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

Risk management by probabilistic assessment. Development of guidelines for practice

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Preface

The International Energy Agency

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

The IEA Energy in Buildings and Communities Programme

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

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

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

The Executive Committee

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

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

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

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

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

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

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

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

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

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

Content

1 INTRODUCTION

1.1 Background

Energy and durability issues are currently amongst the most important topics in industrialised countries. Even though considerable progress has been achieved in energy conservation standards for new buildings (e.g. passive house standard, low and zero energy standards, to name a few) and building services technologies have advanced significantly, the building sector still accounts for the largest share of energy-related carbon dioxide (CO_2) emissions. In many industrialised countries, new construction contributes approximately 1% to the existing building stock annually. However, often more than 50% of the existing building stock dates from before the first energy crisis in the 1970s. Hence, a high potential for energy savings - and consequently a large reduction of greenhouse gas emissions - is presently available in the existing building stock. Building retrofitting measures are therefore of utmost importance for upgrading the building stock.

But, many consumers are only interested in the renovation investment costs and it is rare that lifecycle costs are considered. Actual performance and the risks taken highlight the need for considering the building's lifecycle and imply the need for applicable probability assessment methods supporting sound decision-making for investments. Customer relationships are based on future expectations and confidence to be supported by proper probability assessments.

The results from the IEA-EBC Project RAP-RETRO is intended to improve methods and tools for integrated evaluation and optimization of retrofitting measures, including energy efficiency, lifecycle costs and durability. It will demonstrate the benefits of renewing the existing building stock and how to make reliable solutions to decision makers, designers and to end-users.

The RAP-RETRO *mission* is to answer the following question:

How do we design and realize robust building retrofitting with low energy demand and low lifecycle costs while controlling risk levels for building performance failure?

The results from the project are presented in a number of reports. Each of these reports focus on a specific task: stochastic data description and collection, probabilistic methods, framework for risk assessment, and reports from practice and guidelines in participating countries.

1.2 Who should read the report and why?

When retrofitting existing buildings, it can be expected that energy use variations will exhibit even more randomness from building to building, since the uncertainties are greater than for a new building. The status of the existing building will already give an initial random variation.

As a result, the total lifecycle costs for the operation and maintenance of a group of buildings will vary randomly due to factors such as initial investment, energy use, hygrothermal performance and building performance failures.

All these factors should be included in order to make balanced decisions and sound choices of retrofitting strategies and investments.

Everyone that is involved in the decision-making process will benefit greatly from the results presented in this report.

The first category is,

- Material, building and HVAC-system producers and corporations.

They can assess the risk or reliability of a certain retrofitting technology being developed for market. Using a proper analysis, they can suggest low-risk alternatives and prerequisites for the alternatives. Corporations can minimize economic risks and increase reputation.

Another category is,

- Engineers and Architects.

In specific building projects, they can analyse the special conditions for the project: for instance, the location and use of the building. They can supply their clients with a proper risk assessment considering performance and costs for retrofitting alternatives. They can also collect and communicate the necessary quality assurance requirements.

The following category can demand reliability assessments from their experts and consultants to make better decisions,

- Building and real estate owners and Energy Savings Companies (ESCO).

Risk assessments can guide local authorities to demand using low-risk alternatives. Mandatory requirements and avoidance of a risk for the society societal risk can be facilitated by the following category,

- Government: Federal Government & Municipalities, Local Authorities, Agencies and Legislators.

1.3 References

The following subtasks and corresponding ongoing final reports have been finalized in the Annex 55, RAP-RETRO Project:

Subtask 1 (ST1): **Gathering of stochastic data**

Report: Nuno M.M. Ramos, John Grunewald, Stochastic Input and Validation Data, Report Number 2015:3. Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden. ISSN 1652-9162.

Subtask 2 (ST2): **Probabilistic tools**

Report: Hans Janssen, Staf Roels, Liesje van Gelder, Payel Das, Probabilistic tools, Report Number 2015:4. Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden. ISSN 1652-9162.

Subtask 3 (ST3): **Framework and case studies**

Report: Angela Sasic Kalagasidis, Carsten Rode, Framework for probabilistic assessment of performance of retrofitted building envelopes, Report Number 2015:5. Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden. ISSN 1652-9162.

Subtask 4 (ST4): **Practice and Guidelines**

Reports:

Marcus Fink, Andreas Holm, Florian Antretter, Practice and guidelines, Report Number 2015:6. Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden. ISSN 1652-9162.

Thomas Bednar, Carl-Eric Hagentoft, Risk management by probabilistic assessment- Development of guidelines for practice, Report Number 2015:7. Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden. ISSN 1652-9162.

2 WHY DECISIONS GO WRONG AND HOW TO CHANGE THE BUILDING PROCESS

2.1 Building renovation - each case is unique

Renovation costs of building envelopes are a large financial burden to a property owner, and also a possibility to lose reputation for designers and builders. From a sustainability point of view, substandard practices require more material, energy and human resources than necessary and may create conditions for health risks. In the end, it is important to society as a whole to acquire well-functioning and durable buildings.

Upgrading the building envelope is a common practice to enhance a building's energy performance. Unfortunately, retrofitting measures do not always save the expected amount of energy or achieve acceptable functional performance, and the lifecycle costs of some measures can reach unexpectedly high levels. One important goal is to design and deliver reliable retrofitting measures with predictable and low risk.

Retrofitting building envelopes is a field where a large number of new design strategies are being developed as a result of unique combinations of old and new building materials and technologies. Many of these cases are not (yet) fully covered by design references or practical experiences. Retrofitting buildings thus calls for ways to identify, limit or eliminate risks already occurring in the design process.

Energy use measurements in buildings exhibit considerable variations. This may seem logical, as every building does not have the same overall thermal insulation, heating system, occupancy, etc. But even when the same building technologies are used, a significant range in measured energy use is still observed. Multiple causes contribute to the variance; these may include ventilation rates, airtightness, U-values, building orientation, internal heat gains, human behavior in use and maintenance, weather, workmanship, rate of material aging, etc.

When retrofitting existing buildings, it can be expected that energy use will vary even more from building to building, as the uncertainties are greater than for a new building. Hence, total lifecycle costs for operation and maintenance of a population of buildings will also vary more or less randomly as one adds such factors as initial investment, hygrothermal performance and performance failures. Examples of typical building performance failures are:

- poorly applied additional insulation to the building envelope resulting in higher heat losses than planned air transfer or moisture conditions
- lack of overall thermal comfort leading to occupant compensation by higher average interior temperatures and hence higher energy use
- moisture-damaged wall insulation systems requiring renewed retrofitting sooner than expected.

In reality, there are many reasons why the solution with the lowest risk is not used.

Sometimes, only a limited set of technologies is available due to architectural, aesthetic or economic reasons. One example is the use of interior insulation to preserve the exterior façade. Increased thermal insulation is necessary to reduce heat loss resulting in colder and more moisture-sensitive constructions, increasing risk. When considering building physics, interior insulation is not the safest method to reduce heat transmission, but it is still applied and can be relatively successful if applied correctly.

Another reason to not select the solution with the lowest risk is the habit to follow an established building tradition.

Building traditions are difficult to change, and even though for example, crawl spaces are known to be risky in cold climates, many buildings exist with them and are still being built.

2.2 Unexpected complex interactions

When designing and erecting new buildings, using good practice and well-proven solutions most often lead to good and expected building performance. However, achieving the expected building performance requires that the factors that the design concept is based on fulfil certain standards and are within expected ranges. These factors could for instance be workmanship, interior and exterior climate, maintenance and/or material properties. Quality assurance procedures are a great help to achieve building performance goals.

