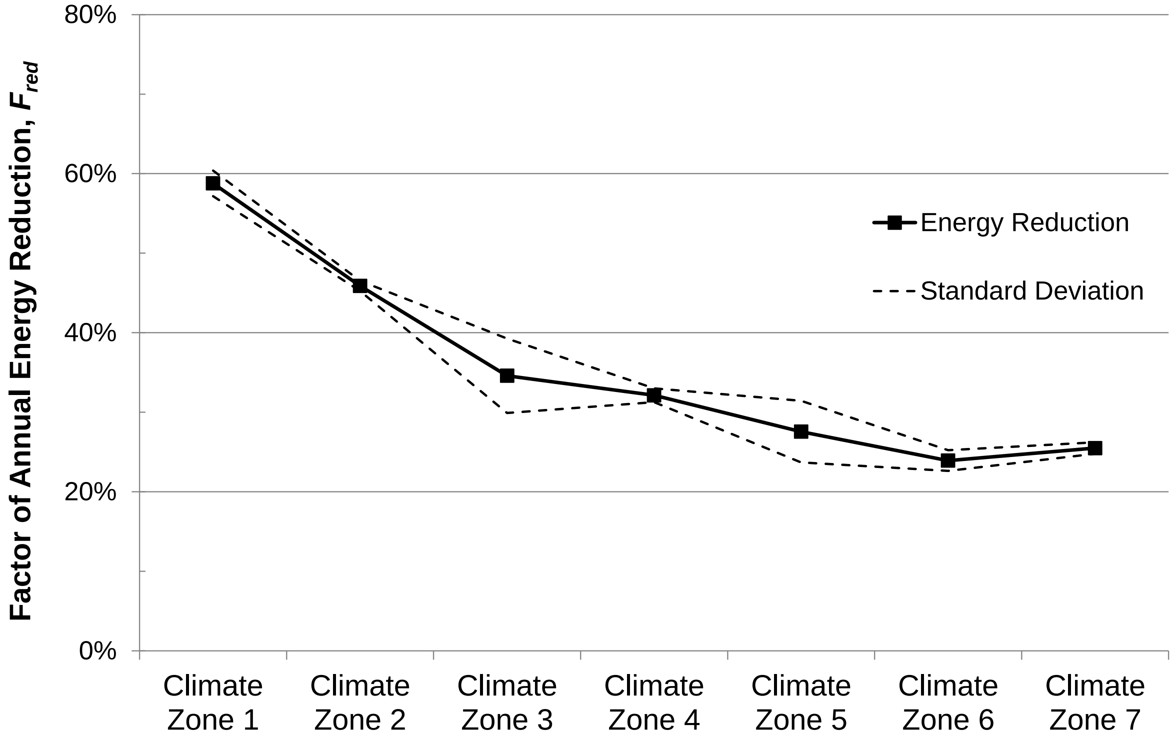


Figure 17 Relative annual reduction of energy consumption when changing the thermostat set-point temperatures from 21.1/23.3°C to 20/25.6°C. The slope of the curve indicates that hotter climate zones are prone to have higher relative savings in energy demand.

The analysis of the F_{red} for the different U.S. climate zones, presented in Figure 17, indicates that hotter climates have a relative higher potential of energy savings compared to a colder climate. The duct leakages from the air distribution system also prove to influence the cycling of the HVAC unit. Figure 18 illustrates the increase in energy demand of the HVAC unit when changing the assumed leakage rate from 4% to 20% in the supply and return duct system. As for the previous analysis with the set-point temperatures, the efficiency of the HVAC unit is not taken into consideration nor the differences between heating and cooling. Since the energy consumption increases when changing the duct leakage from 4 to 20%, the relative deviation in Q_{HVAC} is referred as an increase, F_{inc}.

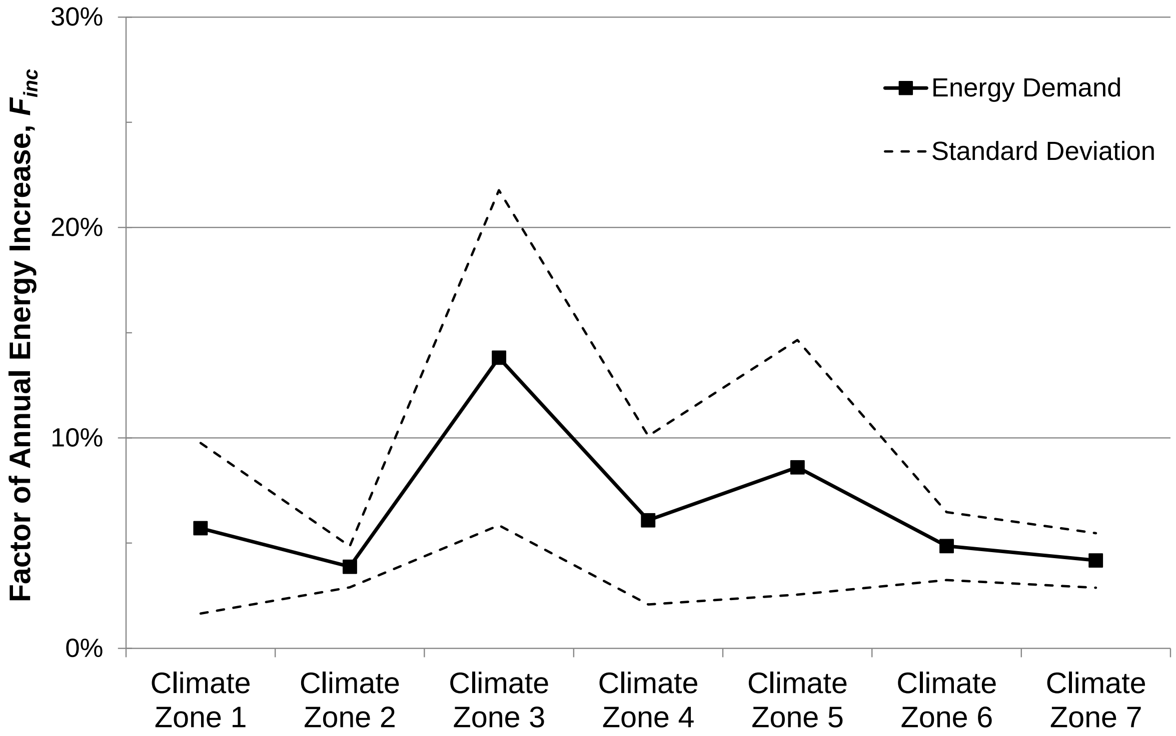


Figure 18 Relative annual increase of energy consumption when changing the assumed ventilation duct leakage from 4% to 20%. The results are presented for U.S. climate zone 1 to 7, where the increases vary from 5% to 14%, thus with large span of uncertainty.

The result of the analysis in Figure 18 shows that the leakage rate of the duct system do make a difference on the annual energy cost, despite that the HVAC unit is located in an conditioned space. The relative increase in energy, required to heat or cool the air, varies between 5% and 14% when comparing a 4% duct leakage with a 20% leakage; though, with a large uncertainty, as seen in Figure 18.

Further, φ_{attic} was investigated due to the risk of mold growth on the inner surfaces of the attic. In all of the 224 simulated scenarios of the unvented attic, none indicated any risk of mold according to the MGI. Therefore, the risk of decay in the OSB sheathing is considered as the highest concern due to moisture safety, and not mold growth on surfaces within the attic space.

- RISK EVALUATION, OPTIONS AND RECOMMENDATIONS *CASE STUDY - 1*

The future hygrothermal performance of an unvented attic, hosting a HVAC system, has been investigated with a risk assessment. 224 different configurations with six varying parameters were simulated for an unvented attic and the adjacent roof construction. Three different performance indicators were investigated; the maximum MC of the OSB, Q_{HVAC} and the MGI of the wood-based materials inside the attic space. The development of MC in the OSB sheathing varies mostly due to whether the SPF is vapor closed or open. Having an open SPF is actually a risk in all the investigated U.S. climate zones, 1 to 7; however, the risk depends on the values of the other varying parameters as well. Naturally, the outdoor climate will influence the MC of the OSB but also the indoor moisture production rate has a significant impact.

A high air leakage rate from the air distribution duct system has a positive impact on the MC of the OSB sheathings due to the dehumidifying effect of the HVAC unit, though a negative influence in terms of Q_{HVAC}. On average, an increase in 5% to 14% in energy demand is predicted for the different climate zones, when comparing a 4% with 20% duct leakage rate. Further, the thermostat set-point temperatures have a large impact on the annual energy demand. Changing from 21.1/23.3°C to 20/25.6°C has the highest impact in hotter climates, but also colder climates have significant decrease in Q_{HVAC} if accepting a wider span of set-point temperatures.

The risk of developing mold on surfaces inside the attic space is negligible for all the simulated plausible cases of an unvented attic. However it is important to emphasize that the outer roof construction is assumed air tight in the simulation model and that any deviation from that assumption will affect the risk of mold inside the attic space. Finally, the presented risk assessment proves that a moisture safe unvented roof can be constructed for each U.S. climate zones. A sensitivity analysis shows which of the parameters that has the largest impact on the hygrothermal performance, as illustrated in Figure 16 to Figure 18, and which alternatives that exist to improve the performances, see Table 4. Generally, a closed SPF is a good decision in terms of the risk of moisture damages in the OSB.

It is important to point out the risk of enclosing an organic material, such as the OSB, between two rather vapor tight materials like the SPF and the roof covering. If water or vapor reaches the OSB sheathing, the drying potential is very low and the moisture becomes trapped. This possible event has not been investigated in this study; though, it should be considered as a potential risk which ought to be further studied. Minimizing the moisture generation from indoor moisture sources may also be an effective approach to increase the moisture safety of the OSB. In concerns of energy, a larger span of the set-point temperatures and reducing the air leakages from the ventilation duct system make a significant difference on the HVAC system energy demand.

5.2. Case Study 2 – External Wall Retrofit with Interior Additional Insulation

The following case study summarizes a hygrothermal risk assessment applied on a retrofitting measure for an external wall, as seen in Paper II.

The purpose of this case study is to make a risk assessment on a recommended external wall retrofitting measure in concerns of moisture safety. Due to preserving interests of the existing façade, the cladding must not be affected by the retrofitting measures; hence a retrofitting measure must be constructed on the inner side of the exterior wall.

- SCOPE ***CASE STUDY - 2***

System Formulation

Energy efficiency improvement for heating is planned for an existing exterior wall. No harm must be made on the façade hence any retrofitting measures must be constructed from the inside of the wall. No consideration is taken to adjacent parts of the building in the analysis, other than those building materials included in the structure of the wall.

The residential retrofitting measure will be analyzed in the climate of Gothenburg, Sweden and the retrofit is assumed to be constructed with satisfying workmanship.

Targets and Concerns

The intention of the retrofitting measure is to improve the thermal performance while maintaining a durable and moisture resistant wall assembly. It is of great concern to create a design which enables a satisfying interaction between the existing and supplementary building materials. Consequently, the major concerns of the retrofit are to both improve the energy demand of the wall and to obtain high moisture safety. A possible unwanted consequence of interest for the risk assessment is the risk of mold.

Existing Conditions

The thermal performance of the existing wall is not acceptable hence a retrofitting measure of the wall is needed to decrease the net energy demand during the heating season. The conditions and functions of the existing building materials are considered to be acceptable, or if damaged, replaced with the same or equivalent materials.

The existing wall is a timber framed exterior wall with intermediate glass wool insulation. A vapor retarder is located between the timber frame and the inner gypsum board.

Strategy Identification

A number of different solutions of the retrofit design of the existing wall are investigated, as seen in Paper II. The most appropriate design is identified, based on the above conditions and presented in Figure 19; a new timber-framed wall, directly constructed on the inner surface of the existing wall. The insulation material is non-rigid and mounted between the studs. An additional gypsum board is mounted on the inside of the new timber frame.

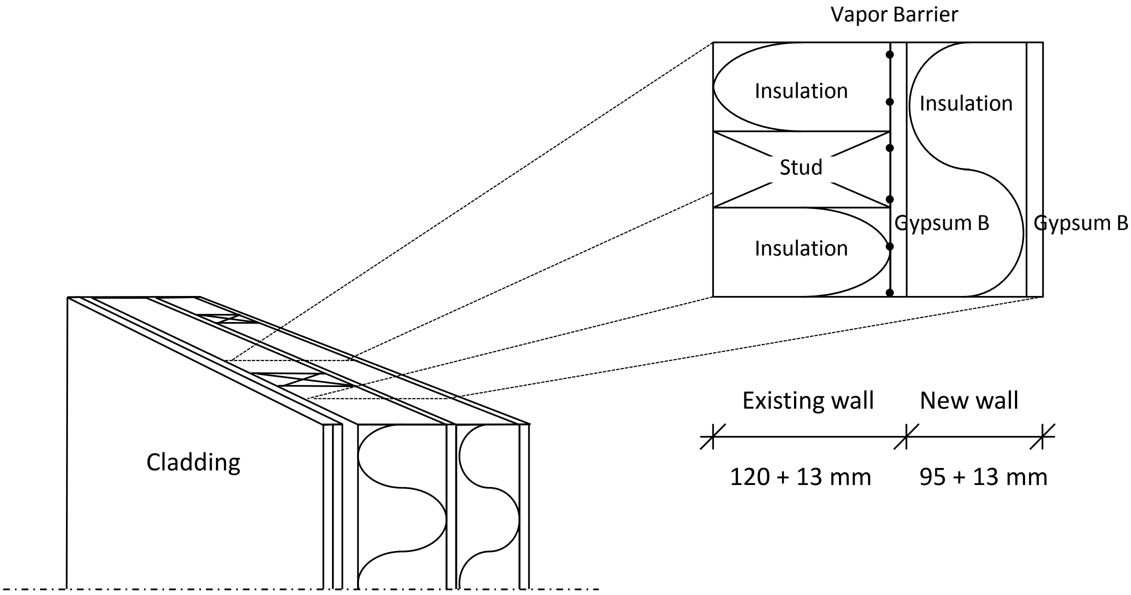


Figure 19 An exterior wall is retrofitted and consists of the following building materials prior to the retrofit; cladding, a timber frame with intermediate insulation (120 mm), a vapor retarder and a gypsum board. The supplement wall is constructed directly onto the gypsum board and consists of a timber frame with intermediate insulation (95 mm), a gypsum board and a wall paper.

In conclusion, the benefit of the studied retrofitting measures is the applicability on existing exterior walls with preserving interests of the façade. The retrofit design allows the existing wall to remain unharmed, thus including the thermal properties of the existing materials; which naturally will minimize the costs from additional building material and optimize the construction time.

