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Abstract:

This report is one of five deliverables related to WP6 'Development and evaluation of guidelines and web-based preliminary assessment tool'. The prime objective of WP6 is to develop and to assess written and web-based guidelines and a web tool (including a feasibility study of possible input and output data) for renovation of historic buildings with internal insulation. This deliverable contains the written guidelines, referring to Task 6.1, consisting of a guideline for setting the goal of applying internal insulation (Section 3), a guideline for deciding whether a building is suitable for internal insulation (Section 4), a guideline for selecting an internal insulation system (Section 5) and a guideline for evaluating the energy saving potential and the environmental impact (Section 6). The written guidelines are also made accessible through a web-site, described in deliverable D6.3.

Keyword list: guidelines, decision making, visual assessment, insulation systems, energy saving potential

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Abbreviations

BYG-ERFA	Danish foundation that disseminates knowledge about constructional conditions with the aim to improve quality of the built environment, mainly done through experience sheets based on constructional problems, and how to avoid these. www.byg-erfa.dk
CM	Calcium carbide method
CML	Critical Moisture Level
D	Deliverable
EPBD	Energy Performance of Building Directive
GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
HAM	(coupled) Heat, Air and Moisture (transfer)
HDD	Heating Degree Days
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MCDM	Multi Criteria Decision Making
PDF	Probability Density Function
PPD	Percentage Person Dissatisfied
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
WAM	Water Absorption measuring instrument
WDR	Wind Driven Rain (load)
WP	Work Package
WTA	Wissenschaftlich-Technische Arbeitsgemenschaft für Bauwekserhalting und Denkmalpflege e.V. (International Association for Science and Technology of Building Maintennace and Monuments Preservation) www.wta.de

1 Executive Summary

This report presents one of five deliverables related to RIBuild's WP6 *'Development and evaluation of guidelines and web-based preliminary assessment tool'*. The overall goal of RIBuild WP6 is to develop and assess written and web-based guidelines and a web tool for renovation of historic building with internal insulation, and consists of three tasks: Task 6.1 about development of written guidelines and a web tool, Task 6.2 about designing a web-site hosting the written guidelines and the web tool, and Task 6.3 evaluating and assessing all three elements. Task 6.1 is reported in D6.1 (web tool, including a feasibility study of possible input and output data), D6.2 (written guidelines, the present report), and D6.5 (simulations), Task 6.2 is reported in D6.3 and Task 6.3 in D6.4.

Compared to external insulation solutions, the implementation of internal insulation is technically more complex and faces several moisture associated risks, such as mould growth, interstitial condensation, freeze-thaw damage, etc. At present, building owners and practitioners are short of knowledge on application of internal insulation. To fill this gap, this deliverable presents written guidelines for internal insulation as part of Task 6.1, linking to the overall goal of RIBuild to develop decision guidelines on how to safely apply internal thermal insulation in historic buildings across EU with solid walls made of brick or natural stone, while maintaining their architectural and cultural heritage.

The written guidelines integrates findings from all the technical work packages (WPs), including the size of the building stock and the composition of external walls in historic buildings (WP1), material properties, test methods and failure modes (WP2), experience from case studies (WP3), hygrothermal modelling (WP4), and life cycle assessment (WP5). The written guidelines contains information at different levels as it is supposed to be read by building owners, building professionals researchers, reflecting different levels of expertise and assumed knowledge. At the website, the user can get access to more detailed information at each section by clicking a 'Read more'-button.

The written guidelines consist of the following four parts:

First, the application of internal insulation starts with **setting the goal(s) and relevant criteria** that describes the goal(s). For example, the goal(s) can be set to reduce energy consumption, to minimize costs, to improve indoor climate, to mitigate environmental impacts, etc. When multiple goals are set, it becomes more complex as criteria may either complement or conflict with each other. Meanwhile, the renovation should comply with the building regulations, district plans and restrictions where national or local authorities have to be consulted. Also, the goals have to be reached without compromising hygrothermal performance and the impact on the heritage value of the building. The first guideline (Section 3) provides principles on how to set the goal and choose the relevant decision criteria, using the multi-criteria decision making (MCDM) method 'TOPSIS' (Technique for Order Preference by Similarity to Ideal Solution).

Second, a prerequisite basis for the application of internal insulation is to **determine whether a building is suitable for internal insulation** at all, as the actual states of buildings vary largely for each specific case. Before implementing any thermal insulation measure, a (visual) assessment must be carried out to ensure its feasibility and evaluate the potential occurrence of various risks before/after the renovation. The assessment includes the actual state of the building envelope, documentation of the wall conditions, identification of damages and associated risks, the driving rain load, the indoor climate, the renovation history of the building, the knowledge of material properties of the building structure etc. The second guideline (Section 4) details the procedure on how to collect such information and measurement methods for required parameters, to determine whether a building is suitable for internal insulation. This guideline also specifies conditions when internal insulation should be avoided or could only be installed if certain remedial actions are taken.