However, when retrofitting or making changes in old buildings, many unexpected processes can take place. For instance, the window airtightness can change the air pressure distribution of the building; it changes the ventilation rate that in turn changes the vapour content of the indoor air. This was not anticipated in practice, even though it could very easily be predicted, and led to bad indoor air quality and moisture damage in Sweden after the first oil crisis in the 1970's. As a single measure to reduce energy demand it was fast and inexpensive. Another example from Sweden is spraying loose fill insulation on the attic floor. Once again, an inexpensive single measure has caused moisture damage in attics. Upon adding attic insulation, the cold attic became colder and more susceptible to rising warm indoor air. Also changing from heating sources can cause problems. Switching from a furnace-based heating system with chimney exhaust to a district heating source, both changes the temperature in the attic as well as the air pressure distribution in the building. Both of these two consequences can lead to moisture damage in the attic.

Building physics-related phenomena are very often strongly non-linear, i.e. small changes can lead to big changes in hygrothermal conditions since heat, moisture and air transfer conditions are strictly linked to each other. Common sense cannot guide you.

2.2.1 “Crawl space” example

A crawl space is a building foundation with low foundation walls or beams and plinths below the rest of the building. With this type of foundation, we have one or more cavities below the rest of the building. The crawl space can be designed with outdoor or indoor air ventilation or on rare occasions without any ventilation at all. In most Swedish buildings, the crawl space is ventilated by outdoor air through a number of evenly distributed air vents through the foundation walls. This design has been used for hundreds of years in Sweden, and was called a “croft foundation” in its early form. However, the modern version of the crawl space differs from the old one in many ways. The thermal insulation in the floor structure is much thicker and we have no heat source in the foundation from a warm chimney. The old buildings were not without problems despite the changes. The thermal comfort was very poor and the buildings often suffered from musty odours from organic material in the foundation that were leaking up to the living space.

Modern outdoor ventilated crawl space foundations often experience moisture and mould problems, especially foundations with a wooden floor structure. The risk for damage and nuisance can be decreased if the surface of the soil under the foundation is thoroughly cleaned and completely covered with good quality plastic foil and with has sufficient overlap in the junctions. By installing thermal insulation over the plastic foil and on the outside of the foundation walls, the risk for moisture damage can be further reduced. In spite of all these measures, the moisture level in the foundation is sometimes too high, especially in the summer. Therefore, the traditional outdoor ventilated crawl space foundation has to be considered as a risky construction concerning mould and odours, especially if the floor structure is made of wood. The main reasons for the problem in the crawl space are the temperature and moisture conditions during the warm period of the year, which are favourable for mould growth. Furthermore, the air pressure distribution in the building will normally transport air, odours and even mould spores from the foundation to the living space. In areas with radon is present in the soil, the air can also transport radon from the foundation to the living space. The fundamental problem with the outdoor ventilated crawl space is the high thermal capacity of the soil. Due to the high thermal capacity, the crawl space “remembers” the outdoor temperature from last winter resulting in a lower temperature in the crawl space than the outdoor temperature during spring and early summer. When moist outdoor air enters the crawl space in spring and early summer, it is cooled and the relative humidity increases – often up to 80-100%. During winter the conditions reverse. General measures to decrease the relative humidity in outdoor ventilated crawl space foundations are to decrease the vapour concentration by dehumidification and decrease evaporation from the soil using plastic foil or by increasing the temperature by insulating the ground.

2.2.2 Additional insulation on the inside example (“inside insulation”)

A very important measure to reduce energy demand during winter in cold climates is to use insulation materials on the exterior constructions. The possibility to place insulation on the inside has long been recognized as being risky as the old construction cools down and possible condensation of interior moisture could lead to mould growth or other moisture-induced failures. The benefits of using inside insulation are,

- Reduced heat losses, enhanced comfort, and a shorter heating-up period;
- Installation independent of outdoor weather conditions;
- The appearance of the exterior façade is not affected, and is sometimes the only possible solution for protected heritage buildings; and
- Uneven wall surfaces can be adjusted.

Due to the benefits, a large body of research has been undertaken searching for new materials to decrease moisture accumulation caused by liquid water transport to the interior, and new design tools based on simulating coupled heat and moisture transport have been developed. Field measurements in demonstration buildings have also helped to understand the real dynamic moisture content in buildings, and in many cases showed good performance. Some studies have also helped to understand the risks. The possible failures and consequences that have been identified are,

- Surface moisture damage close to inside insulation (mould),
- Moisture damage inside the construction (e.g. mould, rot, and frost),
- Off-gassing of toxic substances affecting indoor air quality (e.g. EPS, XPS, and PUR),
- Increased fire risk,
- Decreased frost resistance, and
- Increased influence of thermal bridges.

Figure 2.1 Identified failures due to inside insulation: Frost damage (Hartwig M. Künzel IBP 2011), left; Mould growth inside the exterior wall construction (Th. Bednar, TU Wien, 2012), middle; Mould growth at the junction of an inside insulated outer walls (S. Korjenic, TU Wien, 2007), right.

As there are many buildings with inside insulation that have performed well and some others have showed failures, several attempts have been made to formulate guidelines on how to successfully design walls insulated on the inside (Straube et.al; 2012; May et.al. 2014; FWV 2012). Those guidelines address state of the art design strategies of inside insulated walls, however, the complex interactions between the exterior climate, the existing construction, air flow through the construction, the overall air tightness of the building and user-influenced indoor climate needs a new approach to compare different solutions in a holistic way.

2.3 From a perfect world to reality

2.3.1 The first step - risk thinking

Normally during the building design process, assumptions are made about “normal” operation conditions and “normal” workmanship, which underlie design decisions. *Risk thinking* during the design process anticipates circumstances when a single design does not fulfil design goals. The first step to “risk thinking” is “risk identification”. As an important management task, the design team collects influences on the future performance of the building due to all possible categories of uncertainties.

According to McManus et.al., 2005, categories of uncertainties are,

Lack of knowledge is defined as facts that are unknown or known only imprecisely that is needed to assess performance of the concept: examples include prior building usage, possible salt contents, etc.

Lack of definitions is defined as aspects of the project that are undecided or not specified: for example, future use and maintenance, neighbouring buildings, available funding and associated criteria.

Statistically characterized variables are defined as inputs that cannot always be known precisely but can be statistically characterized or at least bounded: for example, typical material properties (e.g. thermal conductivity, liquid transport coefficient, etc.) are not a single number but are statistically characterized variables. The future airtightness of the building envelope is typically a bounded value. If the renovation is conducted according to current state of the art practices, the future building airtightness is higher than the current state. The future climate conditions are also a bounded variable.

Known Unknowns are defined as aspects known to influence building performance, but have entirely unknown values: for example, the impact of future occupants on the building constructions (e.g. hanging up pictures, placing furniture, etc.), animals that might intrude a construction, destruction by sabotage or climate change.

Unknown Unknowns are defined as aspects that are unknown by definition. A very conservative mitigation strategy might help to handle current unknown aspects in the future.

Identifying uncertainties can be used to assess risks. **Risk** in general can be quantified as (Probability of Failure) x (Severity of Consequence of the Failure). If the risk is too high, possible mitigations may have to be found. As the mitigations are normally expensive, they can be justified because of their impact on reliability, robustness, flexibility or evolvability of the system.

Identification of uncertainties, risk assessment, together with measures for risk reductions, are therefore an essential part of a ***risk management*** process. Procedures for risk management differ between engineering disciplines, and also between the buildings they are applied to within the same discipline. While some are regulated in standards, others are developed freely by teams involved in the risk management process. Both risk assessment and risk reduction can be performed in steps and include iterative processes.

Figure 2.2 Illustration of sequential steps in risk management.

In general, risk management includes the following activities:

- Specifying and understanding a desired performance,
- Anticipating conditions and measures that may lead to a range of performance values,
- Qualifying and quantifying the spread, and
- Evaluating the range in terms of present acceptability and tolerance limits.