Risks identification

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

Influential Parameters, Uncertainties and Correlations

A Fault Tree Analysis, FTA, is a suitable method to determine the influential parameters due to the risk of mold. The top event of the FTA is mold growth in the interior of the retrofitted wall and the following intermediate, conditioning and undeveloped events are coupled with AND and OR operators. Figure 20 illustrates a FTA of an arbitrary exterior wall in which the undeveloped events at the bottom can be seen as the moisture sources. The driving potentials for the mechanisms, leading to mold, is referred as conditioning event i.e. these are not the cause of the consequence but nonetheless necessary conditions or events.

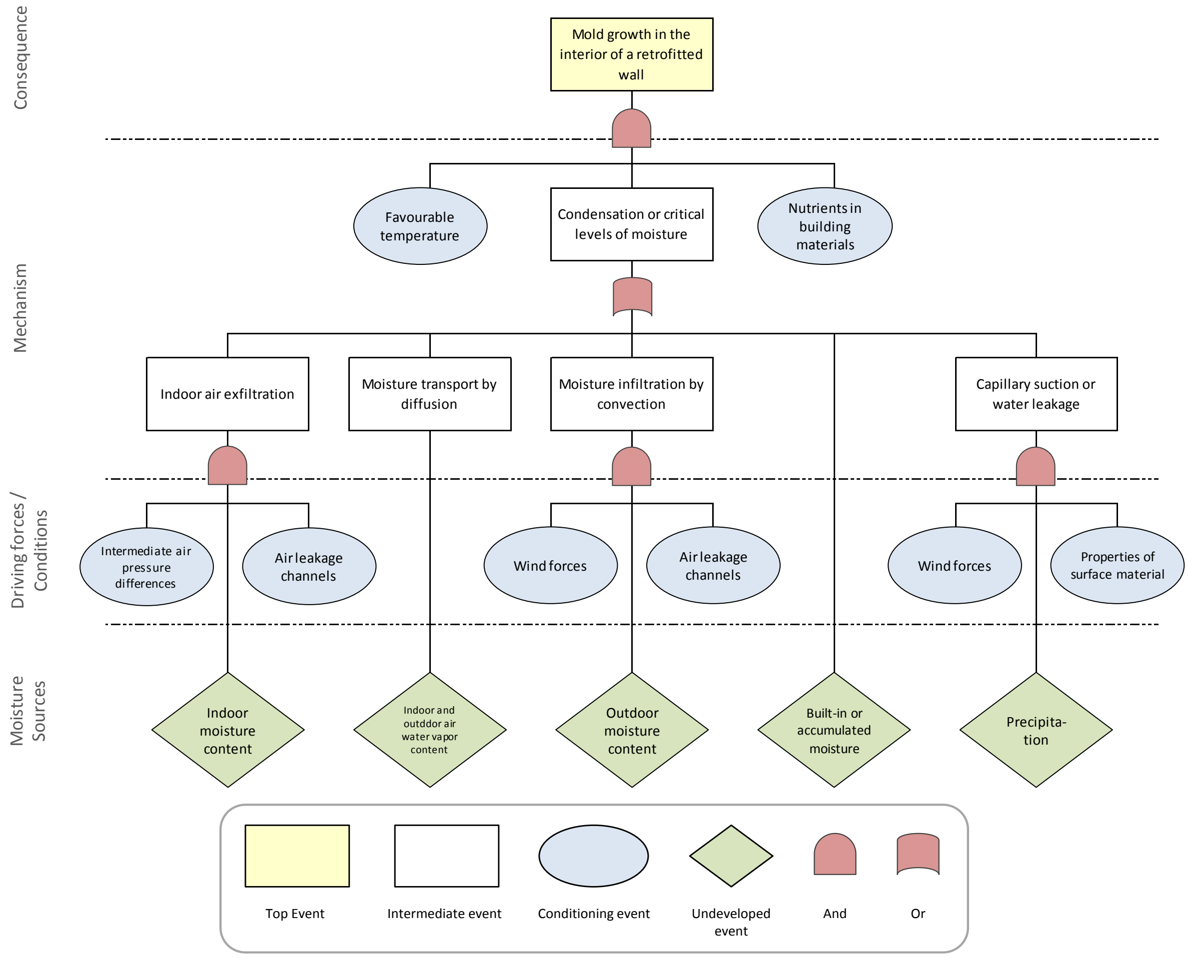


Figure 20 A Fault Tree Analysis (FTA), investigating the risk of mold growth when performing a retrofitting measure of an exterior wall. The undeveloped events of the FTA are the moisture sources, whereas the driving forces and the conditions required for an intermediate event are referred as conditioning events.

In the aspect of the investigated retrofit, some of the most crucial mechanisms can be found in a FTA, as seen in Figure 20. Capillary suction, water leakages and built-in moisture (moisture damp) are presumed checked upon due to inspections of the wall prior the retrofit. The moisture infiltration by convection is not considered as an important mechanism for the post-retrofit performance since, in this study, the conditions and functions of the building materials in the existing wall are considered to be acceptable. However, there are two mechanisms according to the FTA, which probably possess a higher impact on the moisture performance. These are the indoor air exfiltration and the moisture transport by diffusion.

The area of and around the existing studs, as seen in Figure 19, will have a decreased temperature during the heating season in comparison with prior to the retrofit. Therefore, the gypsum board close to the studs will have an increased risk of critical intermediate moisture levels, due to decreased temperatures and therefore moisture acceptance. This critical position will commonly exist in the retrofitted wall due to a shift in the placement of the existing and new studs, which is an approach to avoid thermal bridges.

A vapor retarder is located between the existing studs and the intermediate gypsum board. As a consequence, the indoor air humidity will mostly influence the materials on the inner side of the vapor retarder, including the intermediate gypsum board. Since the acceptance of moisture is lower in the critical position post-retrofit, the risk of mold in the wall is assumingly at the highest in this area. This assumption is also strengthened by the fact that the two most decisive mechanisms of mold growth, according to the FTA, both derive from the indoor air humidity.

An additional aspect that will affect the function and future performance of the retrofit is possible indoor air intrusion in the wall. Timber will shrink, bend and crack depending on moisture content, temperature, quality of the material and the applied load (Breyer et al., 1998). Upcoming and continues structural movements may force the wall and its component to change in dimension and position. A plausible scenario is that minor air gaps are created between the existing and new wall structure due to these structural movements. The size of the air gaps is likely to depend on the condition of the existing wall, the properties of the new building material and the workmanship of the new and existing wall assembly.

In conclusion, the studied retrofitting measure possesses a higher risk of mold growth on the wall in comparison with prior to the retrofit; though, the variability of the performance is difficult to estimate based on available information. In order to make decisions on future performances and costs, a QRA is recommended, including a sensitivity analysis to evaluate input parameters and possible actions of improvement.

- QUANTITATIVE RISK ANALYSIS *CASE STUDY - 2*

Method and Performance Indicators

A model of the illustrated retrofit in Figure 19 is created in HAM-tools, which is a tool developed in Simulink® and especially constructed to simulate heat and mass transport in building and building components in operating conditions (Sasic Kalagasidis, 2004). The simulation model is a one-dimensional model and designed to represent the path of heat and mass transport, crossing the assumed critical position of the retrofit, as seen in the left-hand illustration of Figure 21.

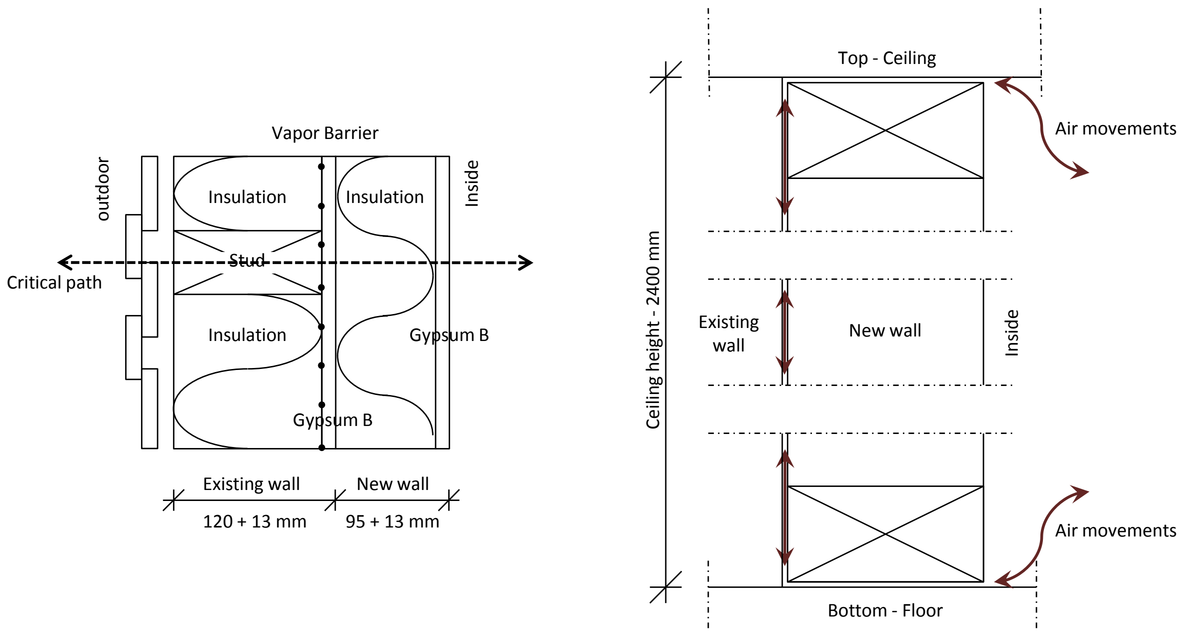


Figure 21 The left-hand plan drawing illustrates the assumed critical path of the retrofitted wall. During the heating season, the area of and around the existing studs, including the intermediate gypsum board, is likely to have a decreased temperature compared to prior retrofit. The right-hand picture illustrates a section drawing of the simulated wall. The two-headed arrows demonstrate possible positions and directions of air intrusion.

An additional simulation model was created to simulate the scenario of a 3 mm air gap between the new timber frame and the existing gypsum board, as seen in the right-hand illustration of Figure 21. The assumed width of the air gap is based on plausible deformations described in Paper II. The air movement inside the gap varies over time and is driven by air pressure differences due to the variations in temperature along the air gap and between the inner environment.

The Monte Carlo method is applied for the sampling of the varying input parameters in the simulation model. The variability of three input parameters are implemented; the outdoor climate, the indoor moisture production and the ventilation rate.

A potential P_{ind} is φ when analyzing the risk of mold growth in building materials and the critical relative humidity, φ_{crit}, defines favorable levels of growth, which is a function of the temperature (Hukka & Viitanen, 1999). Further, both the mold growth potential, m, and the mold growth index (MGI) are suitable P_{ind}s to evaluate the moisture safety; these indicators are briefly described in Section 4.1.

Input Values and Probability Distributions

Three different input parameters are implemented with a variability into the simulation model; the outdoor climate, the indoor moisture production and the ventilation rate.

The weather data consists of 44 simulated years of the climate in Gothenburg, Sweden between 1960-2004 (Nik, 2010). The data is presented as hourly variations of precipitation, solar radiation, wind velocity, temperature and relative humidity. The climate in Gothenburg is considered as an oceanic climate.

The applied ventilation rates are based on measurements made in 417 apartments in Sweden from 2008 to 2009 (Boverket, 2009b). The measurements were performed during two weeks in each apartment and the type of ventilation system varied from a natural ventilated to a mechanical exhaust and supply air handling system.

The variability of the indoor moisture production are based on simulations of 10 000 plausible scenarios of residential multi-family households. The production rate is presented as hourly variations and derives from the study presented in Section 3.2.1.

Design and Run Simulation Model

The simulation model is designed to stochastically choose a configuration of the previously presented input parameters (a scenario) for each run of a simulated year. Subsequently, the number of iterations in the simulation model is equivalent with the number of generated scenarios. In this study, 500 scenarios are generated, in which the values are chosen based on the variability of the input parameters. Hence 500 consecutive years of hourly varying climate data and indoor moisture production rates are produced and with an annually constant ventilation rate, varying only for each simulated scenario. The simulation run continues to until all 500 scenarios have been simulated and the results have been saved.

Result, Sensitivity and Uncertainty Analyses

The area of and around the existing studs is assumed to be the most critical position of the wall in concerns of the risk of mold. Therefore, the variation of the moisture content and temperature in the gypsum board is of interest. Figure 22 illustrates the simulated annual average of relative humidity, φ_{avg}, from the 500 simulated scenarios of the retrofitted wall assembly; both with and without an assumed air intrusion. According to the two probability distributions in Figure 22, an assumed air intrusion increases the value of φ_{avg}. Usually, 80% is assumed as a critical level of φ for wood-based materials at temperatures above 15°C (Hukka & Viitanen, 1999). The simulation results reveal that 32% of the simulated scenarios have a φ_{avg} above the considered critical level. In the case of an assumed air intrusion, the corresponding number of the simulated scenarios, exceeding the critical level, is 43%.

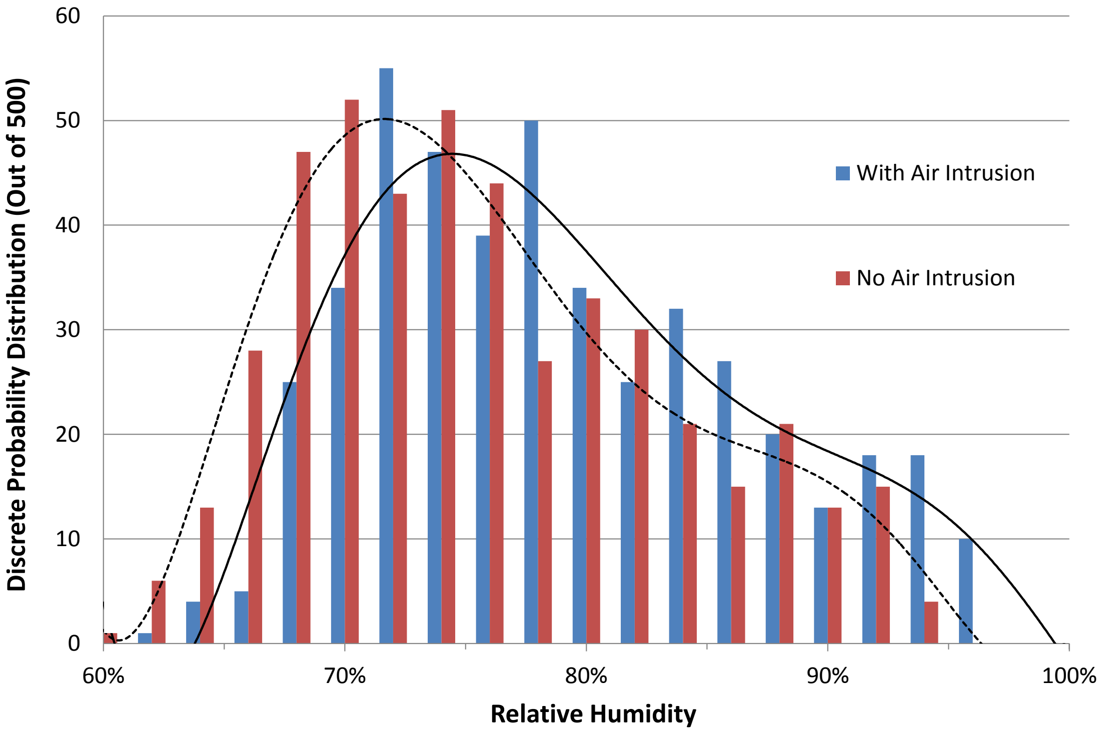


Figure 22 Two discrete probability distributions, representing the variability of the annual average of relative humidity in the intermediate gypsum board post-retrofit. The disparity between the plots is whether an air intrusion is simulated or not. Both plots represent the result of 500 simulated scenarios of the retrofit. In addition, trend lines are added for both plots, hence representing two pdfs.