Third, various types of internal insulation systems and products are available on the market. They differ in terms of material properties, installation method, energy saving potential, environmental impact and costs. To **select the proper insulation solution in a specific case**, it is important to take into account these aspects as well as the possible occurrence of moisture-related problems, such as frost damage, interstitial condensation, mould growth that may occur when an internal insulation system is applied. For this purpose, the third guideline (Section 5) provides knowledge on how to select a proper insulation system for internal insulation. Further, it details calculation methods and simulation tools available for assessing the impact of heat and moisture processes when applying internal insulation material/system, including the Glaser model, DELPHIN, WUFI, and MATCH.

Selecting an optimal internal insulation solution should not only be limited to the evaluation of the energy saving potential and the moisture associated risks, but also take into account sustainability from a life-cycle perspective. The **fourth guideline** (Section 6) **provides support for stakeholders to evaluate the environmental impact and costs** upon the hygrothermally optimized insulation solutions. The developed methodology couples the model of heat transmission losses with the probabilistic life cycle assessment (LCA) and life cycle cost (LCC). The RIBuild WP5 tool enables an efficient assessment for different internal insulation solutions in terms of energy saving potential, probabilistic hygrothermal performance, LCA and LCC analysis (RIBuild Deliverable D5.1, 2017), (RIBuild Deliverable D5.2, 2018).

As an **introduction to the guidelines**, Section 2, summarizes the energy saving potential related to applying internal insulation in historic buildings, and thereby the impact on the CO_2 emission, disregarding the risks related to this energy saving measure.

Reading instructions

For each section and sub-section, the text is structured so that the further the reader goes into the text, the more complex the content. This is done to let readers with different level of expertise read the same report. No predefined marking is used to indicate when the text becomes more complex, as it will be different from person to person when a text is no longer understandable, also within a group of people with the same (professional) background.

2 Introduction – potential impact of applying internal insulation in the European historic building stock

The building sector is the single largest energy consumer, and responsible for approximately 42% of energy consumption, 35-40% of CO_2 emissions, 20% of all waste and 40% of all materials used in Europe (Grytli et al., 2012). It is estimated that 30% of the buildings in Europe are historic, i.e. more than 70 years old (RIBuild Deliverable D1.1, 2015), (European Commission, 2010), Additionally, 40 % of the buildings are more than 60 years old and 50 % are more than 50 years old (Buildings Performance Institute Europe, 2011) (Birchall et al., 2014). Almost 75% of the building stock is energy inefficient and only 0.4-1.2% is renovated each year (EU Commission, 2019). Most of the existing buildings have high energy consumption and the level of thermal insulation is significantly lower than in new buildings. Thermal insulation of existing buildings thus has a significant potential to reduce energy consumption to meet the EU2020 climate and energy goals.

Figure 2–1 illustrates the percentage of the historic building stock (including both residential and non-residential buildings) in terms of the total building stock area and the total building stock number respectively, ranging from 24 % in Switzerland to 35 % in Denmark in terms of total area data, and from 27 % in Sweden to 38 % in Belgium in terms of total numbers (RIBuild Deliverable D1.1, 2015). For Germany, data for number of buildings is available only for the residential building stock.

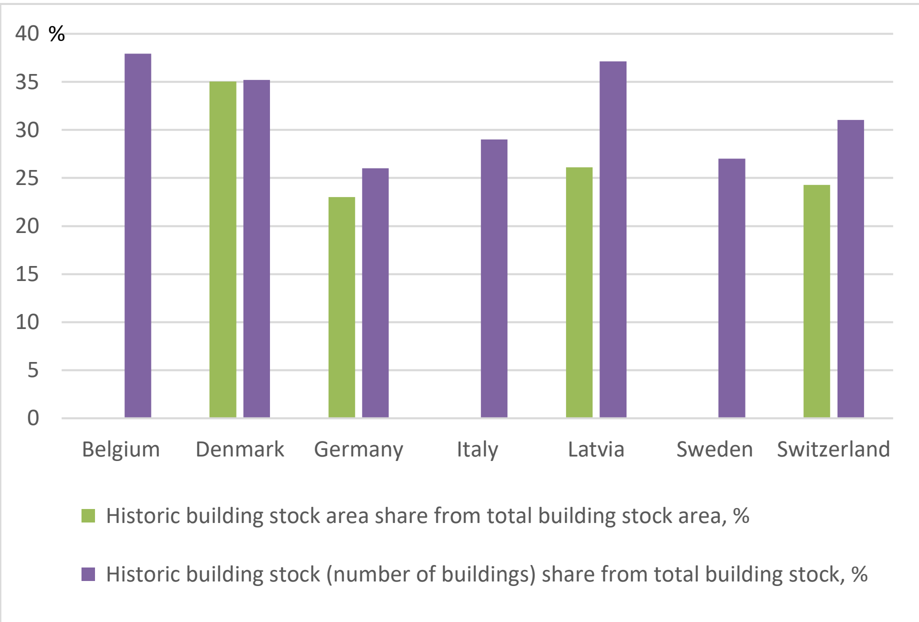


Figure 2–1. Percentage of historic building stock (including both residential and non-residential buildings) in terms of total building stock area (m^2) and total building stock (number of buildings) in RIBuild countries. Number of buildings: For Germany, only residential buildings are included.