When using risk management in the building process to identify reliable retrofitting strategies, the important part of quantifying the range induced by uncertainties is determined using mathematical methods. How the current methods can be enhanced to deal with uncertainties has been part of the body of work in IEA ANNEX 55 Subtask 2. In the next chapter, the developed ideas will be outlined.

2.3.2 Second step – from deterministic to probabilistic assessments

In a perfectly ordered world, information should be available and everything should be done according to a prescribed procedure. This is, of course, not the case in the real world. Figure 2.3 illustrates some of the difficulties we encounter shown as "random variation clouds" or noise. This means, for instance, that we do not precisely know the exact initial conditions, dimensions and geometry in a finalised construction, the ventilation rate in structures and indoors, the coming weather or the actual indoor moisture production. These parameters are all subject to uncertainties.

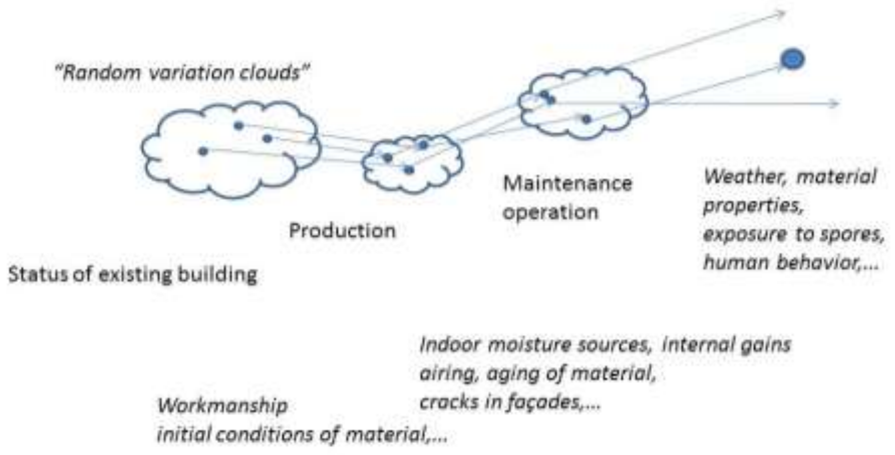


Figure 2.3 Random variation clouds resulting in variability and uncertainties.

All these uncertainties can be expressed with probability distributions. For instance, normal distributions are described by mean values and the standard deviations. Other types of distributions are uniform distributions, and the likelihood to get a certain value for a parameter is the same within a certain interval.

All uncertainties that exist in a retrofitting project propagate into a resulting probability distribution of a certain interest outcome. For example, it could be the energy use in the building or the airtightness. Since we have a large set of uncertain parameters, we can never predict the actual outcome for a certain case.

A special focus of the Annex has been to develop methods for probability risk assessments (PRA) of hygrothermal conditions and hygrothermal-related flows. This is based on the statistically known characterized variables and the known unknowns where the statistical characterization has to be guessed. These variables are used in a hygrothermal simulation or analysis. More information is available in Chapter 3.4.

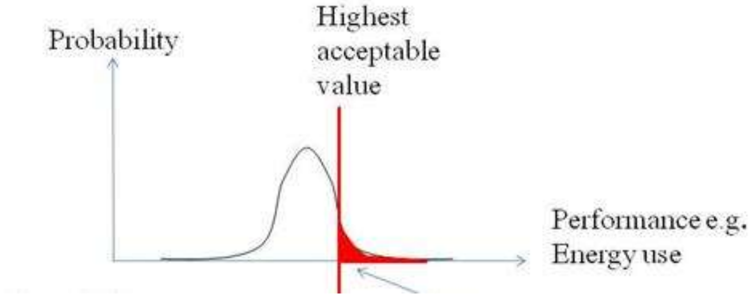


Figure 2.4: This is an example of the final performance probability distribution, e.g. energy use. As illustrated by the figure, the red area below the curve represents the probability that energy use exceeds a certain threshold or highest acceptable value. Since we are using a stochastic analysis, the demand and performances must be phrased in probability terms instead of aiming at a prescribed single value.

Sometimes it is difficult to evaluate the consequential part, i.e. what it costs, and we can instead phrase an issue around failure probability. Figure 2.4 (the previous graph) shows probability density functions for a certain outcome of a certain performance. Instead of aiming in a deterministic fashion at certain specific design values, we can instead look at the probability of exceeding acceptable values.

Figure 2.5 shows a cumulative distribution for lifecycle costing. It indicates that the cost is dramatically increasing for the lesser probability of occurrence when the highest acceptable value is exceeded. For instance, it can mean that if a retrofitting measure results in damage, higher additional costs will be added to the overall lifecycle costs. Thus, the percentage of cases exceeding a certain highest value will result in much higher costs.

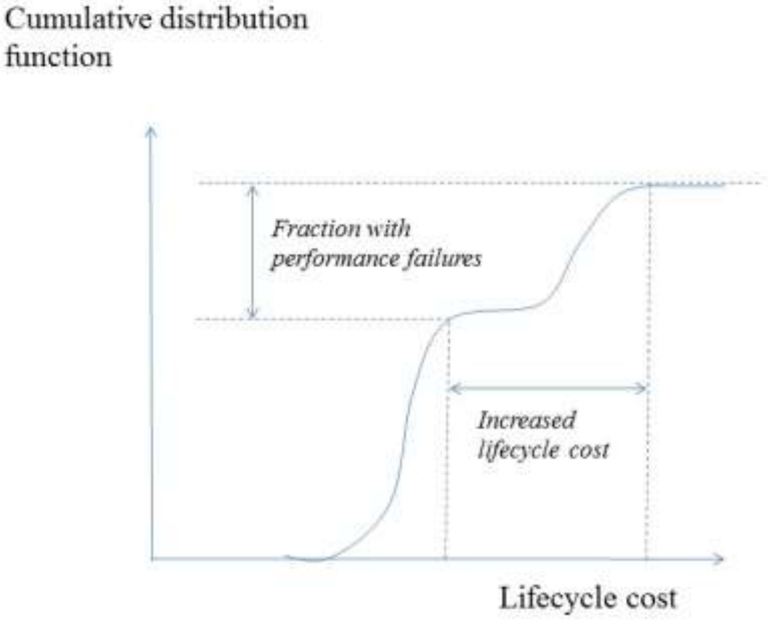
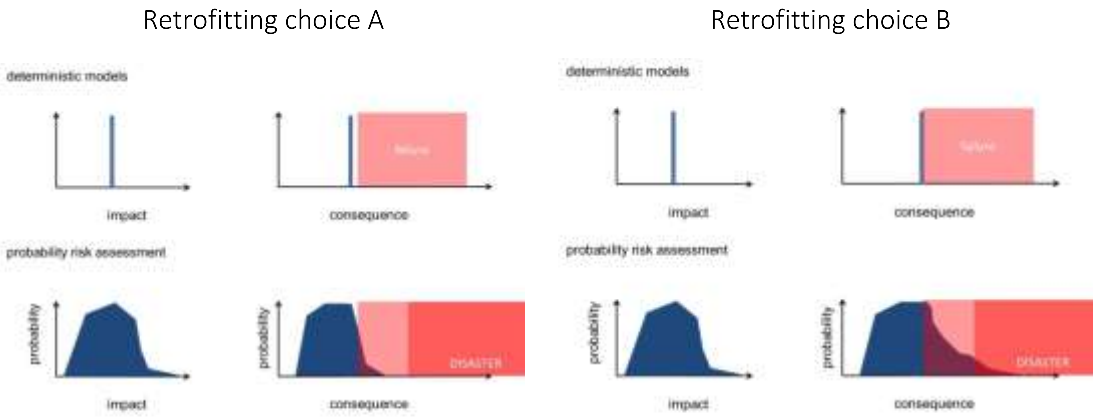


Figure 2.5: The probabilistic analysis gives a range of values and the probability of exceeding certain critical values. If the performance criteria are not met, costly measures are required, leading to unacceptable costs for some of the buildings to be renovated.