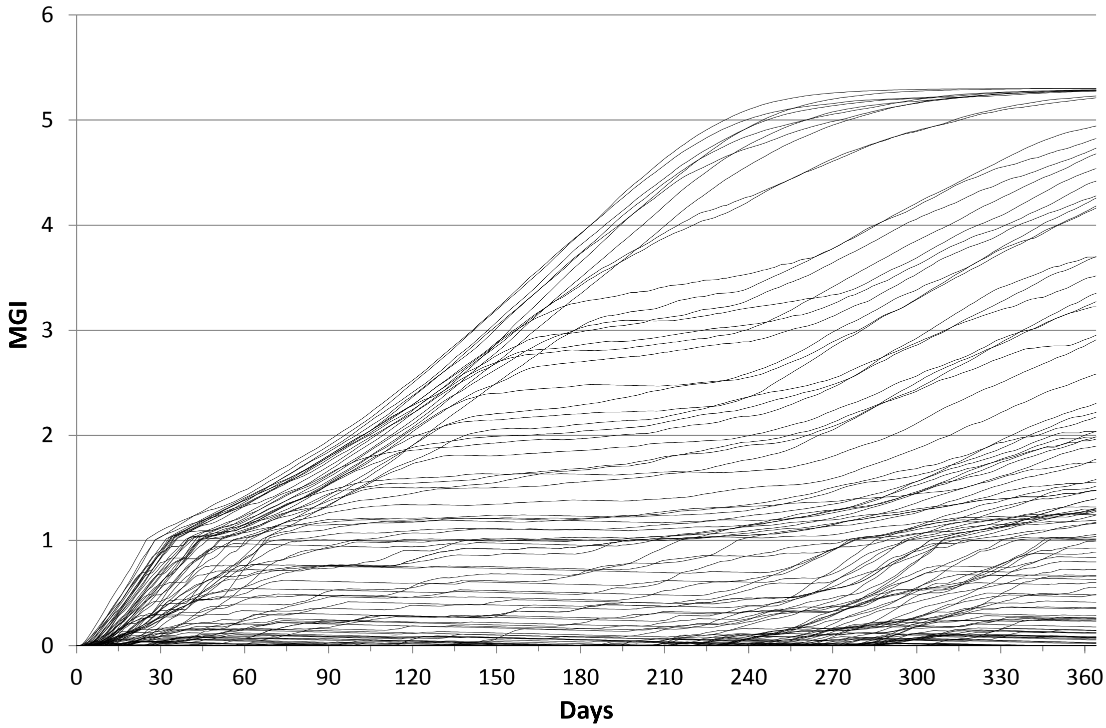


Figure 23 Annual variation of MGI for the simulated scenarios with an assumed air intrusion between the intermediate gypsum board and the new insulation material. Any value of the MGI above 1 indicates, at least, some microscopically or visually detectable mold.

The moisture performance is evaluated using the MGI. The value of the indicator ranges from 0 to 6 in which any value above 1 indicates microscopically or visually detectable mold (Hukka & Viitanen, 1999). Figure 23 illustrates the progression of MGI for the 500 simulated scenarios with an assumed air intrusion, at the inner surface of the intermediate gypsum board and at the considered most critical position for the risk of mold, as seen in Figure 21.

Three input parameters were implemented with variability; the outdoor climate, the indoor moisture production and the ventilation rate. The relative importance of these varying parameters is evaluated using a couple of methods for sensitivity analyses. Both φ and MGI are arbitrary P_{ind}s since both are highly correlated, as seen in Paper II. In this case study, φ serve as the P_{ind} for the sensitivity analyses. Comparisons are made for φ_{avg} and with three analysis methods, defined by O_{sens}, S_i and I_i, as presented in Section 0. The first analysis method, O_{sens}, is performed by repeatedly vary one out of three parameters, while holding the value of the other two fixed. The result of this *One-at-a-time sensitivity measure* is presented as a cdf in Figure 24. According to the three different distributions, one for each varying parameter, the outdoor climate has the lowest impact on the variability of φ_{avg}. However, both the indoor moisture production and the ventilation rate will highly influence the moisture content in the intermediate gypsum board.

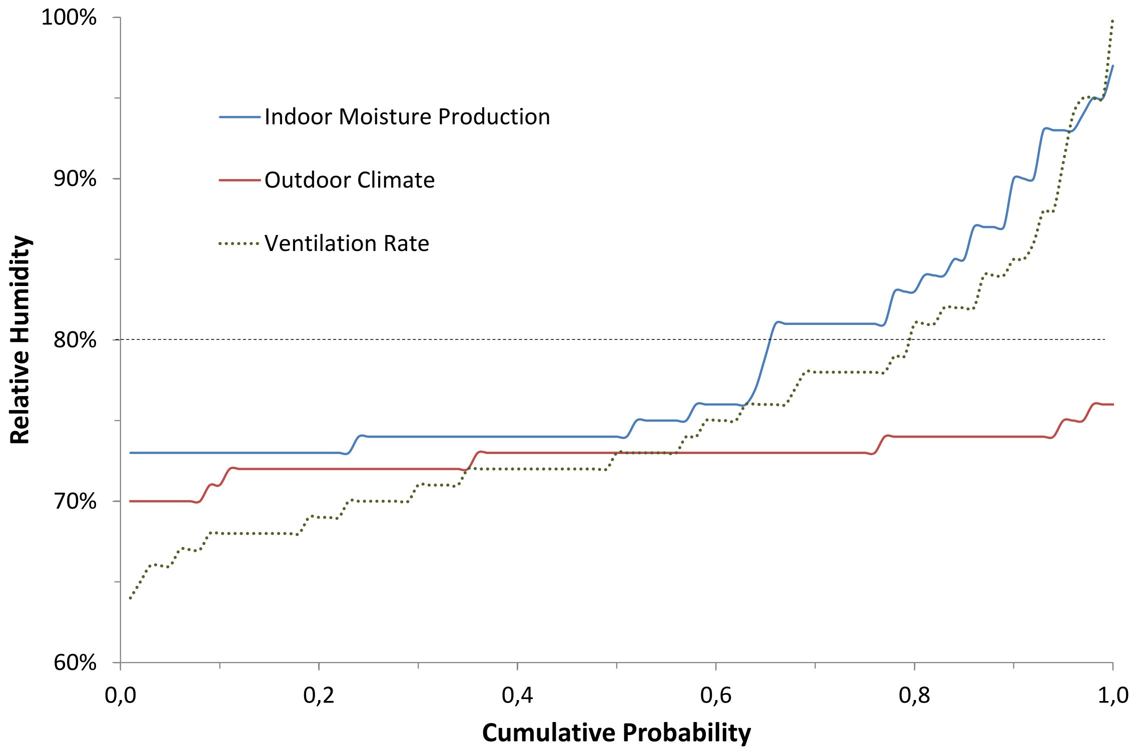
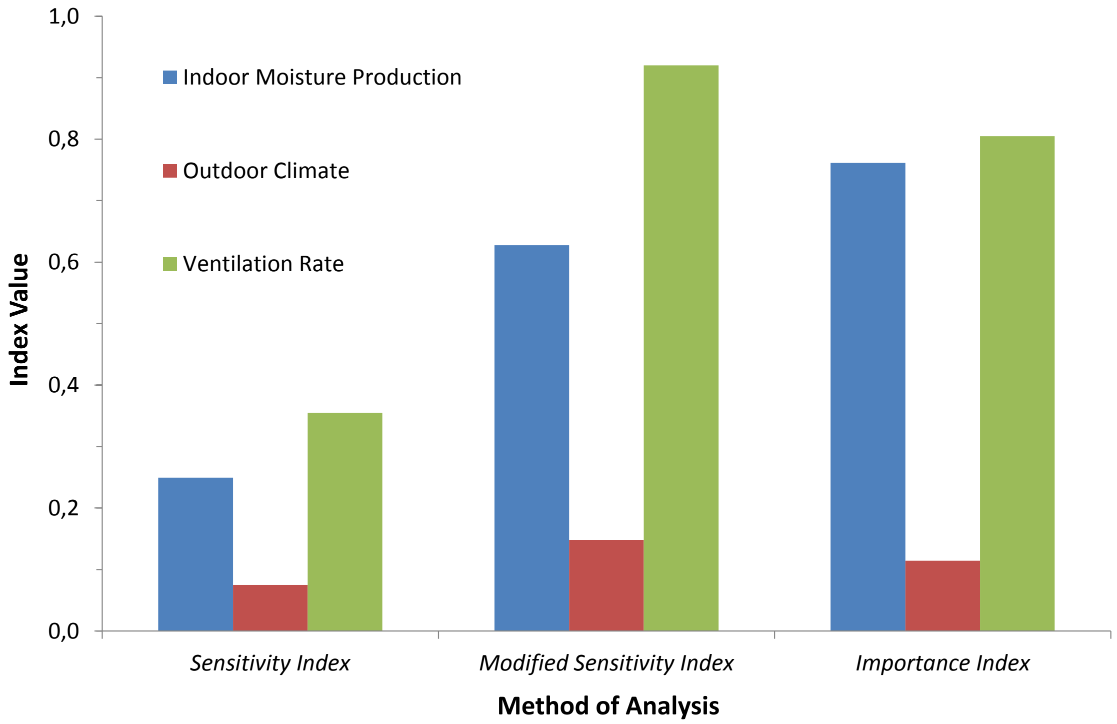


Figure 24 Three cumulative density functions, representing the result from the One-at-a-time sensitivity measure for the varying parameters. According to their distributions, the outdoor climate has the lowest influence on the variability of φ_{avg} at the assumed critical position of the intermediate gypsum board. The dashed horizontal line depicts the considered critical level for mold growth initiation.

In addition, the *Sensitivity index*, S_i, and the *Importance index*, I_i, have been applied to investigate the sensitivity of the input parameters. However, as seen in Equation [5], S_i only evaluates the variability of the studied parameter based on the maximum value of the performance indicator, $P_{ind,j}^{max}$, and not the variability caused by the complete stochastic variability, P_{ind}^{max}. Hence a modified S_i is defined, taking into account the complete variability of the studied performance indicator under the influence of each parameter, p;

$$S_{i,p}^{mod} = \frac{MAX(P_{ind,p}) - MIN(P_{ind,p})}{MAX(P_{ind,})}. \qquad [9]$$

The result of the sensitivity analyses of S_i, S_i^{mod} and I_i are presented in Figure 25 and the following table. The three analyses methods indicate that the ventilation rate has the highest influence on φ_{avg} in the intermediate gypsum board. Also the indoor moisture production proves to be influential, though slightly less.



All parameters fixed but	S_i	S_i^{mod}	I_i
Indoor Moisture Production	0,25	0,63	0,76
Outdoor Climate	0,08	0,15	0,11
Ventilation Rate	0,36	0,92	0,80

Figure 25 and Table 5 present the results from the sensitivity analyses by S_i, S_i^{mod} and I_i. According to all three analyses methods, the ventilation rate has the highest influence on the variability of the moisture content in the intermediate gypsum board close to the existing timber studs. The moisture production also has a high influence, though the outdoor climate has not.

Apparently, the outdoor climate has the lowest influence on the variability of φ_{avg}. According to the table presented above, S_i^{mod} is only 15% for the outdoor climate but the indicator reaches up to 63% and 92% relative influence for the indoor moisture production and the ventilation rate. Though slightly different values, the same order of influences are valid for all three methods.

- RISK EVALUATION,
OPTIONS AND RECOMMENDATIONS ***CASE STUDY - 2***

A recommended design for an external wall retrofit with interior additional insulation has been evaluated with a hygrothermal risk assessment. The most decisive parameters in concerns of the moisture performance was identified; the outdoor climate, the indoor moisture production and the ventilation rate. Further, a critical position was identified in the wall post-retrofit. According to a QlRA, the intermediate gypsum board becomes less warmer during the heating season; especially, in the area of the existing timber studs. Due to lower temperatures in this area post-retrofit and the presence of a vapor retarder on the inner surface of the existing timber frame, the water vapor capacity decreases, and as a consequence, the risk of mold increases.

A model of the retrofit design was developed in a hygrothermal calculation tool. Multiple iterations of simulations were completed with different plausible values of the varying input parameters. An additional aspect was included in the QRA; an assumed air intrusion between the existing and new wall construction, resulting in an air pressure induced indoor air exchange. Both cases were simulated with 500 iterations. The result was presented due to the predefined performance indicators; the relative humidity, φ, and the mold growth index, MGI. The moisture performance was evaluated in the assumed critical position of the intermediate gypsum board. According to the results, 32% of the simulated parameter configurations obtained an annual average of φ larger than the critical value for mold growth. The corresponding ratio was 43% in the wall assembly with an assumed air intrusion. This proves that the indoor climate has a high influence on the moisture performance of the studied area, which was also verified with sensitivity analyses. Four different methods of sensitivity analysis were applied; three existing and one developed. All four methods indicated that the air flow rate of the ventilation system has the highest influence on the moisture content in the intermediate gypsum board. The indoor moisture production is also influential, though the impact from the outdoor climate is low.

In conclusion, the future performance in terms of moisture safety for the studied 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 or increase the ventilation rate.
- Assemble a new vapor retarder behind the new gypsum board.
- Decrease the thickness of the additional insulation.

5.3. Case Study 3 – Mechanically Attached Roof Systems

The following case study summarizes a hygrothermal risk assessment of a cool roof retrofit, as seen in the appended Paper V.