None of the RIBuild member countries has data available on heating energy consumption in historic building stock. Hence energy consumption is calculated based on data collected from literature. The historic building stock consumes a substantial part of the total energy consumption for heating in buildings, as illustrated in Figure 2–2, from 27 % in Switzerland to 49 % in Germany in terms of historic total building stock, and from 18 % in Switzerland to 44 % in Germany in terms of historic residential buildings only. Data for Belgium and Sweden includes energy consumption both for space heating and hot water. German data for historic buildings covers buildings until 1979. This explains why the energy use for the historic building stock is highest in Germany. Specific heat energy consumption cannot be compared as data available in literature sources are measured in different units, e.g. in Belgium per household or dwelling, and in Latvia, Denmark, Italy, Switzerland per heated floor area.

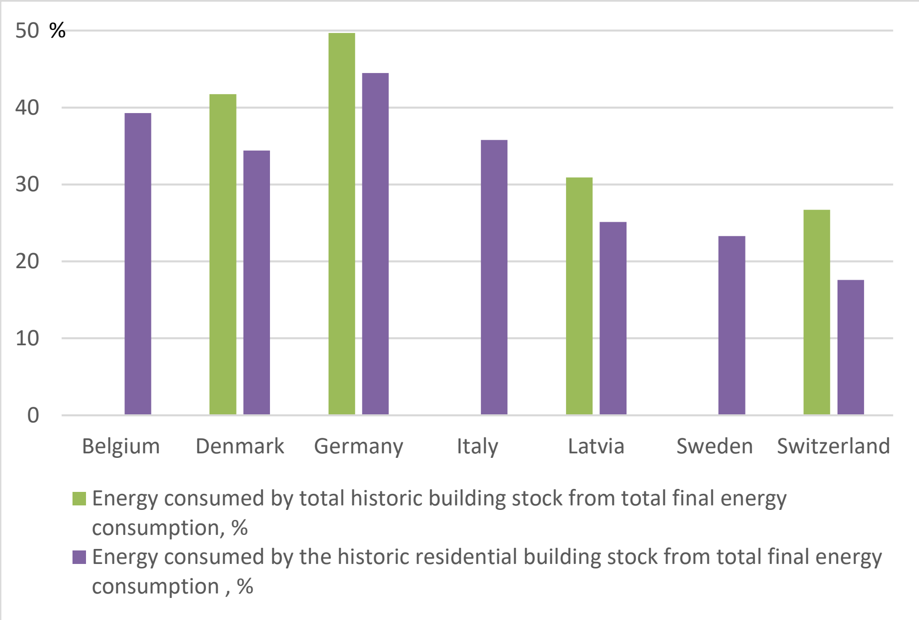


Figure 2–2. Percentage of energy consumed for space heating in the historic total building stock and historic residential building stock of total final energy consumption per country within RIBuild. For Belgium and Sweden energy consumption includes both space heating and hot water. For Germany buildings, data for historic buildings includes buildings until 1979, and data for energy use in non-residential buildings is estimated.

Climate conditions can affect heating energy consumption in historic buildings. This is illustrated by heating degree days (HDD) in Figure 2–3, where RIBuild partners represent countries with different climates. Sweden and Latvia are located in northern part of Europe and have the highest number of heating degree days. Belgium, Germany, Denmark and Switzerland are in milder climate with an average of 3200 heating degree days. Italy has the warmest climate and the least heating degree days.

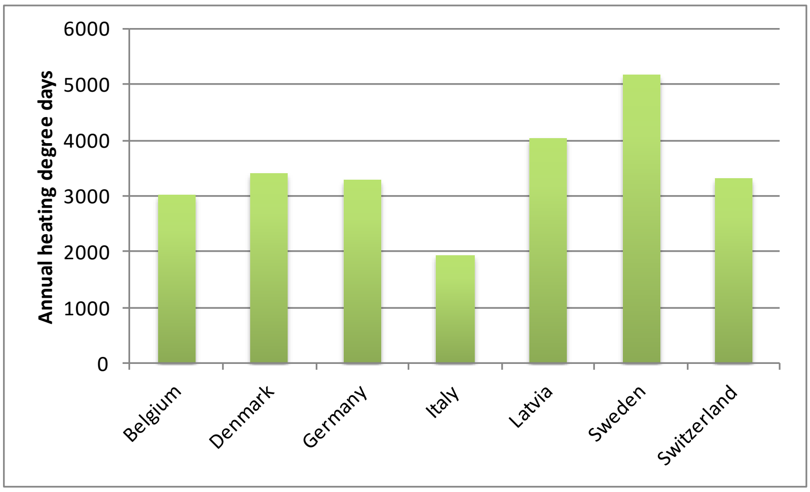


Figure 2–3. Average annual heating degree days in countries within RIBuild.(EUROSTAT, 2015)