The above-described method can be used instead of the current decision methods seeking a cautious solution. Using the same assumptions for the alternative known unknowns solutions, which in the deterministic world are both on the safe side, the two methods can be compared.

As shown in Figure 2.6, using the prescribed approach of the probability risk assessment gives a much better insight into the possibility of falling into an economic disaster.



Retrofitting choice A

Retrofitting choice B

Figure 2.6: Both designs fulfil the performance criteria in a deterministic world (upper row). Using a probability risk assessment the probability of failure is calculated for all possible impacts (red-shaded area in the lower row). In this example, the small change in the deterministic world shows up to lead to a disaster if the uncertainties are accounted for.

2.4 References

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Shahriari, M. (2011). Loss Prevention and Safety - A Practical Risk Management Handbook. Gothenburg, Sweden: Chalmers University of Technology. ISBN/ISSN: 978-91-633-9250-4.

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3 IMPLEMENTATION OF RISK MANAGEMENT IN RETROFITTING PROJECTS

3.1 Risk management during the building process

The building process from planning to management is a complex task which includes a lot of possible risks. In Sweden a method has been developed and published as an industry standard ByggaF to document and communicate moisture safety throughout the whole process (Mjörnell 2012).

It is well known that risk assessment in a renovation project should be done as early as possible. The ongoing flow of decisions should consider risks and opportunities from the beginning.

Uncertainties such as,

- Lack of knowledge about the current state of the building,
- Lack of clear definition of the future building use, and
- Unknown events during construction phase are high in the beginning, but will become more precise during the construction process.

The risk assessment in the beginning will guide decisions during the concept phase in a way that all performance aspects such as costs, durability and energy demand are recognized and not overlooked.

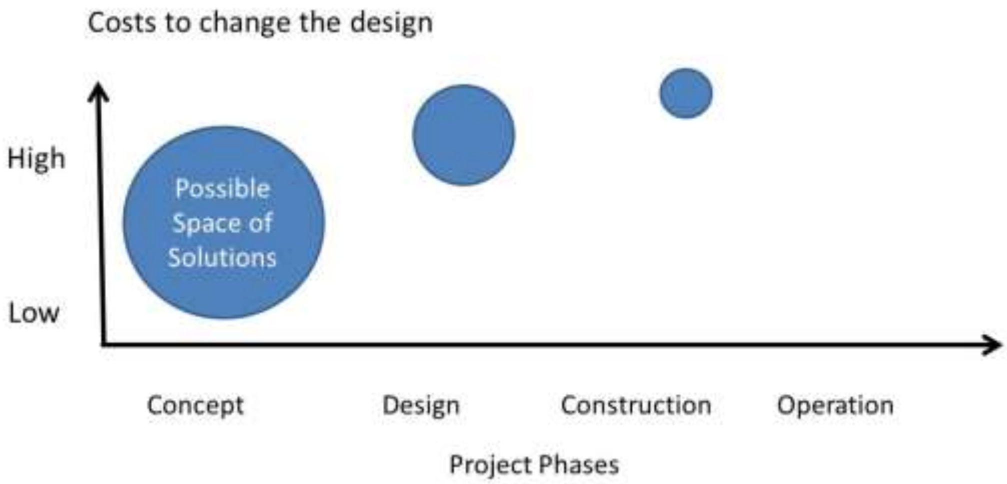

Figure 3.1 The influence of decisions in the early phase of a project has the highest impact on future performance and costs. Risk assessment-based decisions should therefore give guidance from the beginning.

In the beginning, risk assessment is more qualitative. If available, it can be done with guidelines that are produced for common cases. If not only the “GREEN” solutions are possible – the effort needed for deeper analyses can be estimated.

Qualitative methods are typically used during the design phase of the project. At the end of the design phase, the uncertainty in the outcomes has to be quantified.

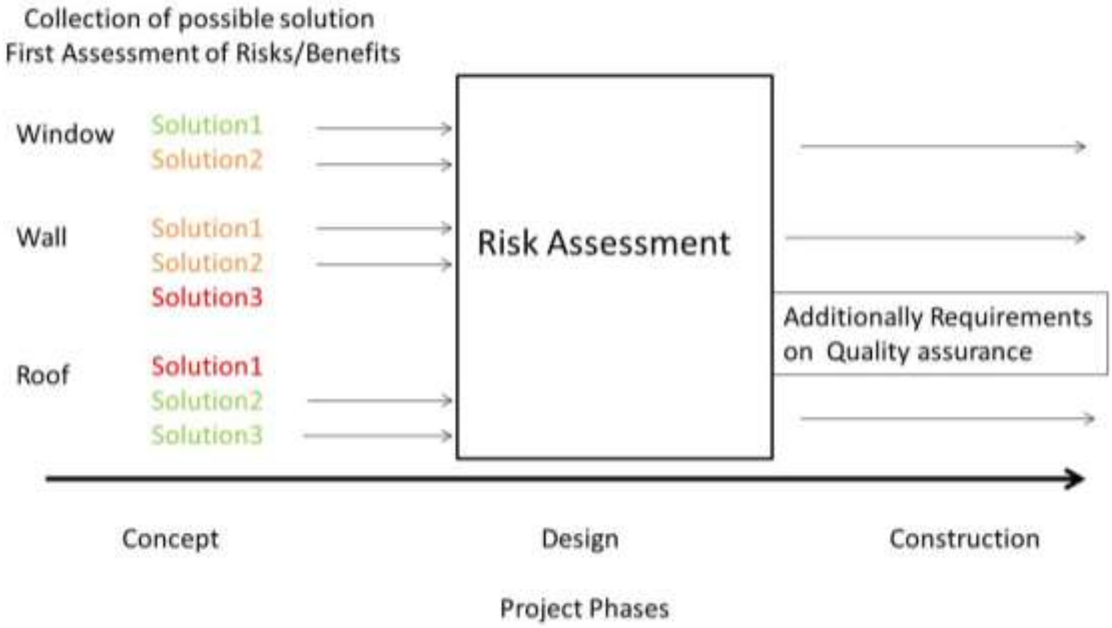

Figure 3.2 Different risk assessment methods are used during the concept and design phases. In the beginning, the possible solutions will be collected and the necessity of deeper analyses is recognized.

For the initial risk assessment, it is important to obtain a clear picture of the performance goals, possible influences and consequences. Different design solutions have to be analysed in a qualitative or quantitative way if possible. Especially for renovation projects, field experience with historical building traditions and quality of workmanship are needed.

The necessary expertise for the risk assessment is discussed in the next chapter.

3.2 Who should be in the team

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

A probabilistic design assessment yields a variety of possible performance results with a most probable outcome and a measure of the uncertainty of the most probable outcome. Understanding the design and the associated uncertainties must be compared to the chosen performance criteria in order to judge whether a design can be deemed adequately reliable for its purpose.

Performance criteria examples of interest in the IEA Annex RAP-RETRO context could be,

- Heat loss (thermal transmittance and U-values) for construction elements or constructions as a whole,
- Lifecycle costs,
- Reasonable and robust values for the relative humidity inside the building envelope, or
- Conditions for mould growth in construction elements and on surfaces.

More can be found in the ST3 Report.

Risk assessment helps to find an optimal solution from the beginning of a renovation project. Depending on the project size and the goals that should be achieved, different competences and knowledge are necessary in the team that works on risk identification and possible mitigation strategies.