A white roof, or cool roof, is constructed to decrease the thermal load from solar radiation, therefore saving energy by decreasing the cooling demand. Cool roofs are common in the U.S. since cooling is usually an including feature of the ventilation system. Converting existing roofs with traditional covering to a cool roof has a high potential of cooling energy savings (Levinson & Akbari, 2010), both in commercial and residential buildings. This case study aims to investigate the potential moisture related risks from converting a mechanically attached roof systems, with a flexible membrane and in northern U.S. climate zones, into a cool roof assembly.

- SCOPE ***CASE STUDY - 3***

System Formulation

Energy savings are planned for a mechanically attached roof systems with a flexible surface membrane. A risk assessment will, in both a qualitative and quantitative manner, investigate the future hygrothermal performance of a cool roof retrofit. Building components, other than those materials included in the structure of the roof, will not be included in the risk assessment.

The retrofitting measure will be analyzed in northern U.S. climate zones.

Targets and Concerns

Unfortunately, cool roofs with a mechanically attached membrane have shown a higher risk of intermediate condensation in the materials below the membrane in certain climates (Ennis & Kehrer, 2011) and also in comparison with similar constructions with a darker exterior surface (Bludau et al., 2009). As a consequence, questions have been raised regarding the sustainability and reliability of using cool roof membranes in northern U.S. climate zones.

In addition, a brief analysis of the energy saving potential is of interest.

Existing Conditions

An existing roof consists of a steel deck, which supports the above mounted insulation boards. The roof covering, prior to the retrofit, could be of any variety for this investigation, though the surface color is considered dark, in a solar reflective matter. The conditions and functions of the existing building materials are considered to be acceptable and the intended cool roof retrofit is assumed to be constructed with satisfying workmanship.

Strategy Identification

First, the existing roof covering is removed, including the insulation material, if damaged or not fulfilling the intended energy efficiency requirement. Polyisocyanurate insulation boards are mounted on top of the steel deck. Subsequently, a flexible thermoplastic membrane, with a cool surface color, is rolled out over the boards and fastened and glued along the seams of the membrane. The design of the cool roof retrofit is presented in Figure 26 and illustrates the roof assembly, consisting of a traditional metal deck; 0,076 m (3-inch) polyisocyanurate insulation boards; and a thermoplastic membrane (representing a flexible single ply membrane). As an alternative, an existing roof assembly, with a flexible membrane, can be applied with a cool color by painting the roof surface.

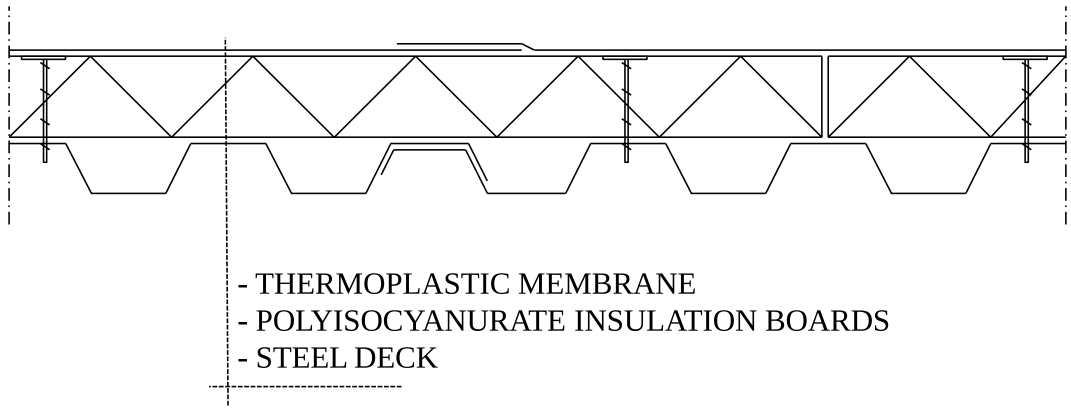


Figure 26 The design of the cool roof retrofit. The thermoplastic membrane is flexible and the surface color is light, in order to effectively reflect the incident solar radiation.

- QUALITATIVE RISK ANALYSIS ***CASE STUDY - 3***

Risks identification

The major risks involved in the analysis of the retrofitting measures derive from a decrease in heat load at the roof surface, post-retrofit. A highly reflective surface color reflects most of the incident solar radiation and therefore minimizes the resulting heat load from the sun. The lower temperatures at the surface also affect the temperature distribution below the surface, which usually will have a positive effect on the cooling demand. However, the maximum air humidity by volume at saturation decreases with decreasing temperature; hence the risk of condensation increases. Depending on the air permeability of the material underneath the membrane, wind forces increase the risk of fluttering (also referred to as billowing) of a flexible single ply thermoplastic membrane (Molleti et al., 2011). Expectably, the wind-induced pressure differences create a convective air flow into the construction (i.e., air intrusion). If the conditions are right, moisture from the exchanging air may condensate on surfaces with a temperature below the dew-point.

Influential Parameters, Uncertainties and Correlations

The directions of the convective air flows through a building envelope is usually very difficult to determine (Künzel et al., 2011). Air movements through the steel deck may exist at perforations, penetrations or between the overlaps of the steel sheets. These leakage channels will, together with the air permeability of the overlaying insulation boards and thermoplastic membrane, define the airtightness of the roof. If the surface membrane is correctly applied and sealed with satisfactory workmanship, the membrane will have high airtightness and therefore prevent air from moving between the inner and outer surfaces of the roof. Instead, the exchange of air may exist underneath the roof membrane, as a consequence of indoor air intrusion (i.e., an exchange of indoor air in the intermediate materials of the building envelope). The air pressure difference is a potential for the air intrusion rate, which is usually thermally driven (stack effect), created by the ventilation system or driven by wind loads acting on the building envelope (C-E. Hagentoft, 2001). Typically, the wind creates an uplifting force on the thermoplastic membrane. Due to the flexibility and elasticity of the surface membrane, it may easily deform in favor of pressure differences, causing the membrane to flutter and balloon (Baskaran & Molleti, 2010). This unintended air intrusion and causes are illustrated in Figure 27.

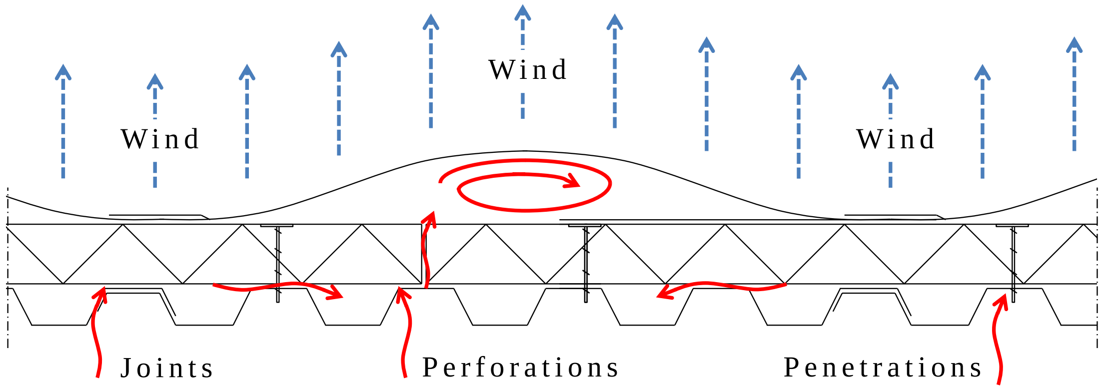


Figure 27 Wind forces, inducing pressure differences on the outer and inner membrane surfaces, cause the membrane to flutter and balloon. Depending on the condition and workmanship of the construction, air intrusion may arise through overlapping joints of the steel deck, penetrations, or perforations. Plausible locations of air intrusions are indicated with solid arrows. The uplifting forces, due to the wind, are indicated with dashed arrows.

The risk of condensation in the investigated roof system, as seen in Figure 26, depends on several parameters. According to previous discussions, the most essential parameters when considering the risk of intermediate condensation is likely the following:

- The outdoor climate, thus wind speed and incident solar and night-sky radiation
- The indoor air humidity, mainly affected by the indoor moisture supply.
- The air permeability of the of the roof construction underneath the surface membrane.

Apparently, a flexible outer membrane may cause air intrusion of indoor air underneath the membrane, if sufficient uplifting wind forces are present. Subsequently, moisture from the exchanging air may condensate on surfaces with a temperature below the dew-point. Unfortunately, the effect of fluctuating wind forces is difficult to estimate as this is a highly dynamic phenomenon and existing standards (ASTM D7586/D7586M-11, 2011) take into account only a steady-state approach (i.e., there are no guidelines or regulations on how to estimate the air intrusion rate). Obviously, more detailed knowledge on the hygrothermal performance of mechanically attached cool roof systems is needed with regard to surface colors, roof airtightness, climate zones, and indoor moisture supply.

In conclusion, a QlRA indicate possible risks and causes of risks in the studied cool roof retrofit. The expected performance of the cool roof mainly depends on the outdoor climate, the indoor air humidity and the air permeability of the roof underneath the flexible surface membrane. In order to investigate these parameters more thoroughly, and their expected influence on the hygrothermal performance, a QRA is highly recommended. Further, a QRA will quantify the risks of condensation and the potential energy savings of the cool roof retrofit.

- QUANTITATIVE RISK ANALYSIS *CASE STUDY - 3*

Method and Performance Indicators

The hygrothermal performance of the mechanically attached roof system will be investigated with numerical simulations. However, due to the lack of knowledge, measurements of the airtightness of the roof construction are necessary to provide reliable input data for simulations. The results from these measurements are presented in the next section of this case study.

In order to perform a QRA on the cool roof retrofit, a tool is required which is capable of modeling heat and moisture transport with transient simulations and with realistic boundary conditions. Long-wave (infrared) radiation must be considered at the exterior surface, otherwise nightly cooling from night sky radiation cannot be taken into account in the simulations of the cool roof. On account of the prerequisites, the hygrothermal software WUFI-1D is used for computations of coupled heat and moisture transport (Künzel, 1995), which has been validated repeatedly (Kehrer & Schmidt, 2008). Further, the air exchange model of WUFI-1D is applied to simulate the exchange of indoor air due to air intrusion underneath the thermoplastic roof membrane. However, first the uplifting wind forces, which is the potential of the air exchange, needs to be determined; hence a relation between the hourly wind speed and the expected wind gusts is established and will be presented in the following section.

In order to evaluate the risks of condensation and accumulation of moisture in the air layer between the thermoplastic membrane and the insulation board, a P_{ind} is defined. The moisture content of the air layer is converted into a condensate layer thickness, d_l, in which the moisture content is assumed to be distributed over the complete surface area. Thus, the accumulation of moisture in the air layer can be evaluated and comparisons between the different simulated scenarios can be established.

In addition, the heat flux through the insulation boards is studied to investigate the energy saving potential of the retrofit. Obviously, a cool roof has a positive effect on the cooling demand but will most likely have a negative effect on the heating demand; since the relation between cooling and heating demands in the cool roof retrofit are evaluated for different U.S. climate zones.

Input Values and Probability Distributions

Two essential parameters must be specified to estimate the air intrusion rate in a roof assembly; the wind speed fluctuation, which causes a fluctuating pressure difference between the outdoor and indoor membrane surfaces, and the air permeability of the roof construction underneath the surface membrane. However, in order to estimate the air intrusion, further investigations of the wind load and roof permeability must be established. This section briefly presents the results from the studying of these influencing parameters, as seen in Paper V.

The wind speed is typically presented as an average speed for a defined period of time (e.g., 1 hour). Wind speeds that are based on measured averages at shorter time intervals, referred to as gusts (Harper et al., 2010), are essential to estimate the fluctuation of the wind speed which is the potential of varying uplifting forces; subsequently, the continuous air exchange underneath the surface membrane.

Since climate files usually consist of hourly averages of wind speed, an approach to convert the average wind speed into an expected deviation in wind gusts is established. In this study, minute-based measurements of wind speed in Holzkirchen, Germany, are applied to determine the correlation between hourly average wind speed and wind gusts. Typically embedded wind gusts in an average wind speed are presented in Figure 28. Further, the hourly averages of wind speed, given from the four U.S. climate zones, are adjusted to instead represent a plausible deviation of wind gusts at each given hour, thus a potential for air intrusion.

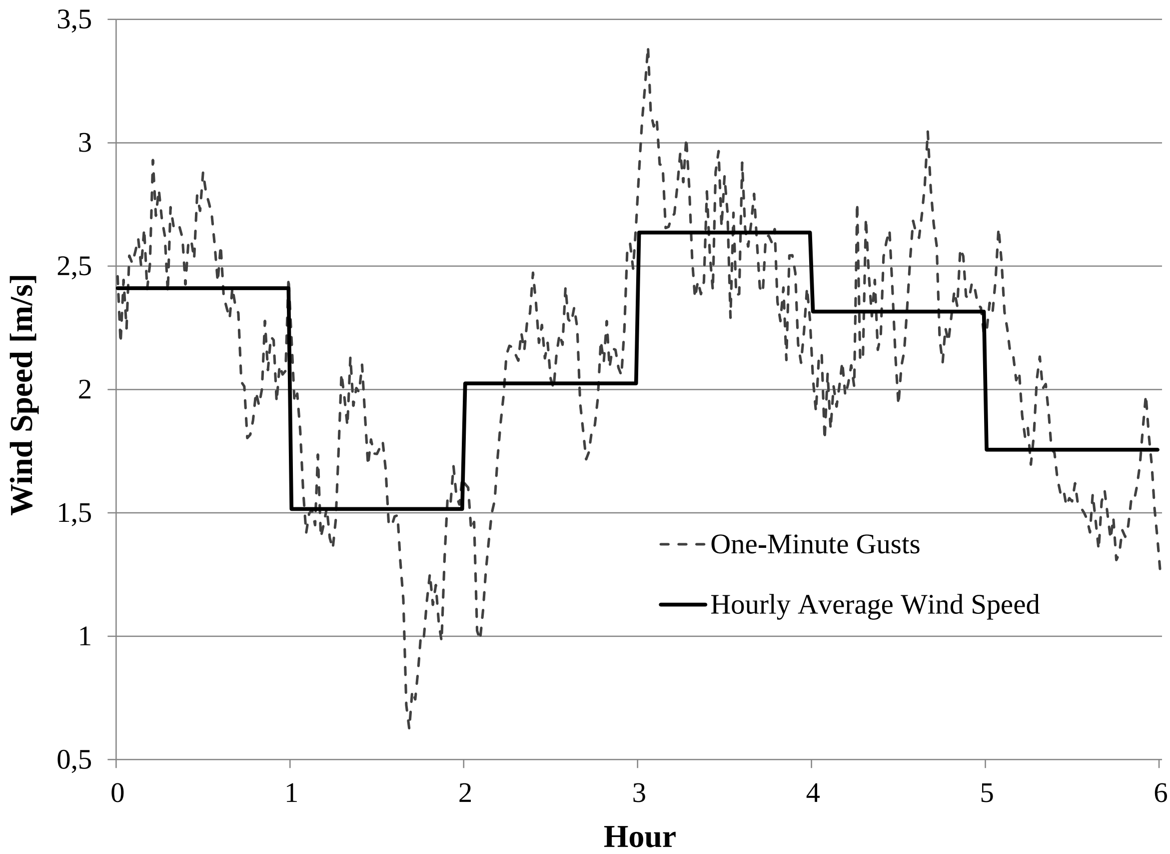


Figure 28 Six hours of extracted hourly averages and one-minute wind gusts measurements in Holzkirchen, Germany (Unpublished).