Case studies identified in RIBuild Task 5.1 on energy saving potential (part of WP5) within RIBuild show that application of internal insulation of the building's façades can potentially reduce the energy need for space heating by 9 to 43 % compared to the energy demand of the original building (de Place Hansen & Wittchen, 2018). For the overall building stock the energy saving potential will of course be lower as the historic building stock makes up about 30 % of the total building stock, and the figure will also be dependent on how large a share of historic buildings that may become internally insulated.

This is illustrated in **Table 2-1**, also showing the energy saving potential in the historic building stock ignoring that historic buildings makes up only a fraction of the total building stock (right column). Assuming that in the near future different targets for energy saving would be posed on different groups of the building stock (e.g. dependent on their age), including not only historic buildings, such numbers would be relevant as well. It also shows that a rather large share of historic buildings need to be internally insulated to make this renovation measure a sizeable contribution to the overall reduction of energy use and CO_2-emission from the European building stock.

Table 2-1: Potential energy savings in historic buildings and buildings in general when applying internal insulation at external walls.

Percentage of historic buildings that become internally insulated at external walls	Potential energy savings in *historic* building stock by applying internal insulation in relation to the *total* building stock	Potential energy savings in *historic* building stock by applying internal insulation in relation to the total *historic* building stock
25 %	0.7 - 3.2 %	2.3 – 10.8 %
50 %	1.4 - 6.6 %	4.5 – 22 %
75 %	2 – 9.7 %	6.8 – 32 %

Guideline for setting the goal of application of internal insulation

3 Guideline for setting the goal of application of internal insulation

3.1 Decision making process

The main goal of this guideline is to provide information for building owners and consultants to set the goal for application of internal insulation and relevant criteria that describe the goal.

Deciding whether and how to implement energy efficiency in historic buildings is a complex process since it involves different technical solutions, heritage value, indoor environment, cost efficiency, interests of stakeholders etc.

Application of internal insulation is a manifold process since it is composed of many variables that can be either independent or interlinked. These are hygrothermal properties of existing and applied building materials, indoor and outdoor climate, energy costs, operation and maintenance costs, human behaviour, occupation loads, mechanical and engineering systems in the building, environmental impact, heritage value, financial resources and their availability, location of the building, building regulations, productivity etc. Decisions about retrofit measures are made based on the goal that has to be reached. The goal can be described by a single criterion or a set of different criteria that are important to the building owner.

The decision making process should be seen as an iterative and circular process, as illustrated in

Figure 3–1. The definition of the main goal and decision criteria for process assessment, definition of alternative solutions, estimation of performance, evaluation, and solutions and proposals are strongly interlinked.

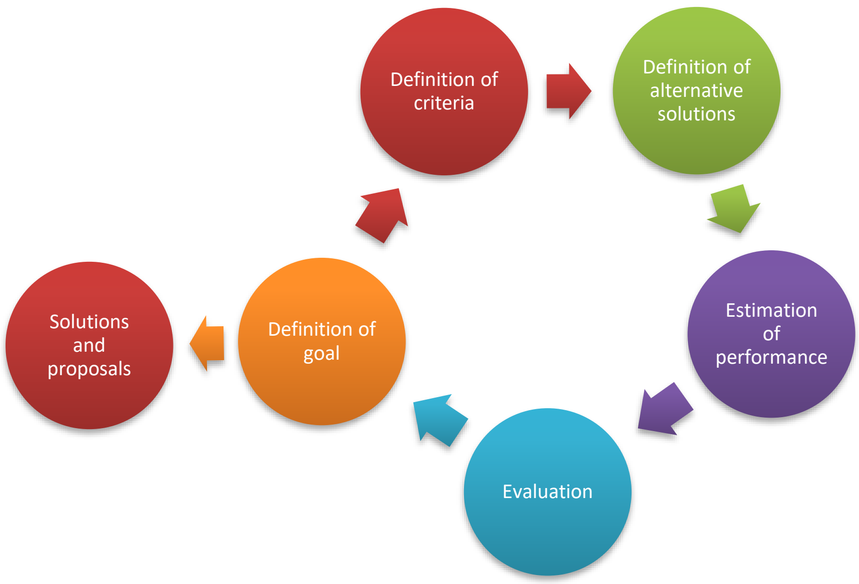


Figure 3–1: Decision making process during planning phase (adapted from (Allane, 2004)*)*

A decision making process starts with setting the goal(s). It can be either a single goal like reducing energy consumption or several parallel goals, e.g. reduction of energy costs and reduction of environmental impact. Each goal can be described with one or more criteria.