Consider the following competences and knowledge within the group:

- Field experience with existing/historic constructions,
- Knowledge about hygrothermal loads including local microclimate and local soil moisture conditions,
- Hygrothermal performance of building components,
- Engineering assessment of reliable constructions,
- Fire safety assessment of individual constructions,
- Cost analyses (construction and operation),
- Architectural aspects, and
- Funding regulations, legislation.

Someone who has the role of the “Devil´s Advocate” is also very helpful as to not to overlook important aspects. Typical questions like the “impact of cheap workers, or cheap materials” would lead to important assessments and conclusions afterwards.

To handle the uncertainties (such as statistically characterized variables or bounded known unknowns) during the quantitative assessment, an expert in stochastic analyses helps to manage the calculation process in an efficient way.

Depending on the complexity of the project, a team of experts could handle the above-mentioned knowledge requirements. Sometimes one person could cover more than one of the necessary competences.

3.3 The framework

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

The framework includes step-by-step instructions for anticipating conditions leading to adverse performance of the building envelope, and to systematically test, evaluate and document these effects. It also clarifies, via examples, the expert methods that can be used when designing a non-standard or a new solution. However, none of the instructions are mandatory and can be revised during the process.

The probabilistic assessment of building envelope performance is a core activity of the framework. Since the calculated probabilities will serve as a basis in the decision-making process, the scope, objectives and limitations of the assessment should be clearly presented in order to provide unambiguous results. The calculated probabilities may also require another format than using the language of mathematics in order to be understood by a larger public. Therefore, there are other activities associated with probabilistic risk assessment that are not directly covered by the framework. Details about data preparation and tools for probabilistic assessments may be found in the “ST1 and ST2” Reports. The “ST3 Report” includes a detailed description of the framework.

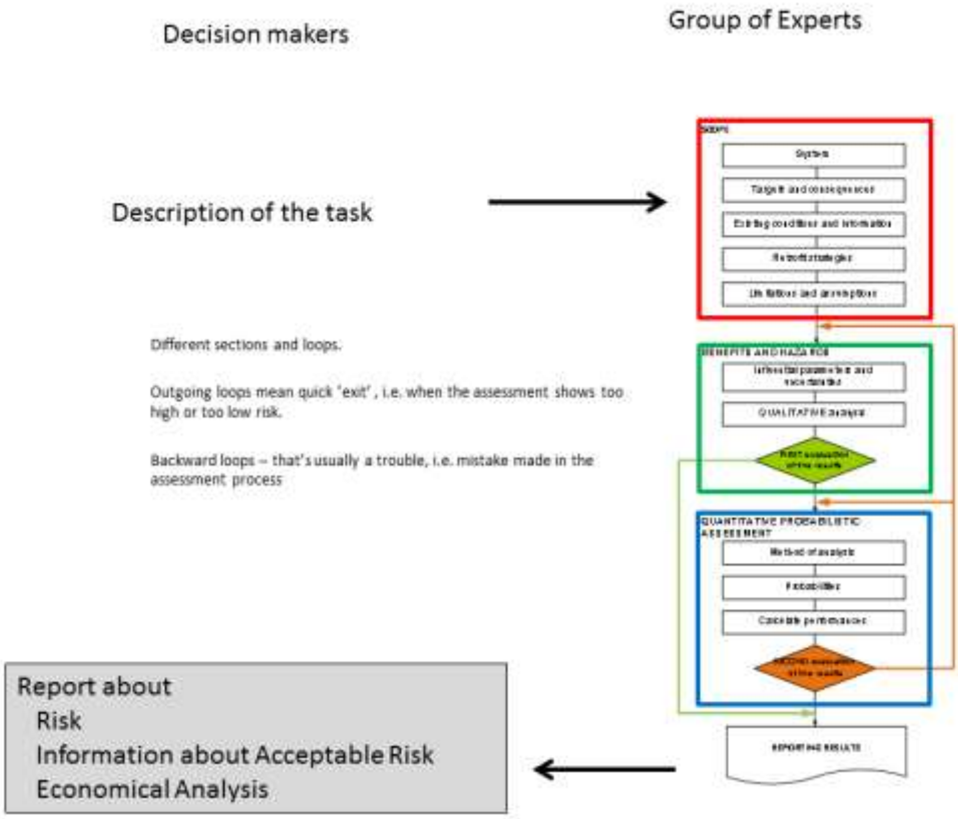

Figure 3.3 The framework for risk management.

The analysis starts with the definition of an analysis, *Scope*, which is organized in several sub-steps. In the *System*, a spatial scale of the analysis can be defined as a whole building, a zone in the building or a building envelope.

In the next step, termed *Targets and Consequences,* the analysis performance criteria are presented along with the consequence prediction when the criteria are not fulfilled. Consequences of not meeting the target values are suitably described as increased project costs referring to operation costs and building maintenance after the retrofit, of improved or degraded safety and well-being of the tenants, gained or lost reputation of the building owner and of the design team, etc. Due to the large variety of aspects included in the retrofit, it is advised to carefully reflect on the motives of choosing a retrofitting strategy in the *Existing conditions and information* phase, and to consider alternative retrofitting strategies. The latter will make room for relative ranking of the results. Finally, *Limitations and assumptions* of the assessment should be clearly declared to avoid erroneous generalization of the assessment results.
A *qualitative performance assessment* is enclosed in the *Benefits and hazards* phase and starts by considering the *Influential parameters and uncertainties*.

A qualitative analysis is basically a process in which a 'pool' of possible influential parameters is narrowed down through consistent evaluation of their significance. The purpose of the qualitative analysis is to sort out conditions or operation scenarios where one or several influential parameters are involved, leading to very high or very low risks of failure in fulfilling the performance goals.

The qualitative analysis can be fully based on available knowledge in the field, which is usually provided in the form of documents and recommendations summarizing practical experiences. If these are not available, logic charts in the form of fault trees or similar, could be used to perform the qualitative assessment.

At the end, a *First evaluation of the Result* is presented, and decisions about the necessity of further analyses are taken. For example, if the qualitative analysis identifies scenarios with high or low risk of leading to the deviations from the specified performance goals, further assessment of the exact value of these risks is not necessary, and the assessment can be ended by reporting the results. However, the scenarios with 'some risks' can be considered for quantitative analyses.

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

Finally, the total result of the assessment is evaluated (the second evaluation of the results), the reliability is checked, and all efforts are *Reported*. The risk of consequences is compared with the performance indicators and the predefined concerns. Discussions and recommendations for further analyses are made and suggestions are given about possible redirection alternatives. Ultimately, a decision is made about risk acceptability.

3.4 Proposed probabilistic methods

Today, advanced validated simulation methods are available for simulating the hygrothermal building conditions as well as indoor climate and building energy use. They are based on deterministic analysis and mimic the physical processes in building materials, components and systems. This means that the simulations predict the conditions in the structure second by second based on the surrounding driving climatic conditions. These deterministic models can also be used for probabilistic evaluation. The ST2 Report discusses and evaluates various probabilistic methods, such as sensitivity analysis and the Monte Carlo method. The latter has been found to be a very appropriate method in building physics.

Monte Carlo methods consist of sampling input variables according to their probabilistic characteristics and feeding them into the calculation tool to predict the corresponding output parameters as seen in Figure 3.4. A response sample is obtained in this way. The quality of the outcome is dependent upon the number of simulations performed, and the sampling scheme used.