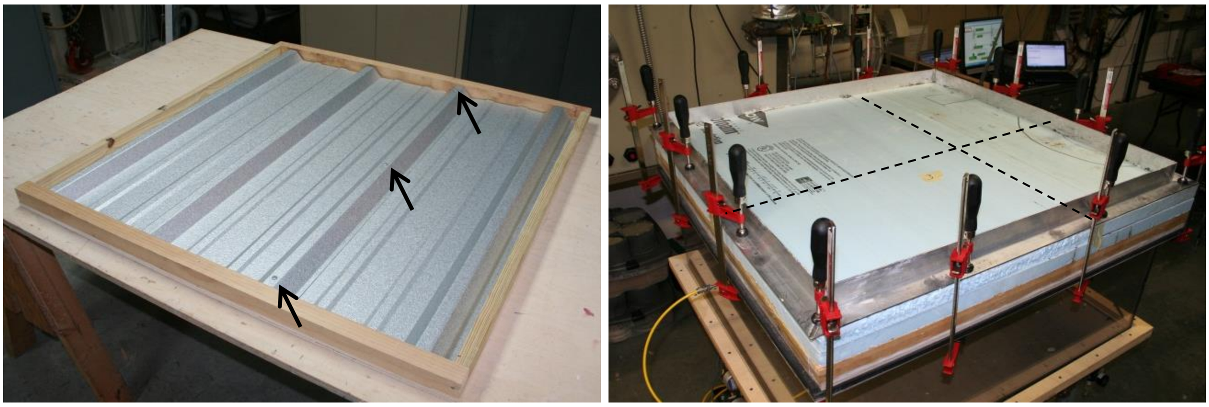


Figure 29 A specimen of the roof assembly underneath the thermoplastic membrane was constructed, in which the airtightness was tested in accordance with standard (ASTM E2178-11, 2011). The specimen was constructed with a steel deck (including a joint) and two overlapping 0,038 m (1,5-inch) insulation boards. The screws, ensuring a tight overlap, are indicated with arrows, and the joints between the overlapping insulation boards are indicated with dashed lines in the right-hand picture.

The air permeability of the studied cool roof assembly underneath the flexible membrane is tested in accordance with the ASTM E2178-11; a standard for testing the air leakage rate (ASTM E2178-11, 2011). Consequently, the specimen represents the roof construction, as defined in Figure 26, except for the outer thermoplastic membrane. The reason behind the exclusion of the membrane in the construction of the specimen is that only the air permeability between the indoor environment and underneath the membrane is requested.

Figure 29 displays the constructed roof specimen. The steel deck includes one overlapping joint and has been screwed tight at three positions along the overlapping ridge, as indicated with solid arrows in the left-hand picture. Further, two layers of overlapping 0,038 m (1,5-inch) insulation boards are mounted on top of the wood-framed steel deck. The roof specimen was tested in five different assemblies; sealed joints and sealed screw penetrations; steel deck only; full assembly; full assembly with two 0,005 m (3/16-inch) steel deck perforations and finally, the full assembly with eight 0,005 m (3/16-inch) steel deck perforations. The results of the measurements are presented in Table 6.

Table 6 The results from measuring the air leakage coefficient, C, and the pressure exponent, n. In total, five different assemblies were measured, with various repetitions in which the results are presented as average values of the measurements.

Results From Airtightness Tests	C [m^3/s,Pa]	n [-]	Q_{50} [m^3/s]	Q_{50} [l/s]
1. Sealed joints and sealed screw penetrations	$3,3 \cdot 10^{-07}$	0,99	$1,7 \cdot 10^{-05}$	0,02
2. Steel deck only	$6,5 \cdot 10^{-06}$	0,95	$2,6 \cdot 10^{-04}$	0,26
3. Full assembly	$6,2 \cdot 10^{-06}$	0,96	$2,7 \cdot 10^{-04}$	0,27
4. Full assembly, 2 perforations	$6,9 \cdot 10^{-05}$	0,54	$5,6 \cdot 10^{-04}$	0,56
5. Full assembly, 8 perforations	$1,3 \cdot 10^{-04}$	0,72	$2,1 \cdot 10^{-03}$	2,09

There are some important conclusions to make out of the results presented in Table 6. First and most naturally, the roof assembly with steel deck only and with sealed joints and penetrations, is a very air tight construction. Secondly, the air permeability of the overlapping insulation boards is apparently insignificant hence the permeability of the steel deck is decisive. This is confirmed by the comparison between roof assembly 2 and 3. Finally, even small perforations, such as 0,005 m (3/16-inch) drilled holes, influences greatly the airtightness of the roof assembly, as seen in the airtightness tests of roof assembly 4 and 5. Noteworthy is that the tested assemblies do not include any installation or structural penetrations that need to be sealed and would naturally exist in situ. In fact, steel decks have been proven leaky, so sealing the joints of the steel sheets and ensuring a non-perforated steel deck is important for the overall airtightness (Walsh, 2007). A literature study prepared for the California Energy Commission in 2006 presented an average Q_{50}-value of 4,0 (l/s,m^2) based on air leakage tests in 267 commercial buildings (Gadgil et al., 2006). Further, field measurements of roof assemblies, similar to the investigated construction of this study, resulted in air leakage rates between 2 to 6 (l/s,m^2)(Hens et al., 2003).

The QRA of this study will be based on simulations with importance sampling (Vose, 2008) of the four input parameters, which have been determined as decisive on the hygrothermal performance of the studied cool roof retrofit. A brief explanation of the varying parameters will follow.

Four different U.S. climates are used, representing climate zones 4 to 7. The chosen cities are; Baltimore, Maryland; Chicago, Illinois; Minneapolis, Minnesota and Fargo, North Dakota. The chosen climate for each city represents the 10th percentile coldest climate and is presented with hourly values of temperature, relative humidity, wind speed, solar intensity, etc. These classified climates are applied to serve as design reference years for the estimation of the hygrothermal performance in buildings (Sanders, 1996).

The solar absorptivity used in the simulations of this study is set to either 0,3 or 0,85; which is representative of a light or a dark surface respectively. Apparently, these values assume that a cool roof reflects 70% of the sunlight and a dark surface reflects only 15%. The variation in solar absorptivity allows the hygrothermal performance of a cool roof color to be compared to that of a traditional darker roof color.

Four different variations of indoor air humidity are used in the simulations, in accordance with different standards (ASHRAE 160-2009, 2011; Standardization, 2007). The four different variations are chosen to represent the range of both low and high indoor moisture supply.

The final varying input parameter is the air permeability of the roof assembly underneath the surface membrane. Four different values of airtightness are applied and mainly chosen due to the results presented in Table 6. The Q_{50}-values used in the simulations of the roof are as follows;

- 0,27 (l/s,m^2), representing a perfectly assembled roof construction with regard to both material properties and workmanship.
- 0,56 (l/s,m^2), an assumed satisfactory roof assembly though with minor perforations in the steel deck.
- 1,0 (l/s,m^2), a semi-leaky roof construction, arbitrarily chosen.
- 2,0 (l/s,m^2), representing a leaky roof construction, based on both measurements of this study and previous air leakage tests (Hens et al., 2003)

The values of the air leakage coefficient, C, and pressure exponent, n, are provided from either Table 6, or C is calculated by assuming n=0,65, which in lieu of provided values, usually is a good assumption (Gadgil et al., 2006).

Further material properties are presented in Paper V.

Design and Run Simulation Model

An air layer is created in the simulation model of the cool roof retrofit, in order to simulate the air intrusion underneath the surface membrane. In this case study, the air layer is assumed to have an average thickness of 3 cm, therefore representing the fluttering-induced air cavity. The mechanical resistance of the membrane is neglected; therefore, any applied pressure on top of the membrane is immediately, and without resistance, equalized underneath the membrane.

In total, 128 (4x2x2x2) combinations of the varying input parameters are simulated, representing all possible scenarios. Each scenario is numerically simulated in WUFI-1D.

Result, Sensitivity and Uncertainty Analyses

The accumulation of moisture in the air layer between the thermoplastic membrane and the insulation board is evaluated with a condensate layer thickness, d_l. The variations of d_l for each simulation are presented in Figure 30. Typically, d_l increases during the heating season, when the difference between the indoor and outdoor moisture content is the greatest.

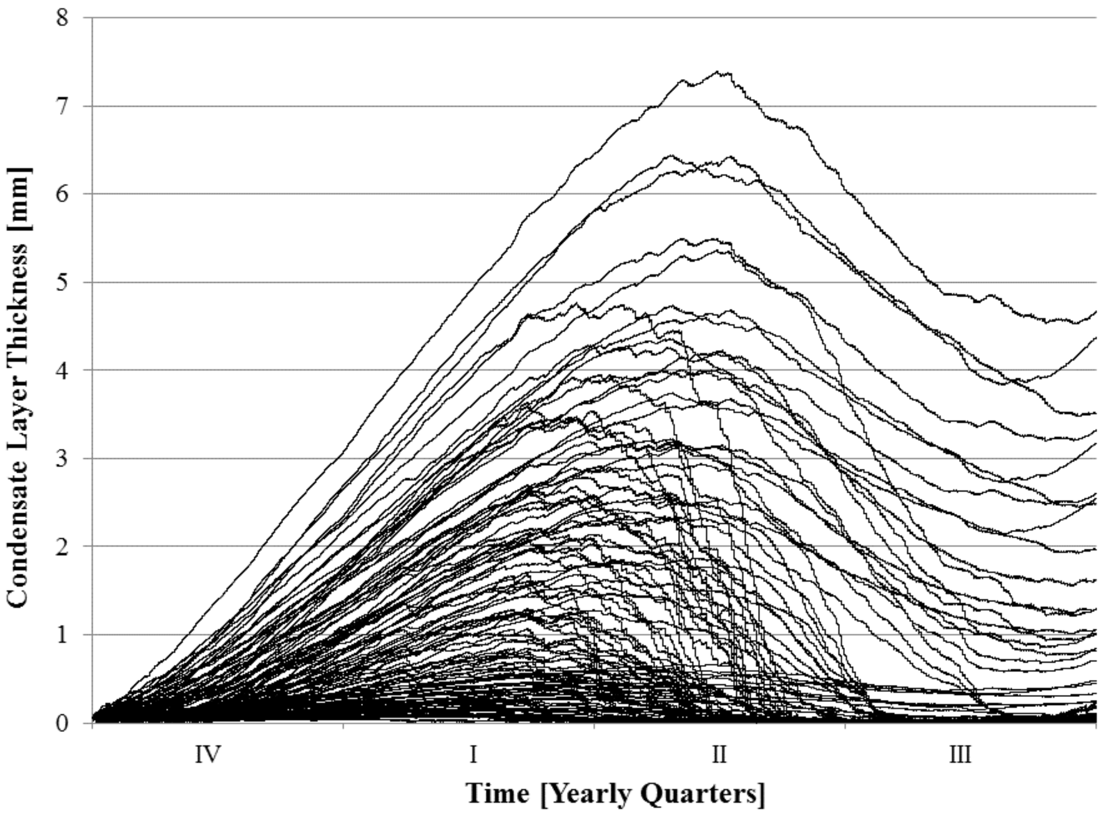


Figure 30 The condensate layer thickness, d_l, for the 128 simulated roofs with a mechanically attached outer membrane and in four different U.S. climate zones. Typically, the thickness increases during the heating season.

The importance of the solar surface reflectance can be evaluated by comparing the maximum values of d_l in Figure 31 and Figure 32. Four different curves are presented in the figures and divided into four segments, representing different air permeability of the roof assembly underneath the surface membrane. The slope of the curves indicates the influence of the simulated climate. In conclusion, the only difference between the presented results in Figure 31 and Figure 32 is the solar reflectance, and apparently, there are great disparities in d_l between the curves.

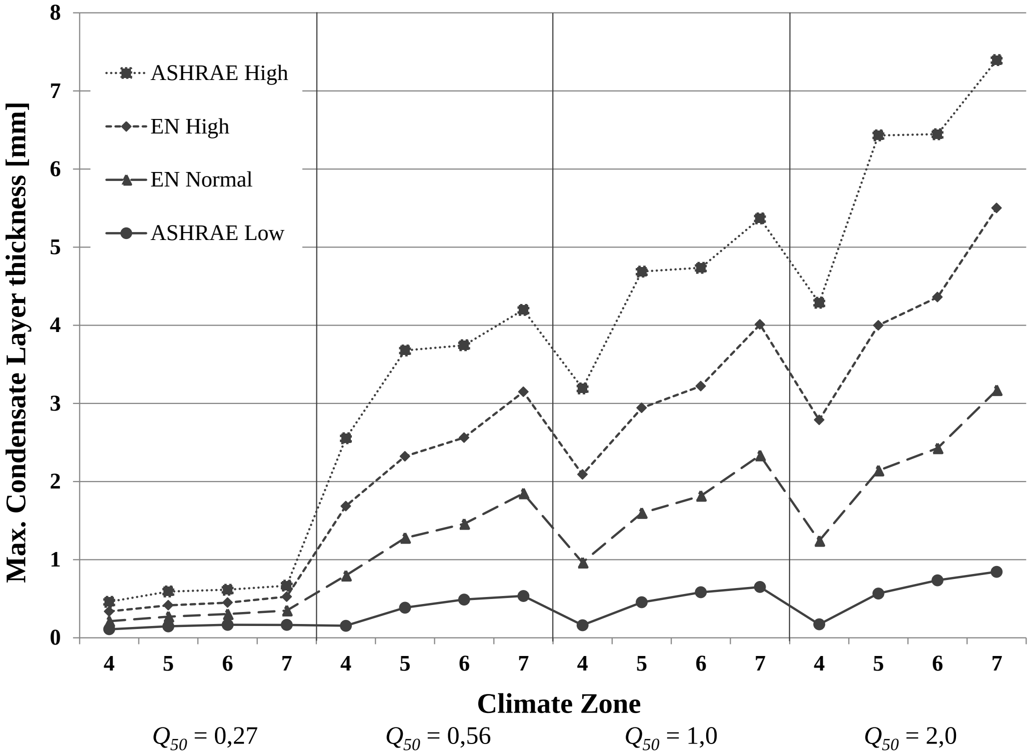


Figure 31 The maximum value of d_l for the simulated roof assemblies with a light membrane surface. One curve is presented for each level of indoor moisture supply. Four segments separate the simulated airtightness, which subsequently are compared for U.S climate zone 4 to 7.