Work on historic buildings might be challenging in regards to both applicability and unacceptable hygrothermal risks as a consequence of applying internal insulation. Application of internal insulation in historic buildings can be carried out based on several goals: energy consumption reduction or energy savings, purely economic goals, indoor climate improvement, loss of floor space and reduction of environmental impact as illustrated in Figure 3–2 and further described in Section 3.2 - 3.6.

These goals have to be reached without compromising hygrothermal behaviour of existing wall (for more details, see Section 4) and heritage value.

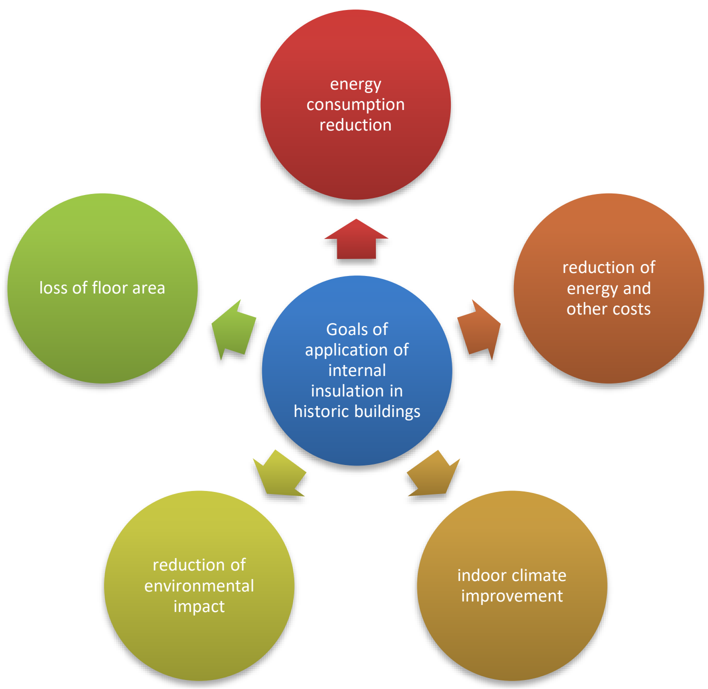


Figure 3–2: Classification of goals for internal insulation in historic buildings used in the RIBuild guidelines and web tool.

European standard EN 16883:2017 *Conservation of cultural heritage. Guidelines for improving the energy performance of historic buildings* (EN 16683, 2017) provides a holistic approach to energy efficiency in historic buildings. The standard is a guideline on how to sustainably improve the energy performance of historic buildings, and it presents a normative working procedure for selecting measures to improve energy performance, based on investigations, analysis and documentation of the building, including its heritage significance. EN 16883:2017 has a much broader scope than RIBuild as it is not limited to specific measures targeted at specific building components but looks into all kind of renovation of historic buildings, aimed at improving the energy performance. EN 16883 includes a list of assessment categories that are relevant when downsizing the number of potential measures:

- Technical compatibility
- Heritage significance of the building and its settings

- Economic viability
- Energy performance
- Indoor environmental quality
- Impact on the outdoor environment
- Aspects of use.

3.2 Reduction of energy consumption

This goal is to minimize building's operational energy consumption, expressed as energy spent for either heating, ventilating or cooling the building regardless the energy source. RIBuild web tool uses heat loss[1] (W/m^2 year) for the uninsulated case and after applying a specific insulation system and thickness, as the criteria for energy consumption reduction goal.

Example:

The owner of a historic building has collected data about specific heating energy consumption during the last three years and the average consumption is 150 kWh/m^2/year. This number is very high compared to requirements for new buildings. The owner sets the goal to reduce energy consumption by at least 25% without risks caused by changes in hygrothermal behaviour of the wall and without impact on the heritage value of the building.

Other energy use criteria can be

- U-value of wall ($W/(m^2K)$) (used in the RIBuild web tool)
- heating and cooling load for conditioned buildings (kWh/year; MWh/year) (not used)
- normalized specific energy consumption for heating and cooling (kWh/m^2/year; MWh/m^2/year) (not used)
- energy savings reached by internal insulation expressed as fraction from baseline energy consumption (%) (not used)

Example:

The building owner would like to carry out major renovation of his historic building. National building regulations demand to reduce energy consumption of buildings if major renovation is carried out. U-values of external walls are defined in national or local building regulations and based on this the building owner sets the goal for internal insulation to reduce U-value of external walls from 1.9 $W/(m^2K)$ to 0.2 $W/(m^2K)$.

3.3 Reduction of environmental impact

This goal is to reduce possible environmental impact when applying internal insulation. It can be either reduction of CO_2 emissions to lower the impact on climate change during operation phase of the building or reduction of environmental impact considering cradle-to-grave approach (incl. the construction phase, the operation and maintenance phase, and the end of life phase).