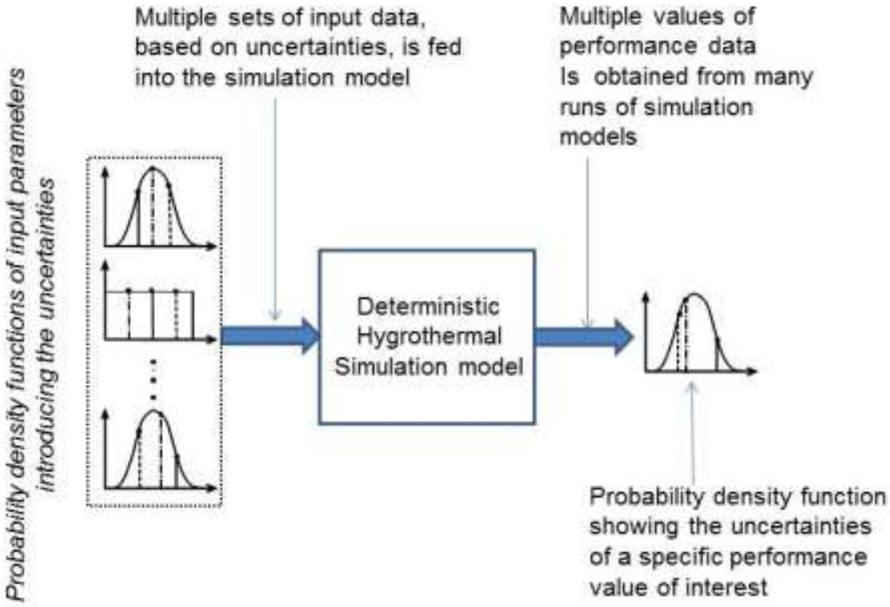

Figure 3.4 Multiple runs of the simulation model, based on input data sets generated from their probability functions, create the corresponding density function of a particular performance value of interest. The uncertainties of the input data propagate into uncertainties of the output value generated by the simulation model.

The main advantage of the Monte-Carlo method is that the method can be applied to all kinds of problems using both static and dynamic simulation models, and for all kind of probabilistic variables.

A simple static example could be represented by the U-value calculation of a layered wall. The thermal conductivities of the various materials together with the actual thicknesses determine the U-value. A corresponding distribution can be found for the U-value of the whole wall starting with the thermal conductivity probability distribution of the different materials.

For dynamic, time-dependent problems, the process is a bit more time consuming.

Example – Mould growth risk in a cold attic

The Monte Carlo method has been used to calculate the maximum mould index for multiple randomly chosen and simulated whole years. One of 30 Swedish weather data years (1961- 1990) with hourly values was selected randomly for each simulation. The attic is assumed to be damaged by mould growth if the Mould Index (MI) according to Hukka and Viitanen (1999) exceeds 1 (no growth, spores not activated).

Figure 3.5 shows a number of simulation results. In the simulations, the cold attic starts with dry conditions in the middle of the summer. The risk assessment is based on the fraction of simulations resulting in a mould growth index exceeding one. In this example, 17 of a total of 128 simulations results in a failure, i.e. the risk for mould growth is 13%.

SimpleColdAttic is a stand-alone software for HAM-simulations of cold attic temperatures, relative humidity and mould growth index. The program, which is a spin-off from the Annex, can simulate both in deterministic as well as in probabilistic (random) modes. The Monte Carlo-based simulations shown can be performed using the program. The program is based on a simplified HAM-model for an attic; the theory can be found in (Hagentoft, 2011) and (Hagentoft and Sasic, 2011,2012,2014).

The free software can be downloaded from:
http://www.byggnadsteknologi.se/downloads.html.

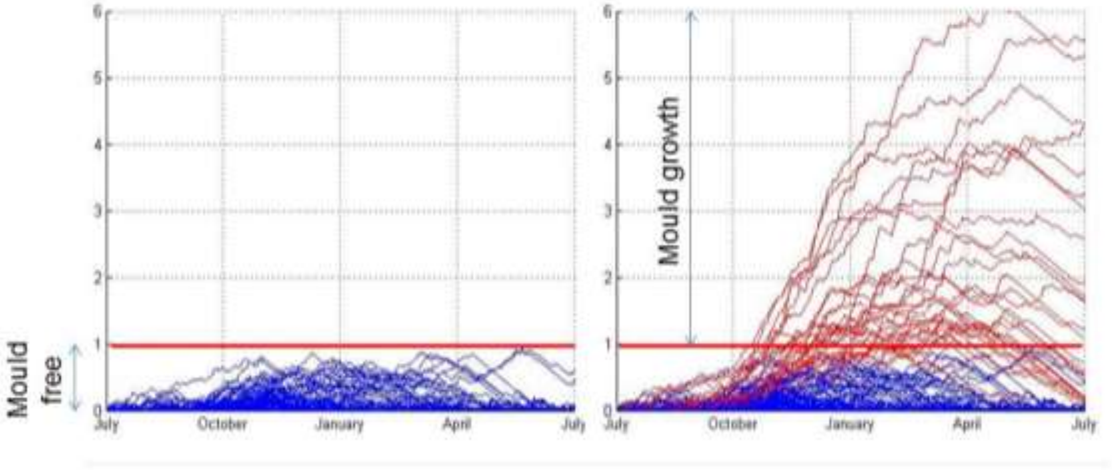

Figure 3.5 An example of simulation results for randomly chosen years and input parameters is shown. The figure to the left represents the damage-free simulations and the additional ones in the right figure represent cases with mould growth.

3.5 Building-up knowledge

It is important to follow-up using the prescribed documentation in the framework and experiences during construction to create awareness in the future using the analyzed retrofitting technologies. This makes it possible to enhance the learning culture in the involved expert groups and organizations.

Example – flat timber roofs

Flat timber roofs are very common for large shopping centers or production plants. The framework from Annex 55 can be used to assess which construction is the best solution for a small residential building with a very high airtightness and without a ventilation system. The team of experts helping the company to make decisions may ask additional questions about nearby lakes (local microclimate effects) and possible roof shading. They will include the current company practice to realize airtight construction. The result of the assessment is presented in *Figure 3.6*.

In addition to the specific situation assessment, the team of experts can identify the most important uncertainties. The most influential parameters in the current example are the shading of the roof, the achievable airtightness of the construction and the amount of excessive indoor moisture.

In Chapter 4, how to make guidelines for upcoming projects with similar preconditions is shown. The risk assessments used in the example for timber flat roofs led to the development of a guideline for *“Reliable Wooden Flat Roofs”.*