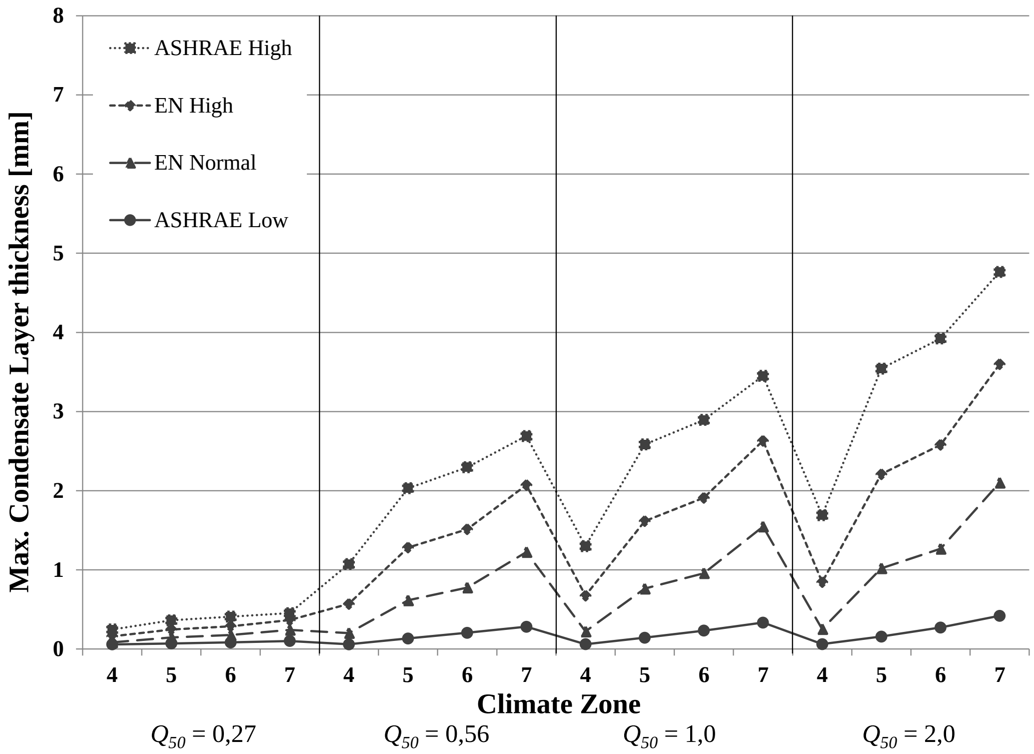


Figure 32 The maximum value of d_l for the simulated roof assemblies with a dark membrane surface. One curve is presented for each level of indoor moisture supply. Four segments separate the simulated airtightness, which subsequently are compared for U.S climate zone 4 to 7.

A critical d_l is commonly taken as 0,5 mm to avoid dripping (DIN 4108-3, 2001; Hens et al., 2003), hence this value is considered a maximum for a safe and reliable roof construction. Additionally, a d_l between 0,5 and 1,0 is considered risky, and values beyond, are rated as failures in terms of the risk for condensation. The results of the risk evaluation for the 128 simulations are presented in Table 7.

Table 7 Results from the 128 simulated scenarios, indicating the reliability of the roof construction in concerns of the risk of intermediate condensation. Table cells with no background color indicate a safe roof construction, gray cells indicate a risky construction, and black cells indicate an expected failure with respect to condensation. D stands for a dark roof surface, and L stands for light.

Climate Zone 4								
Indoor Moisture Supply	Q_{50} = 0,27		Q_{50} = 0,56		Q_{50} = 1,0		Q_{50} = 2,0	
ASHRAE – Low	D	L	D	L	D	L	D	L
EN – Normal	D	L	D	L	D	L	D	L
EN – High	D	L	D	L	D	L	D	L
ASHRAE – High	D	L	D	L	D	L	D	L
Climate Zone 5								
Indoor Moisture Supply	Q_{50} = 0,27		Q_{50} = 0,56		Q_{50} = 1,0		Q_{50} = 2,0	
ASHRAE – Low	D	L	D	L	D	L	D	L
EN – Normal	D	L	D	L	D	L	D	L
EN – High	D	L	D	L	D	L	D	L
ASHRAE – High	D	L	D	L	D	L	D	L
Climate Zone 6								
Indoor Moisture Supply	Q_{50} = 0,27		Q_{50} = 0,56		Q_{50} = 1,0		Q_{50} = 2,0	
ASHRAE - Low	D	L	D	L	D	L	D	L
EN - Normal	D	L	D	L	D	L	D	L
EN - High	D	L	D	L	D	L	D	L
ASHRAE - High	D	L	D	L	D	L	D	L
Climate Zone 7								
Indoor Moisture Supply	Q_{50} = 0,27		Q_{50} = 0,56		Q_{50} = 1,0		Q_{50} = 2,0	
ASHRAE - Low	D	L	D	L	D	L	D	L
EN - Normal	D	L	D	L	D	L	D	L
EN - High	D	L	D	L	D	L	D	L
ASHRAE - High	D	L	D	L	D	L	D	L

The main reason behind a cool roof retrofit is to decrease the cooling energy demand. However, as a result of the retrofit, the heating demand can increase, since both aspects should be considered in an energy efficiency analysis. In addition, the generation of indoor heat and the thermostat set-point temperatures play significant roles in an analysis of potential energy savings. Figure 33 presents the relative energy savings if changing the solar absorptivity of the studied roof construction from 0,85 to 0,30 i.e. from a dark to a light surface color. The potential energy savings are presented as an annual average value and are separated into heating, cooling or the combined heating and cooling energy demand for the U.S. climate zones 4 to 7. Further, the impact due to the ranges of thermostat temperatures is evaluated, in which two different ranges of are studied; a small span of 21,1/23,3°C (70/74°F) and a wider span of 20/25,6°C (68/78°F). According to Figure 33, the impact of the thermostat temperatures is most significant on the energy cooling demand, though proven rather insignificant in heating or when considering both heating and cooling. The most important conclusion of the results in Figure 33 is that the energy saving potential is negative for the U.S. climate zones 6 and 7; however, under conditions with no assumed indoor heat supply.

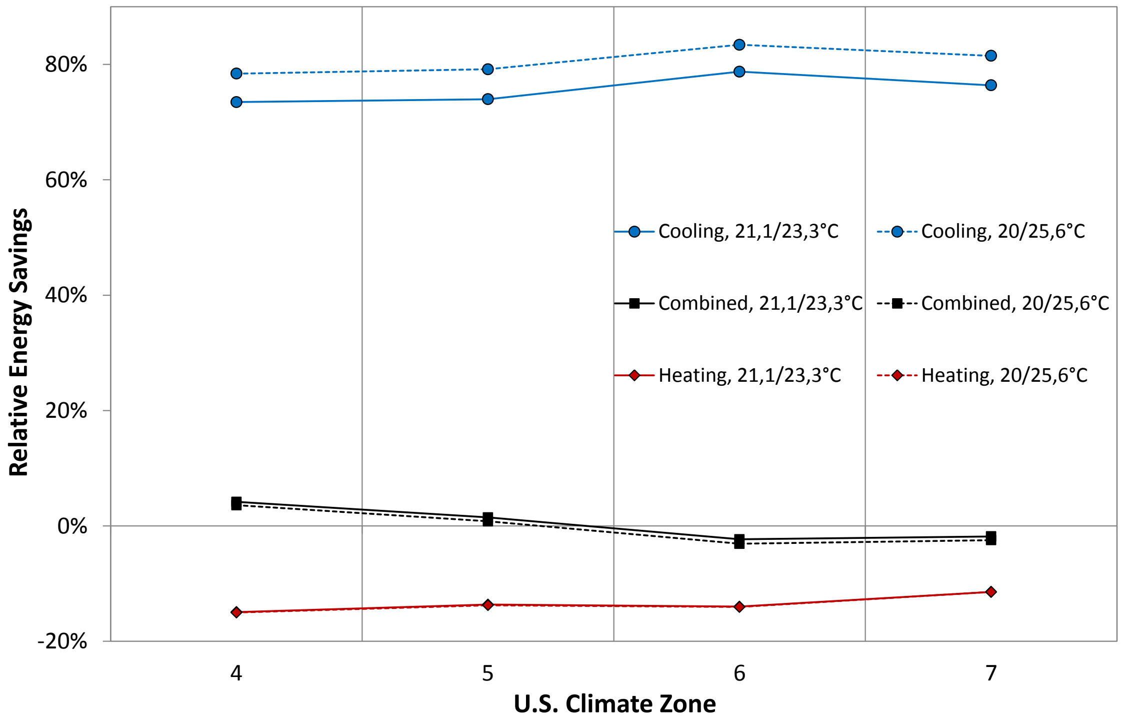


Figure 33 The decrease in energy demand when converting from a dark to light colored roof surface. The variations are separated into cooling, heating and combined energy heating and cooling demands. The values represent the U.S. climate zones 4 to 7 and with two different ranges of thermostat set-point temperatures. A negative value of the relative energy savings equals an increase in energy demand. The reason why the curve for the combined heating and cooling demand is far closer to the curve for heating demand than for cooling, is that the energy demand for heating is higher than for cooling in the studied U.S. climate zones.

Apparently, the impact of the indoor heat supply is more significant than the thermostat temperatures. In Figure 34, three different scenarios of indoor heat generations are considered; no heat supply, 2°C and 5°C heat supply. According to the presented results, a cool roof retrofit in climate zone 6 and 7 are still questionable if assuming an indoor heat supply from appliances, humans and solar radiation of 2°C. In cases with an assumed high indoor heat supply, the potential energy savings is positive for all simulated U.S. climate zones.

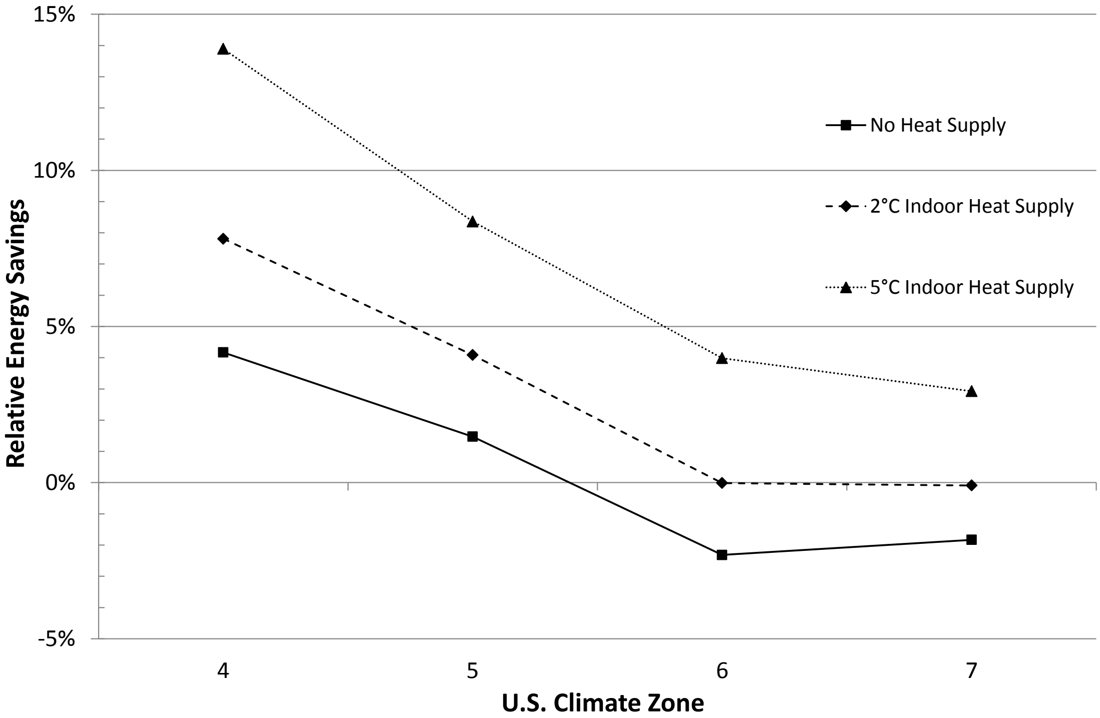


Figure 34 The decrease in the combined heating and cooling energy demand when changing the solar absorptivity of the surface membrane from 0,85 to 0,30. The variations are presented for the U.S. climate zones 4 to 7 and with varying indoor heat supply. A negative value of the relative energy savings equals an increase in energy demand.

- RISK EVALUATION, OPTIONS AND RECOMMENDATIONS *CASE STUDY - 3*

A cool roof retrofit has been evaluated with both a QlRA and a QRA. The quantitative analysis revealed the assumingly most important parameters, which were later applied with variability into the simulation model. The combination of the parameters resulted in 128 different scenarios of the roof, which was simulated in WUFI-1D. The varying parameters are the outdoor climate, the solar surface absorptivity, the indoor moisture supply, and the airtightness of the roof assembly underneath the surface membrane.

In terms of the risk of intermediate condensation, the results presented in Figure 31, Figure 32 and Table 1 emphasize the importance of the solar reflectance at the roof surface. The amount of accumulated moisture is almost doubled in a cool roof construction compared to a traditional dark roof surface. The indoor moisture supply is highly influential on the expected hygrothermal performance and the risk of condensation. Actually, a comparison between a low and a high moisture supply can cause as much as a 10 times difference in the amount of condensation. The variability of the airtightness indicates similar importance as with the indoor moisture supply.

Increased air permeability also increases the amount of condensate moisture. The final varying input parameter, the outdoor climate, was proven to also have an influence on the amount of accumulated or condensate moisture, and apparently, a colder climate increases the risk of condensation. In conclusion, all the investigated and varying parameters of this study are highly influential on the risk of condensation.

An analysis of the energy efficiency potential reveals that the cooling energy demand is significantly lowered by a cool roof retrofit, though simultaneously, the heating demand is increased. Therefore, the combined heating and cooling demand ought to be included in an energy efficiency analysis. Apparently, a cool roof retrofit in U.S. climate zone 6 and 7 can actually have a negative effect on the energy demand if no, or very low, indoor heat generation is expected.