[1] Heat loss in W can be converted to kWh. A 1000 W heat loss for 24 hours equals a consumption of 24 kWh

The RIBuild web tool strives as a parameter to provide the net CO_2 emissions from energy consumed during manufacturing, transport, assembly and end-of-life, and energy saved during the building operation phase (kg CO_2/m^2/year). However when finalising this deliverable (D6.2) (June 2020), it was not clarified whether this would be possible. Nevertheless, results obtained from the web tool, guiding the user to specific internal insulation systems, can be used further to assess cradle-to-grave life cycle impact for 1 m^2 of surface with the RIBuild LCA tool.

Example:

A state owned university has signed a voluntary agreement with the government to reduce CO_2 emissions by 2000 t CO_2/year. University campus comprises several historic buildings with heritage value and external insulation is not applicable. The university management decides to reach the goal by implementing different measures, including reduction of CO_2 emissions by applying internal insulation.

CO_2 emissions is used as climate change impact criterion while a set of different indicators is used for the environmental impact for assessment of life cycle impact from cradle to grave. Environmental impact criteria are

- annual CO_2 emissions (t/year)
- for life cycle impact assessment for the functional unit:
  - climate change
  - biodiversity
  - use of non-renewable natural resources
  - human health.

Detailed information about life cycle assessment for 1 m^2 of surface using the RIBuild LCA tool is available in (RIBuild Deliverable D5.1, 2017).

Example:

The building owner has decided to apply internal insulation to external walls of his historic building. His aim is to use materials that have the lowest life cycle impact environmental score according to ISO standard 14044 assessed for the proper functional unit (per 1 m^2 of insulated surface area).

3.4 Reduction of energy and other costs

This goal is set to minimize all costs for application of internal insulation in historic buildings, in particular energy, material and installation costs as well as life cycle costs. It may also consider other costs relevant for a specific case. When preparing the RIBuild web tool, valid data for costs of material and installation (EUR/m^2) were not available. Therefore, this goal is not dealt with in the RIBuild web tool.

Example:

A housing company owns rental apartment buildings. Only internal insulation can be applied to external walls due to heritage value. The company has set the goal to reduce annual energy costs with maximum investment budget for material and installation cost of 1.000.000 EUR.

Other costs criteria are encompassing (not included in RIBuild web tool)

- reduced energy costs (EUR/year)
- investment costs (EUR)
- annual maintenance costs (EUR/year)
- net present value of the investment (EUR)
- internal rate of return of the energy investment (%).

Example:

A municipality owns a vast number of buildings in the historic part of a city and the majority of these buildings contains facades with heritage value. Energy tariffs are increasing every year leading to increasing spendings for energy from the budget. The mayor of the city has set the goal to get a 3 % internal rate of return of an investment to reduce energy consumption.

3.5 Improvement of indoor climate

This goal is set to improve the indoor thermal comfort. Unsatisfactory thermal comfort is related to low surface temperature of the wall which causes thermal asymmetry.

Example:

An office is located in a 200 year-old building. Employees with desks close to external walls complain about being cold during the winter season. They are more absent due to illness than other employees. The owner's goal is to increase inner wall surface temperature to +18°C if the room temperature is +20°C.

Other indoor environment criteria is Predicted Mean Vote (PMV) often used together with Percentage of Person Dissatisfied (PPD) (not included in the RIBuild web tool).

3.6 Loss of floor area

This goal is set to have the least possible loss of floor area due to internal insulation (not included in the RIBuild web tool).

Example:

An office is located in a very expensive part of the city and loss of any floor area reduces income from the rent to the building owner and might reduce the possibilities to design the office. The building owner therefore has set the goal to apply internal insulation by losing a minimal amount of floor area, limiting the thickness of the possible solution.

3.7 Combination of different goals

When multiple goals are set by the building owner they can either complement or oppose each other. For example, reducing energy consumption and reducing CO_2 emissions are complementing goals while minimising energy consumption and at the same time maximising the income for renting out the building can be opposite goals. Energy costs are reduced but so is the floor area and considering the price of the floor m^2 in some area and the investment costs, insulating a building is often not profitable. Each goal has its weight - some goals can be more important than others. In the RIBuild web tool the user can assign weight to a number of parameters (low, medium, high). Based on simulation results, insulation systems are ranked, based on multi-criteria decision making analysis.

Multi-criteria decision making (MCDM) is applied if an decision maker, e.g. building owner has several possible alternatives available (e.g. internal insulation systems and materials) and has to select one of them, without any knowledge of which one is the best. Decision is made based on several criteria.

MCDM methods are used to help decision makers making their decision according to their preferences and to help them integrating the information so that they feel confident about making a decision. Mathematical methods provide quantification and prioritization of personal judgments. To use MCDM a complex problem needs to be broken into its smaller components and set importance or priority to rank the alternatives in a comprehensive and general way to look at the problem mathematically.

MCDM methods differ in the nature of the model, in the information needed, and in how the model is used. However, they have in common definition of alternatives, criteria and the relative importance of the different criteria.