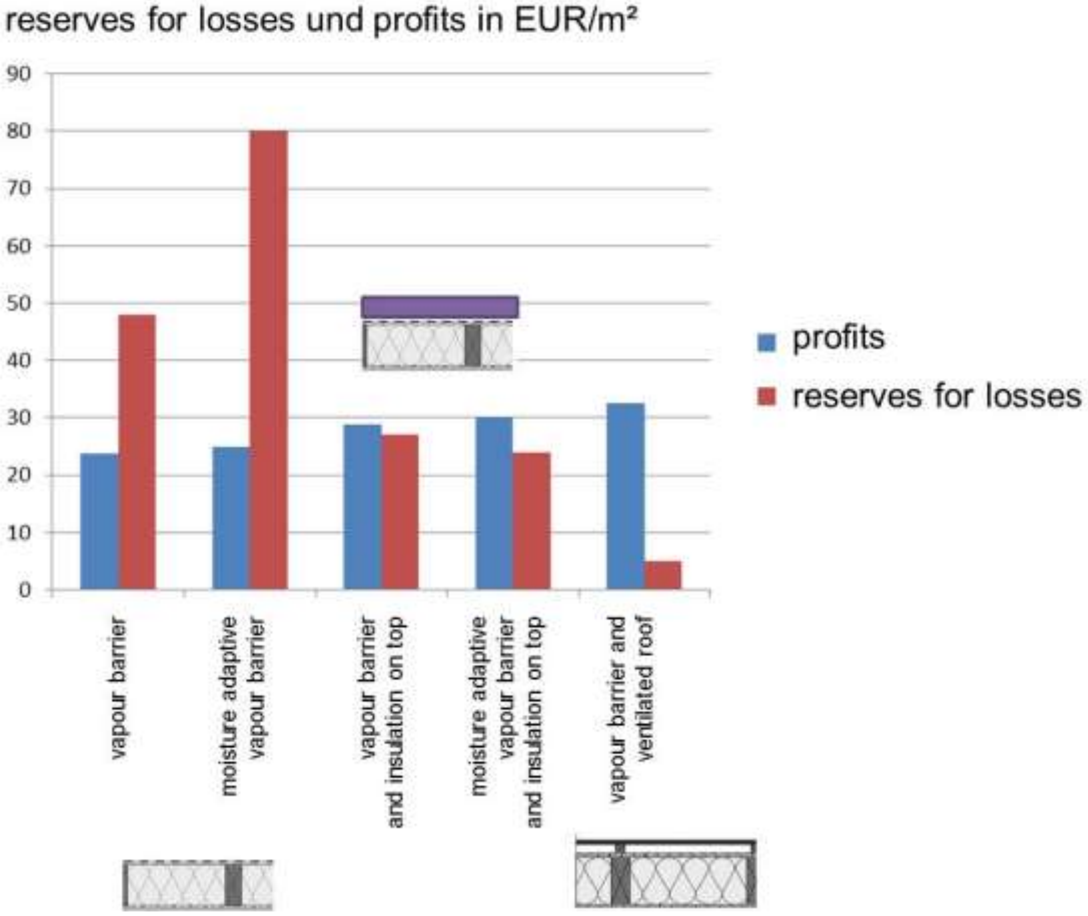

Figure 3.6: Profits and loss reserves for different flat roofs for a specific situation (Harreither et al. 2012). The reserves include the possible impact of the uncertainties for a specific residential building, and the quality of workmanship of a specific company. All solutions would fulfil the performance criteria for "normal" operation. The probability risk assessment used to calculate the lifecycle costs helps to identify robust solutions.

3.6 References

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4 DEVELOPMENT OF PRACTICE GUIDELINES

4.1 How to use the ANNEX 55 framework

By using the framework from Chapter 3, it is possible to develop general guidelines for typical decisions, which can speed up the process and at the same time raise awareness for the associated risks.

In an early phase of a construction project, it is important to quickly collect information about possible solutions and associated risks. As many renovation projects in a certain climate region are dealing with similar constructions, the development of guidelines indicating risks associated with a certain type of construction is very helpful.

Of course, it is only possible to develop general guidelines if there are enough common aspects like historic building construction, local outdoor climate and ventilation strategy and use.

Such a guideline typically rates solutions according to risk. It could also provide information about benefits like energy savings or additional information about technical parameters of a certain solution.

The development of such a guideline for common cases needs a task force of experts (technical and economic) with necessary knowledge as described in the previous chapters. Additionally, they have to decide upon a simplified general economic performance assessment, as there is no specific company involved. Typically market studies about costs are part of that work.

4.2 Typical guideline contents

A guideline has to give a minimum amount of information about the cases and scenarios it has been developed for to be useful.

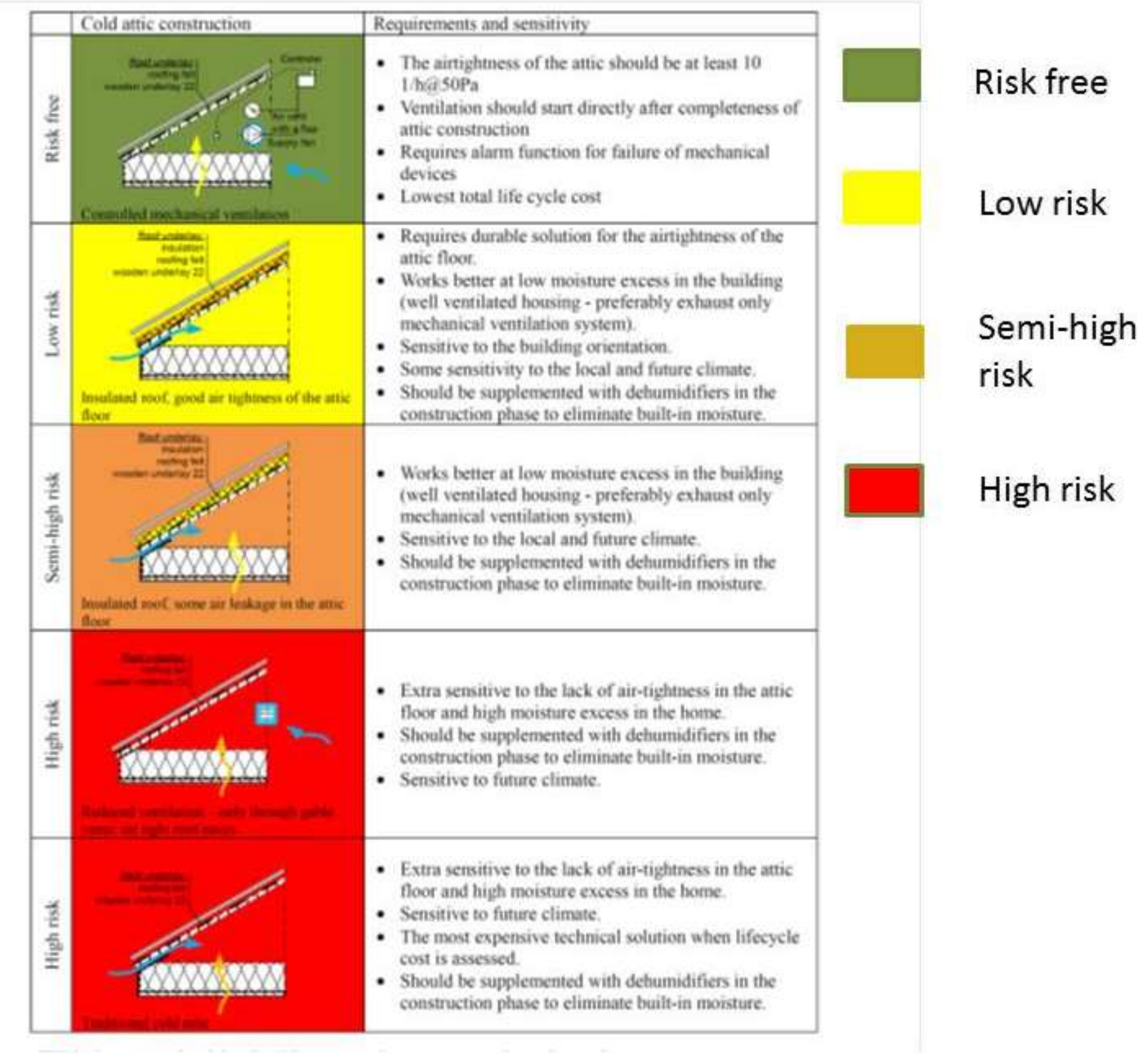
The typical contents are:

- Building type
- Construction type
- Local climate region
  - Future climate scenarios
- Building use
- What are the assumptions / limitations of the guidelines?
  - Quality of workmanship
  - Quality assurance on the building site
  - Hygrothermal load (e.g. indoor moisture supply, solar radiation, etc.)
- Applicability
  - Could be a decision tree if the guideline is applicable to the decision.
- For each investigated building component,
  - A technical description,
  - The impact on other performance parameters (energy, architecture, and fire safety to name a few),
- Criteria for the “Colour”-Scale, and
- an assessment of constructions.

4.3 Guideline Examples

Guideline for "Cold Attics in Sweden"

Problems with high humidity levels in cold attics have been remarkably increasing in Sweden over the last decade. Besides clear evidence – significant mould growth on the wooden parts of cold attics, which is recently confirmed in about 60-80 % single-family houses in Västra Götaland region (largely, the Gothenburg region), mould odours in indoor air seem to be one of the most frequent side effects. A risk assessment-based guideline has been developed to give guidance to companies. The risk assessment included mould growth and lifecycle costs. The results are presented with a colour scale to indicate the risk level and a summary of the requirements and sensitivities.