The mechanical resistance of the roof membrane has not been taken into account in this study. Likely, this means that, at some lower limit of wind-induced pressure, the uplifting force is lower than the weight and flexible resistance of the membrane, thus preventing any air intrusion. Therefore, a complete depressurization analysis of a mechanically attached roof system is needed to fully analyze a cool roof assembly at realistic and fluctuating wind loads.

However, it is of great concern to emphasize that a single ply roof, including an interior vapor retarder, is not necessarily equivalent with an airtight construction. Either insufficiently sealed overlaps, perforations or penetrations of the vapor retarder/steel deck, may cause high air intrusion rates and therefore increase the risk of intermediate condensation.

Finally, the following practical conclusions can be stated:

- If a very low indoor moisture supply is assumed, no condensation is expected, except for light surfaces combined with high air intrusion rates.
- For dark roof surfaces, the joints of the steel deck do not necessarily need to be sealed to be considered safe, though penetrations and perforations must.
- The previous statement is also valid for light roofs, only with a low or normal indoor moisture supply.
- For all other roof assemblies with varying indoor and outdoor climates, an interior air barrier is recommended.

5.4. Case Study 4 – Retrofit of Below-Grade Walls

Below-grade walls are one of the most common building components with moisture damages (Boverket, 2010a). Usually, the thermal resistance of these basement walls is relatively low; hence below-grade walls are desirable retrofit targets.

- SCOPE ***CASE STUDY - 4***

System Formulation

A retrofitting measure for below-grade walls is investigated in concerns of the hygrothermal performance and how it is affected by the properties of the surrounding ground materials and the indoor climate. The retrofit design is studied in the climate of Gothenburg, Sweden, and the basement is considered inhabited. No other building components are included in the study.

Targets and Concerns

The purpose of the retrofit is to decrease the energy losses through the below-grade walls and to ensure a good indoor environment. The retrofitting measure must also ensure a satisfying moisture safety of the existing wall assembly.

The influence of the surrounding soil textures will be investigated and the importance of their properties on the hygrothermal wall performance.

Existing Conditions

The existing wall is made of concrete and rendered with cement on both the interior and exterior surfaces. Further, the part of the wall, which is below ground level, is considered to have a high moisture content. If the walls have cracks or other damages, these are assumed to be repaired prior, or as part of the retrofit construction. The walls are also expected to have a low thermal resistance due to the lack of insulation materials in the wall assembly.

Strategy Identification

A common approach, to both increase the thermal resistance and to decrease the moisture content of a below-grade wall, is to expose the complete exterior surface and mount a drainage and insulation board (Isodrän, 2005; Jackon-Sverige, 2011). A landscape fabric is mounted on the exterior board surface and the rest of the created construction hole is refilled with the previously removed ground material. The design of the below-grade wall retrofit is illustrated in Figure 35. The advantages of the drainage/insulation board in the retrofit design are, according to several manufactures the following (Isodrän, 2005; Pordrän, 2009); reliable and effective drainage, prevents capillary suction of ground water, effective exterior drying of the existing wall (by the water vapor transportation of diffusion) and improved indoor thermal comfort by the increase of the total thermal resistance. In addition, applications of organic materials are, according to the manufactures, allowed on the interior basement wall surfaces, since the retrofit is designed to raise the interior surface temperature and to enable moisture to dry from the existing wall to the ground.

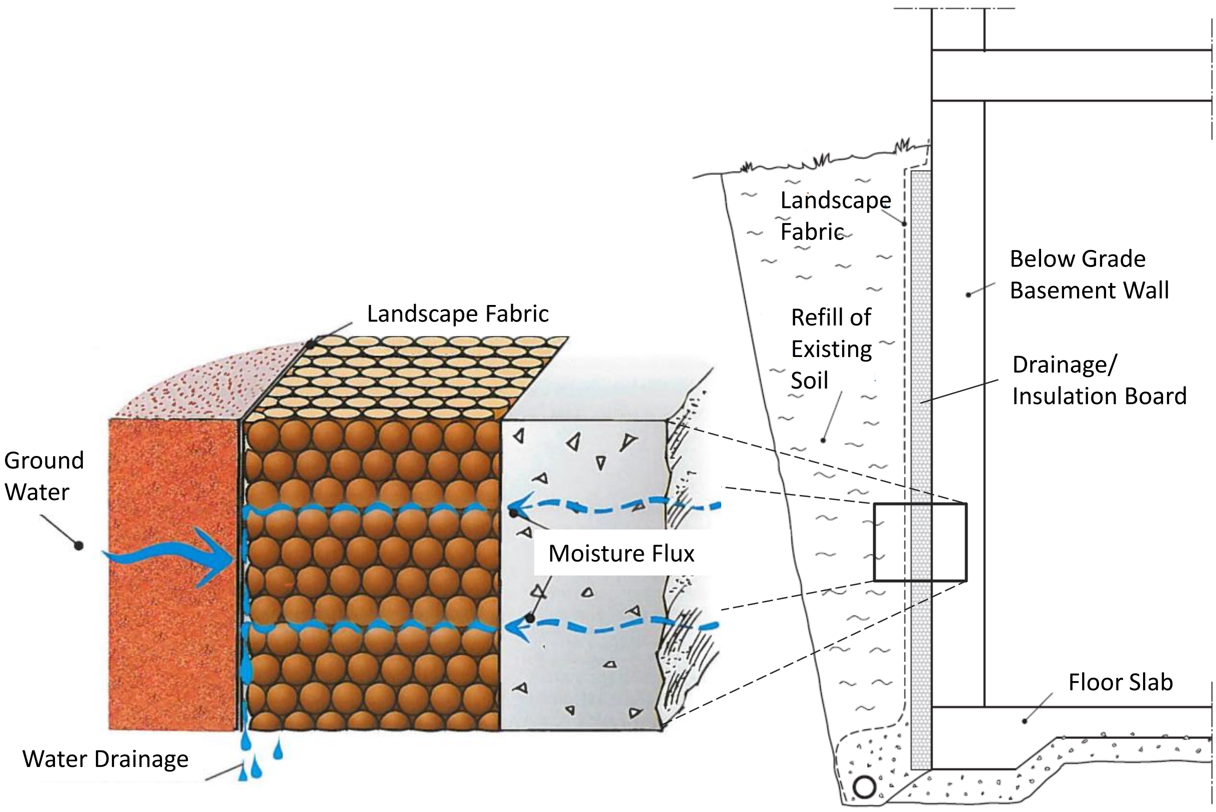


Figure 35 An illustration and function of a below-grade wall retrofit, according to the manufacture (Isodrän, 2005). The purpose of the retrofitting measure is to increase the thermal resistance, prevent ground water penetration and to enable outwards drying of the wall.

Risks identification

There are risks which the retrofitting measure in Figure 35 is designed to decrease. The application of a landscape fabric between the drainage/insulation board and the soil prevents ground material to penetrate the board and to change its hygrothermal properties. A flashing is mounted on top of the drainage/insulation boards and prevents penetration of ground materials but also stops water from precipitation to enter the boards. Below the level of the floor slab, perforated drain pipes ensures the transportation of excess water. If any of these construction details fails, the consequences could be devastating on the hygrothermal performance and the intention of the retrofit could be jeopardized. For example, Figure 36 illustrates risks of water penetration between the flashing and the below-grade wall due to an unsatisfying workmanship.

Figure 36 Photo of the investigated below-grade wall retrofit, at a visited construction site in Gothenburg. The photo depicts two major concerns in terms of the risks of water penetration between the drainage/insulation boards and the below-grade wall. First, the flashing is somewhat twisted, most likely due to an uneven wall surface and due to a too large distance between the flashing attachments. This result in an unsatisfying flashing and wall interface, which enables water to penetrate. Second, the landscape fabric is damaged at the location of the drain pipe, which can result in the penetration of ground materials into the drainage/insulation boards.

There are other risks which may occur even if the construction of the retrofit design is satisfying. A high water pressure in the soil, acting on the exterior surface of the drainage/insulation board, could theoretically result in water movement into the structure of the board. If water enters, it will drain downwards, though in both directions; meaning, water will reach the exterior surface of the concrete wall.

The intended mechanism of outwards drying is a result of water vapor diffusion, deriving from the difference in temperature between the exterior below-grade wall surface and the soil next to the drainage/insulation board. Actually, the intended drying potential is the difference in humidity by volume at saturation between the two materials. Since the temperature of the below-grade wall surface, in general, is assumed to be higher than the soil temperature, an outward drying is expected. However, the transport mechanism of diffusion may as well be directed inwards. If the basement temperature is lower than the temperature of the soil, next to the drainage/insulation board, the drying potential may be reversed. A higher soil temperature may exist if the outdoor temperature is, or has been, higher than the basement temperature or if solar radiation is, or has been, absorbed at the ground surface.

Influential Parameters, Uncertainties and Correlations

In the analysis of this case study, except of the previously discussed causes of risks, there are some material properties which will influence the expected hygrothermal performance of the above grade walls and the indoor comfort. As seen in Section 3.2.2, there are 12 different classified soil textures which all vary in hygrothermal properties. Depending on the soil, the heat losses and the drying potential are expected to vary. The existing moisture condition of the concrete wall will also influence the drying potential.

Naturally, the outdoor climate and the direction and exposure of the studied wall retrofit will have a large impact on the performance and the intentions of the design. Most likely, the retrofit is not suitable in hot climates with a wet soil; in which the direction of the water vapor diffusion is expected inwards.

- RISK EVALUATION ***CASE STUDY - 4***

There are a number of parameters which will influence the risks of the studied retrofit. First, there are risks which derive from an unsuccessful construction of the retrofitting measure. Water may penetrate the drainage/insulation board if the flashing is improperly installed; the landscape fabric is damaged, or not sufficiently attached and overlapped; or if the drain pipes are missing or nonfunctional. The causes and risks of consequences are summarized in Table 8, using the risk identification procedure of HAZOP, as described in Section 3.1.

Water vapor diffusion is a slow moisture transportation process and therefore, the drying potential of the wall assembly is small. In time, and under favorable hygrothermal conditions, the moisture from the concrete wall will be dried to the exterior. Unfortunately, due to the slow drying process, the studied retrofit must be considered as moisture sensitive; especially, if organic materials are allowed on the interior surface of the basement, or if moisture is prevented from drying inwards due to an applied vapor tight paint or wall membrane at the inner surface.

Table 8 A HAZOP study of the below-grade wall retrofit.

Guide Word	Deviation	Cause	Consequence	Recommendation
Wetting of exterior wall surface, thus increased water content inside the wall.	Water transportation through drainage/ insulation board.	1. High water pressure in the soil. 2. Dysfunctional landscape fabric.	1. Biological growth on the interior wall surface. 2. Condensation on adjacent building materials.	1. Drainage materials outside the drainage/ insulation board. 2. Mount a moisture tight membrane on the exterior board surface.
	Water leakage behind flashing.	Inadequate connection between the flashing and the wall.	1. Biological growth on the interior wall surface. 2. Condensation on adjacent building materials.	Apply an elastic sealant between the flashing and the wall.
	Water vapor diffusion directed inwards.	The temperature in the soil is higher than at the exterior wall surface.	1. Biological growth on the interior wall surface. 2. Condensation on adjacent building materials.	Mount a moisture tight membrane on the exterior board surface.
Less energy efficient	The thermal resistance of the drainage/ insulation board decreases.	1. Soil or other organic materials penetrate the board. 2. Water penetrates the board.	Increased heat flow at the interior wall surface.	Mount a moisture tight membrane on the exterior board surface, which naturally is a material barrier as well.

Specific values of risks are difficult to determine based on solely the QlRA. However, simulations of the studied retrofit will enable to determine the level of sensitiveness for moisture. The retrofitting measure can also be investigated under the influence of different soil textures and their impact on both the moisture transportation and the retrofit energy efficiency potential. Consequently, a QRA is performed to better evaluate the expected hygrothermal performance.

Method and Performance Indicators

The model must be able to simulate transient heat losses from the basement, through the ground and up to the surface; hence at least, a two dimensional hygrothermal simulation model is required. Further, the maximum drying potential of the existing above grade walls will be based on the assumption of a water vapor saturated soil, thus representing plausible conditions of soils in Gothenburg (Sundberg, 1988). The water vapor content at saturation of the soil and the exterior wall surface depends on the temperatures; hence the moisture transfer can, for simplification, be excluded from the simulations. Later, when the transient temperature distribution between the soil and the concrete wall has been defined, the maximum drying potential can be determined out of the relative humidity by volume at saturation.

If assuming moisture saturated concrete and soils, the disparity in temperature will determine the maximum diffusion rate. Therefore, a soil with a higher temperature next to the drainage/insulation board has a lower drying potential. In terms of finding the most decisive scenario for the simulations, a retrofit turned in a south-west direction is likely to be governing; at which solar radiation will have the highest influence on the ground temperature.

Two P_{ind}s are suitable for the study of the hygrothermal performance of the below-grade wall retrofit; the heat flux, q, and moisture flux, g (W/m^2 and g/m^2,s). q enables an energy efficiency analysis and g helps to determine the moisture sensitivity of the retrofit.

Input Values and Probability Distributions

The simulations will include the 12 classified soil textures and their hygrothermal properties, as presented in Section 3.2.2; hence representing a possible soil variability. The P_{ind}s will be studied at three depths from the ground surface; 0,2; 0,8; and 1,6 m.

The basement is assumed inhabited with a constant indoor temperature of 18°C. The concrete and the soil are assumed water vapor saturated. The hygrothermal properties of the drainage/insulation board, presented by manufacture (Isodrän, 2005), are also implemented into the simulation model.

Design and Run Simulation Model

A simulation model of the retrofitting measure is developed in WUFI-2D and according to the retrofit design, presented in Figure 35. The material of the below-grade wall is concrete and with a thickness of 0,2 m. The thickness of the drainage/insulation is 0,095 m. The retrofit model is simulated 12 times in total, using 12 different classified soil textures (USDA, 2008). Each retrofit scenario is simulated for one consecutive year, as this time period is assumed sufficient for the requested result and comparison analyses.

Result, Sensitivity and Uncertainty Analyses

The temperature variations of the simulated retrofit is studied at the exterior surface of the below-grade wall, in the soil next to the drainage/insulation board and at three different depths; 0,2; 0,8 and 1,6 m. Apparently, the annual variation of the temperatures at the exterior wall surfaces deviate slightly, independent of depth, although greater closer to the ground surface. The soil temperatures however, vary significantly on a yearly basis, depending on the distance to the ground surface, as seen in Figure 37.