In the RIBuild web tool, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method is used (Yoon & Hwang, 1981). The method is applied in the following steps:

1. Construct the decision matrix and determination of the weight of criteria.
   The multi-criteria problem can be expressed in matrix format in the following way:

	C_1	C_2	…	C_n
A_1	X_{11}	X_{12}	…	X_{1n}
A_2	X_{21}	X_{22}	…	X_{2n}
…	…	…	…	…
A_m	X_{m1}	X_{m2}	…	X_{mn}

where:

$A_1, A_2,\dots, A_m$ – alternative of internal insulation systems/materials

$C_1, C_2, \dots C_n$ - the criteria for which the alternative performance is measured

x - the value of alternative A_i with respect to the criterion C_j.

Criteria of the functions can be either benefit functions when more is better, e.g. wall surface temperature, CO_2 reduction, reduction of energy and other costs, reduction of energy consumption or loss functions when less is better, e.g. total costs of internal insulation. The relative importance of each criterion is given by a set of weights which are normalized to sum to one.

Let X = (xij) be a decision matrix and W = [w1,w2 , ... ,wn] a weight vector, where xij ∈ℜ, wj ∈ℜ and w1 + w2 + …+ wn = 1.

2. Calculate the normalized decision matrix.

   Various attribute dimensions are transformed into non-dimensional attributes. It allows comparisons across criteria. Since various criteria are measured in various units, the scores in the evaluation matrix X have to be normalised to one scale. The normalization of values is carried out by standardized formula and the normalized value n_{ij} is calculated as:

$$n_{ij} = \frac{x_{ij}}{\max x_{ij}} \quad (3.1)$$

3. Calculate the weighted normalized decision matrix.

   The weighted normalized value v_{ij} is calculated in the following way:

$$v_{ij} = w_j n_{ij} \text{ for i=1,…,m; j=1,…,n} \quad (3.2)$$

   where w_j is the weight of the j-th criterion, $\sum_{j=1}^{n} w_j = 1$.

4. Determine the positive ideal and negative ideal solutions.

   Identify the positive ideal alternative (extreme performance on each criterion) and identify the negative ideal alternative (reverse extreme performance on each criterion). Positive ideal solution A^+ is calculated as:

$$A^+ = (v_1^+, v_2^+, \ldots, v_n^+) = \left(\left(\max_i v_{ij} | j \in I\right), \left(\min_i v_{ij} | j \in J\right)\right) \quad (3.3)$$

   Negative ideal solution A^- is calculated as:

$$A^- = (v_1^-, v_2^-, \ldots, v_n^-) = \left(\left(\min_i v_{ij} | j \in I\right), \left(\max_i v_{ij} | j \in J\right)\right) \quad (3.4)$$

   where I is associated with benefit criteria and J with the loss criteria, i = 1, … , m; j = 1, … , n.

5. Calculate the separation measures from the positive ideal solution and the negative ideal solution.

   The separation of each alternative from the positive ideal solution is calculated as

$$d_i^+ = \left(\sum_{j=1}^{n} (v_{ij} - v_j^+)^p\right)^{1/p}, \text{ i=1,2,…,m} \quad (3.5)$$

   The separation of each alternative from the negative ideal solution is calculated as

$$d_i^- = \left(\sum_{j=1}^{n} (v_{ij} - v_j^-)^p\right)^{1/p}, \text{ i=1,2,…,m} \quad (3.6)$$

   where $p \geq 1$.

   If p = 2 the n-dimensional Euclidean metric is used for calculation

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}, \text{ i=1,2,…,m,} \quad (3.7)$$

$$d_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2},\ i=1,2,\ldots,m, \qquad (3.8)$$

6. Calculate the relative closeness to the positive ideal solution. The relative closeness of the i-th alternative A_j with respect to A^+ is defined as

$$R_i = \frac{d_i^-}{d_i^- + d_i^+}, \qquad (3.9)$$

where $0 \leq R_i \leq 1$, i = 1,2, … , m.

7. Rank the preference order or select the alternative closest to 1.
A set of alternatives now can be ranked by the descending order of the value of R_i.

3.8 National building regulations

Before setting the goal(s) for the renovation of a building, it is important to check whether the renovation complies with the building regulations in the specific country. Be aware that in some countries building regulations are laid down by federal or national authorities, while in other countries building regulations are also set by regional or local authorities, e.g. in Belgium.

Remember also to check district plans, covering land use/zoning questions and similar. Such plans may contain restrictions to the expression of the building (external architecture). Further restrictions are applied to listed and worth preserving buildings, where national or local authorities have to be consulted before deciding to change the building.

National building regulations contain rules to follow when renovating a building, all implementing and complying with the Energy Performance of Building Directive (EPBD) (Directive 2010/31/EU). This means setting cost-effective minimum requirements for the energy performance of the building after renovation. In some countries requirements are only stated for major renovation, involving a number of measures, or for renovating building installations (ventilation systems and similar).