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

🟩 Risk free

🟨 Low risk

🟧 Semi-high risk

🟥 High risk

Figure 4.1 Summarized risk levels of the various designs presented together with some requirements (Hagentoft et.al. 2014).

Guideline for "reliable wooden flat roofs"

To help designers and contractors choose the best roof for a certain building situation, risk assessment-based guidelines have been developed in Austria. The risk assessment took into account different levels of workmanship, exterior situations (shading, green roof, etc.), indoor climates and workmanship. The first approach resulted in a decision tree that helps to find a reliable construction for a specific case (Nusser; 2012). Furthermore, an overall assessment for residential buildings helps to identify the risks already in an early design stage.

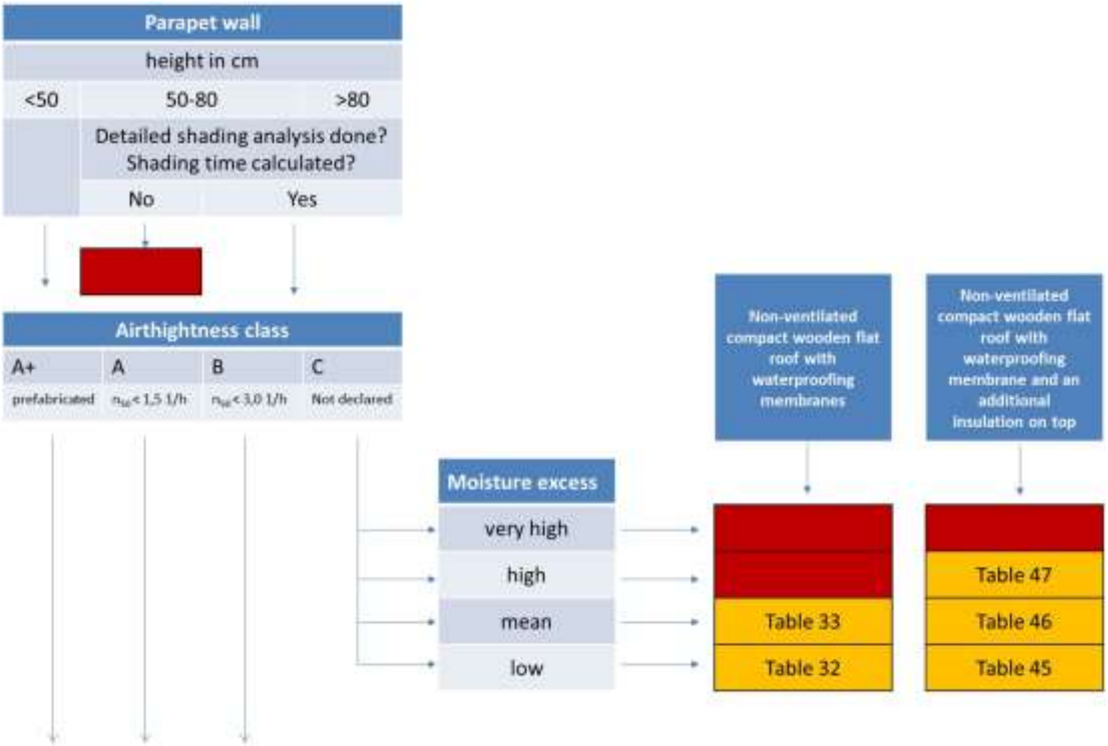


Figure 4.2 Part of the decision tree looking for low risk constructions (Nusser 2012, Teibinger et.al. 2014, translated from German to English).

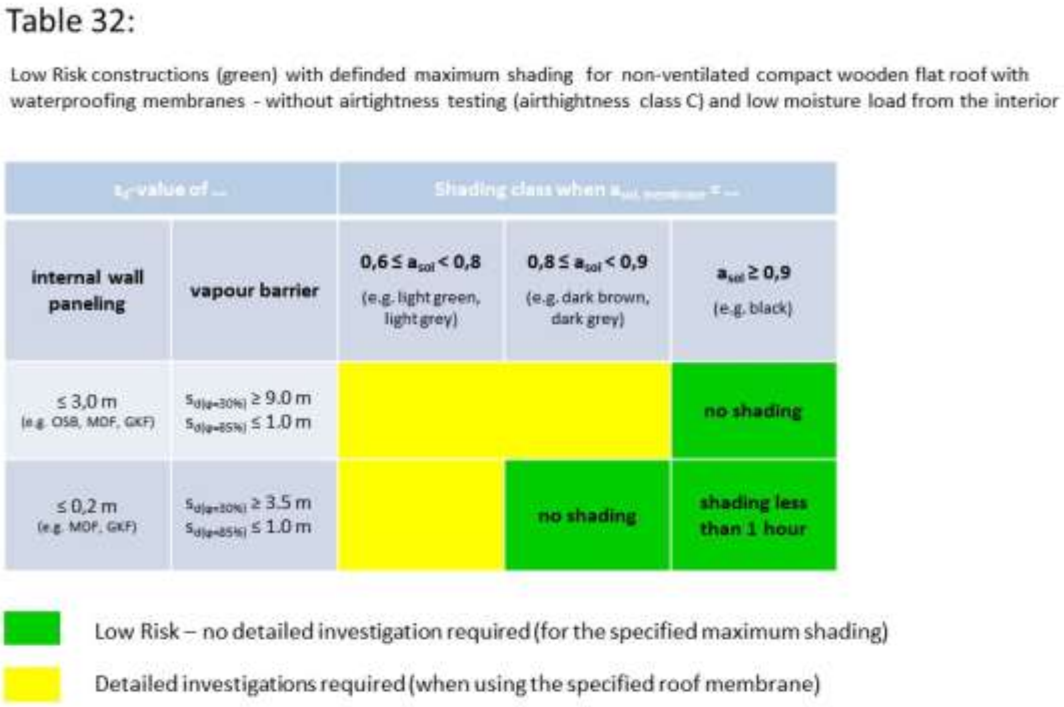


Table 32:

Low Risk constructions (green) with definded maximum shading for non-ventilated compact wooden flat roof with waterproofing membranes - without airtightness testing (airthightness class C) and low moisture load from the interior

s_d-value of ...		Shading class when $a_{sol,membrane}$ = ...		
internal wall paneling	**vapour barrier**	**$0,6 \leq a_{sol} < 0,8$** (e.g. light green, light grey)	**$0,8 \leq a_{sol} < 0,9$** (e.g. dark brown, dark grey)	**$a_{sol} \geq 0,9$** (e.g. black)
$\leq 3,0$ m (e.g. OSB, MDF, GKF)	$s_{d(\varphi=30\%)} \geq 9.0$ m $s_{d(\varphi=85\%)} \leq 1.0$ m	🟨		🟩 **no shading**
$\leq 0,2$ m (e.g. MDF, GKF)	$s_{d(\varphi=30\%)} \geq 3.5$ m $s_{d(\varphi=85\%)} \leq 1.0$ m	🟨	🟩 **no shading**	🟩 **shading less than 1 hour**

🟩 Low Risk – no detailed investigation required (for the specified maximum shading)

🟨 Detailed investigations required (when using the specified roof membrane)

Figure 4.3 Decision tree to find a reliable construction for a specific case (left; Nusser 2012), and recommended flat roof constructions for residential buildings (right; Teibinger et.al. 2014). The colour code indicates the associated risk. The recommendation depends on the shading of the roof membrane. A green roof or a roof covered with gravel is similar to a fully shaded roof.

4.4 References

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