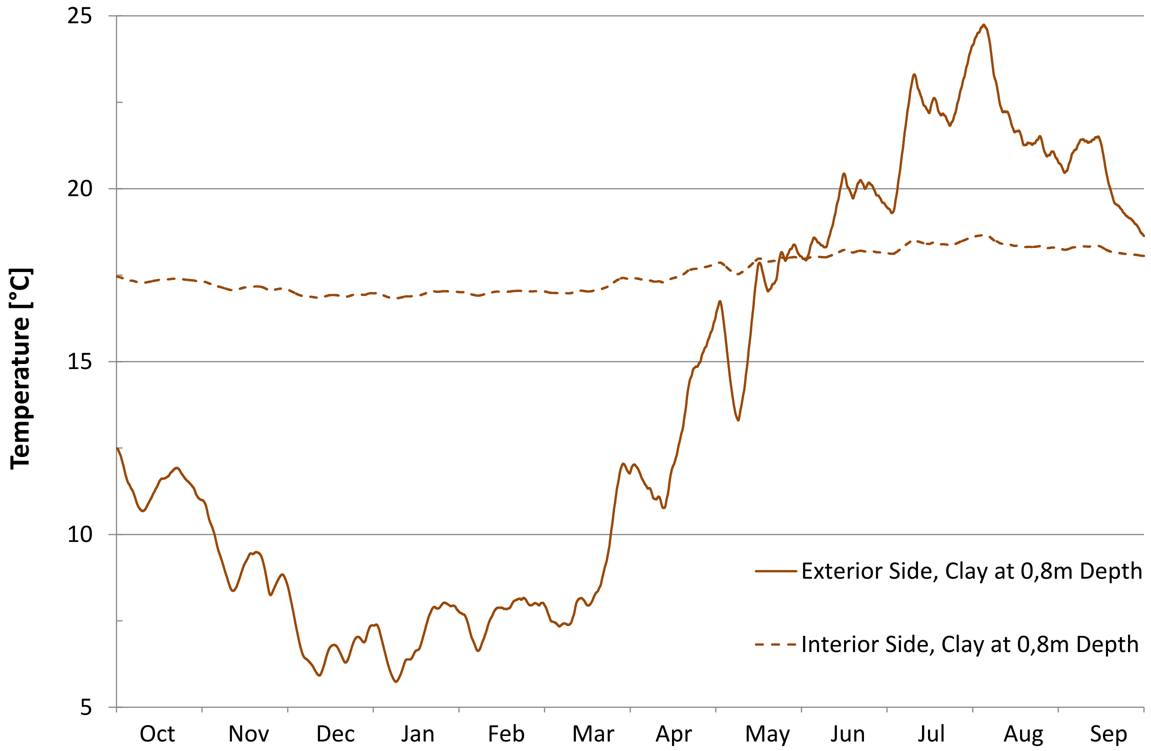


Figure 37 Annual temperature variations at the exterior side of the concrete wall and at the soil next to the drainage/insulation board. The temperatures are studied at a depth of 0,8 m and the arbitrarily chosen soil texture is Clay.

The variations of the simulated temperatures at the studied depths of 0,2; 0,8 and 1,6 m are applied to determine the variations of water vapor contents at the wall surface and in the soil. This is possible due to the assumption of a 100% relative humidity in the soil and the concrete material; meaning, the water vapor content can be determined since the temperature and the relative humidity is known. Subsequently, the deviation in water vapor content becomes the maximum potential for drying of the concrete exterior wall surface. Water vapor contents below saturation of the concrete wall surface results in lower potential and therefore a lower moisture flux. If the water vapor content at the wall surface drops below the water vapor content of the soil, the flux is turned inwards. This is also the case if the temperature of the soil is higher than the surface temperature of the wall, which is apparently the situation at the depth of 1,6 m between July and September, as seen in Figure 38.

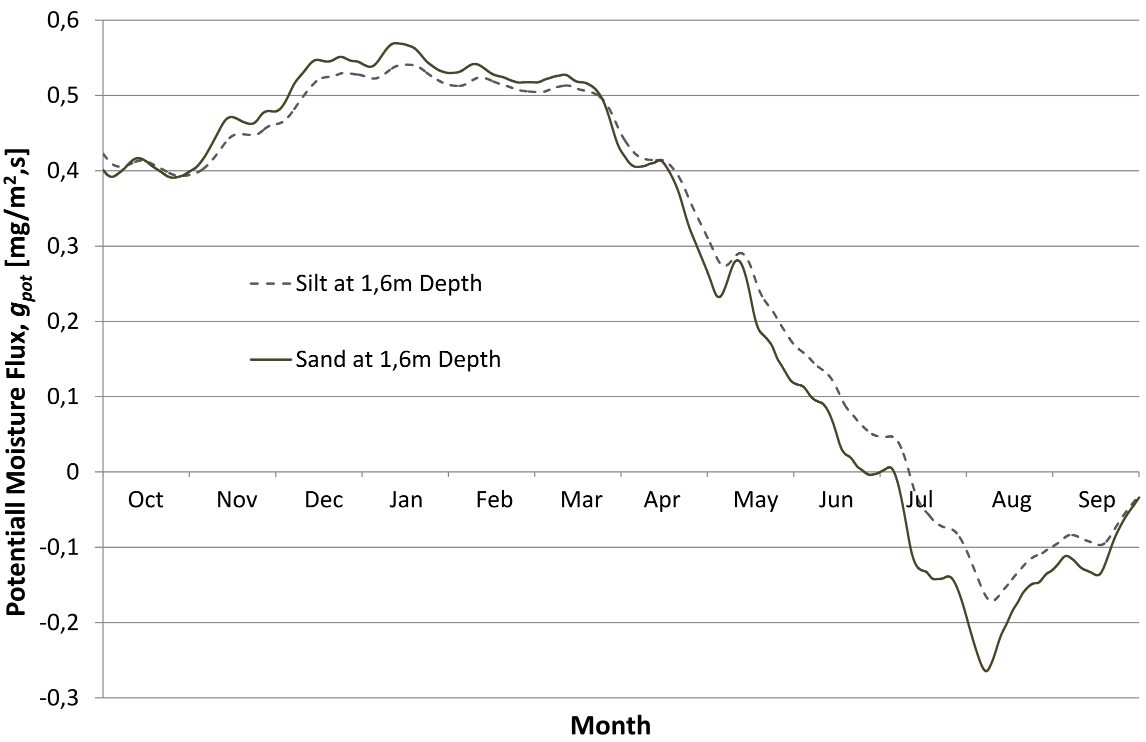


Figure 38 Annual potential moisture flux, g_{pot}, at the exterior surface of the below-grade wall. The flux is determined based on the difference in humidity by volume at saturation between the surfaces of the drainage/insulation board and the soil at a ground depth of 1,6 m. The annual variation of g_{pot} are presented for two different soil textures; Silt and Sand.

The annual average moisture flux, g_{pot}, at the studied depth of 0,2; 0,8 and 1,6 are at maximum 5,8; 8,4 and 8,9 (kg/m^2,year), meaning drying of the wall. The deviation in g_{pot} between the different soil textures is small, since the standard deviation varies only between 1-2%.

The heat flux, q, is simulated at the inner wall surface of the basement and the annual variation of heat losses and gains are presented in Figure 39. The variations in q between the 12 soil textures are higher than for g; since q can deviate about 10% depending on the type of soil. The largest deviation in q is seen between Silty Clay and Sand, and their annual variations of q are presented in Figure 39.

Figure 39 Annual variations of the heat flux, q, at the inner wall surface of the basement. The expected heat losses and gains deviate about 10%, depending on whether the simulated ground material is Silty Clay or Sand.

- RISK EVALUATION,
OPTIONS AND RECOMMENDATIONS ***CASE STUDY - 4***

A QlRA shows that the studied retrofitting measure is sensitive to moisture and that it is crucial that the retrofit is constructed as intended. The flashing, the landscape fabric and perforated drain ducts are all essential features of the retrofit and must be present and correctly applied to ensure a satisfying hygrothermal performance of the below-grade wall retrofit.

The retrofit is presented as an energy efficiency measure which simultaneously allows moisture from the below-grade wall to dry outwards. However, the moisture transportation is slow and, according to the simulation results, only about 6 to 8 (kg/m^2) of the moisture in the wall can be dried annually, at maximum. There is also an expected negative moisture flux, meaning wetting of the wall surface, during the late summer months of the studied retrofit, if the wall is turned in a south-west direction.

The total annual rain load of the outdoor climate of Gothenburg, used in the simulations (Künzel, 1995) is larger than 1000 (mm/m^2). If for some reason, any of the rain load, directly hitting the ground or drained from the upper wall surfaces, penetrates the drainage/insulation board, the expected drying potential is affected. Actually, only 0,6% to 0,9% of the precipitation, incident on a square meter of the ground surface, is allowed to penetrate the drainage/insulation board (not including drained precipitation from upper wall surfaces), if the drying potential should maintain positive. If the water penetration is larger, the drying potential will be equalized or reversed. This means that the wall will be wetted under such conditions; hence the investigated below-grade wall retrofit must be considered sensitive to exterior moisture loads.

One of the claimed advantages with the recommended retrofit design is that any materials can be mounted on the interior basement surfaces. However, the annual average of relative humidity, φ, at the exterior wall surface is about 84%, under the conditions of an assumed saturated soil. Due to the relatively low thermal resistance of the concrete wall, the temperature at the interior and exterior wall surfaces is similar. Consequently, about the same φ can be expected at the interior wall surface if the moisture content of the wall is equally distributed. Hence the interior application of organic materials, such as wood or wall paper, must not be recommended.

An energy efficiency analysis of the simulation results shows that the type of soil texture can influence the heat losses through the basement wall with as much as 10%. Under the simulated indoor and outdoor conditions of the retrofit (turned in a south-west direction), heat gains through the wall can be expected from June to September. The retrofit is designed as an inhabited basement, if the space is not conditioned, a lower temperature is expected; hence the drying potential of the wall is lowered, equalized or reversed.

To ensure a positive drying potential between the soil and exterior wall surface, preferably, the landscape fabric could be replaced with a water and vapor barrier. Since a moisture barrier would prevent water from the soil to penetrate the drainage/insulation board and also prevent the excess of water vapor from the soil to transport inwards under such favorable conditions. As an alternative, the refilled soil can be replaced with a drainage material to prevent a high soil water pressure. However, the refill of a drainage material solely, next to the drainage/insulation board, will not prevent inwards water vapor transportation by diffusion; hence the first alternative for improvement is considered most suitable.

6. **Conclusions**

The work of this thesis proves that a risk assessment of a retrofitting measure is doable, in concerns of the hygrothermal performance of a building or a building component. The advantages of a probabilistic risk assessment in comparison with a traditional deterministic approach are many. The most distinguished advantage is the possibility to include the natural variability and uncertainty of the parameters which have an influence on the hygrothermal retrofit performance; consequently, increase the credibility of the outcome of the retrofit design. Typical parameters which have a high impact on the hygrothermal performance of a building are the outdoor climate, indoor heat and moisture supply, material properties of the building materials, features of the technical equipment and indoor appliances, and occupants' user behavior. A risk assessment will present an expected variability of an analyzed performance indicator (a value which measures the performance), such as energy demand, mold growth potential, indoor air quality or occupants' level of comfort. Mainly, the reliability and accuracy of the risk assessment results depend on the correctness and applicable knowledge of the influencing parameters. In other words, if the influencing parameters can be defined with reliable and realistic variability, thus with a low level of uncertainty, the result is also expected to be reliable and realistic.

A risk assessment algorithm is presented, which has been developed as a step by step guideline on how to perform a successful hygrothermal risk assessment on a residential retrofitting object. Following each step of the procedure, enables to increase essential knowledge of the retrofitting measure, predict the likely performance and to investigate possible unwanted consequences post-retrofit. Consequently, by the application of the proposed risk assessment procedure, it is possible to identify the most efficient and reliable retrofit design and to determine the most suitable building materials and technical solutions. The final outcome of a hygrothermal risk assessment serves as the foundation of the decision making and should also, depending on the results of the analyses, present alternative continuance strategies. The hygrothermal risk assessment procedure has been developed to be applicable in the design of residential retrofitting measures; however, the procedure can equally apply in the design of new buildings, both commercial and residential.

The hygrothermal risk assessment mainly consists of two analysis steps; a qualitative and a quantitative risk analysis (QlRA and QRA). This thesis describes all the steps of the risk assessment and provides examples of methods and approaches for both the QlRA and the QRA. A QlRA is a relative measure of risk where all influencing parameters are defined and their importance are ranked, which could also include the determination of possible unwanted consequences post-retrofit and defining their likeliness of occurrence. Typical unwanted consequences concerning the hygrothermal performance of a retrofit are insufficient energy savings, indoor air quality deficiency, mold growth, rot, fungus or occupants' comfort issues such as draught, cold radiation or inadequate ventilation. Experience, expertise and competence are usually important qualities of someone conducting a credible QlRA; hence tools and predefined procedures are helpful to aid the analysis. A QRA uses concrete values of risks and estimates the variability, sensitivity and uncertainty of the analysis results. The importance of including the parameter variability and uncertainty is shown, as it will define the variability and uncertainty of the result. A result, sensitivity and uncertainty analysis can identify the most influential parameters, and equally identify the parameters with the lowest estimated impact on the future hygrothermal performance of the analyzed retrofitting measure.

The development of a simulation model that should represent the investigated retrofitting measure is usually a good approach to estimate the hygrothermal performance of a retrofit; thus a valuable tool of a QRA. However, the simulation model must take into account the variability of the input parameters, perform multiple simulation runs (preferably without interference) and save the results needed for the post simulation analyses. The credibility of a QRA increases if using stochastically varying input parameters in the simulation model, which either can be obtained from measurements, statistics or stochastically simulated. In this thesis, two parameters have been studied in detail in order to increase the knowledge of their natural variability. The two studied parameters are the indoor moisture supply in residential buildings and the hygrothermal properties of soils. The increase in knowledge of their variability has been proven both useful and important for some of the presented case studies of the thesis.

An important advantage with a risk assessment, which takes into account the variability of the input parameters, is that the result will represent the likely future performance of the building post-retrofit. Consequently, a performance indicator will not be presented as a single best-estimate; it will be presented with an expected mean, variance, spread and shape of the variability. This feature enables the decision makers to analyze realistic results and therefore make trustworthy conclusions on whether the risks of deviating from the expected performances are acceptable or not. Four different case studies conclude the thesis, and serve as examples on how to successfully follow and perform the presented risk assessment algorithm. The four cases represent the retrofit of commonly retrofitted building components in the building envelope; the roof, the wall and the basement.

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