EPBD specifies major renovation as renovation of a building where the total cost of renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building, or when more than 25 % of the surface of the building envelope undergoes renovation. In some countries major renovation is specified as renovation of more than e.g. 1000 m^2 of floor area. Other countries defines two levels of major renovation, where at first level, defined as refurbishment of e.g. more than 25 %, 50 % or 75 % of the building envelope (and eventually the building installations), requirement for new buildings is to be followed (Concerted_Actions, 2013) (Concerted Action, 2016).

In some countries following the EPBD approach of major renovation (25 % limit), there may (e.g. Italy) or may not (e.g. Estonia) be requirements for renovation projects covering less than 25 % of the building envelope (Concerted Action, 2016). In the latter case, this means that a building element can be installed with the same energy performance as the one being replaced.

Gradually, national building regulations include requirements to be followed for all kind of renovation projects, no matter the size. This means that if only a part of the building is renovated, e.g. the external wall, it sets requirements for this specific building element and the joints to surrounding building elements, e.g. the foundation. Typically, requirements are given as a maximum U-value for the building element, expressing the maximum heat loss allowed (or the minimum thermal insulation performance of the building element). These requirements may vary between different parts of a country, based on climatic zones. If the country is divided into climatic zones, the U-value requirements may vary from one climatic zone to another. In some countries, the specific level of requirements (U-values) are dependent of the type of building (dwelling, office, production etc.)

In some countries, e.g. Denmark, the U-values are not mandatory to fulfil if lack of economic viability or moisture safety can be documented, but viable, safe measures getting as close as possible must be complied with. In other countries, e.g. Switzerland, the U-values are mandatory and they are set to ensure thermal comfort and a condensation-free surface. Be aware that to get a building energy certificate (or energy label), which is not mandatory when renovating a building, a full building analysis is often required.

National building regulations also put restrictions concerning fire resistance, indoor climate (comfort), pollution from building materials, moisture conditions and acoustic conditions that could be of relevance when renovating historic buildings, as it might set limitations for the use of internal insulation, if no further actions are taken. Example: when adding internal insulation to the external walls, even when it is a capillary-active system, containing no vapour-barrier, the building normally becomes more airtight, at least in window reveals. This could in some cases reduce the air change rate below the required level and – depending on the user behaviour – increase the relative humidity to a critical level if no further actions are taken. When it comes to fire resistance, there are different rules among European countries regarding the kind of insulations systems that are allowed, some of which might give rise to toxic smoke if a fire breaks out.

Any kind of renovation has to comply with at least the level of requirements that was set when the building was constructed. However, the renovation also includes e.g. replacement of the ventilation system, then the requirements of the present building regulations are to be complied with for this specific replacement.

For listed and worth preserving buildings, building permits can be obtained with less strict requirements. This means that renovation can be done without fulfilling the same level or extent of improving the energy efficiency if this cannot be done without affecting the architectural and cultural heritage. This is often the case when considering insulating external walls of existing buildings, especially in the case of buildings having both worth preserving inner and outer surface of facades. In such buildings other measures such a replacing the heating or ventilation system are often easier to implement without affecting the facades or structural parts of the building. In any case, local or national authorities responsible for listed and worth preserving buildings have to be involved to ensure that a renovation project including internal insulation is allowed to be carried out.

Each of the EU Member States has to a certain extent prepared a long-term national/regional building renovation strategy for mobilising investment in the renovation of residential and commercial buildings. This is required to comply with the Energy Performance of Buildings Directive (EPBD) together with the Energy Efficiency Directive and the Renewable Energy Directive (Castellazi, Zangheri, & Paci, 2016). Details about the progress of implementing the EPBD can be found in the reports from Concerted Action: Energy Performance of Buildings (Concerted_Actions, 2013) (Concerted Action, 2016).

No detailed descriptions of national building regulations are given in this guideline as these may change from time to time. Further information is to be found at the relevant authorities in the specific country. Links to authorities in some of the countries can be found e.g. in the Concerted Action country reports (Concerted Action, 2016).

The RIBuild web tool contains the output of numerous hygrothermal simulations done as part of the project, based on a probabilistic approach. Simulations are based on 1 m^2 of external wall, disregarding thermal bridges although these have a rather large effect of the behaviour of the wall in the case of internal insulation. Therefore, when it comes to checking whether a specific solution complies with the relevant building regulations, a more detailed calculation of the U-value for the whole wall is required, including thermal bridges.

Guideline for determining whether a building is suitable for internal insulation

4 Guideline for determining whether a building is suitable for internal insulation

The main goal of this guideline is to provide support to building owners or the building owner's consultant to determine whether a building is suitable for internal insulation.

4.1 Introduction

4.1.1 Damage risks in historic buildings

Brick, mortar, plaster and natural stones, the main materials in external walls of historic buildings, deteriorate when exposed to the environment. The rate and symptoms of deterioration processes are influenced by a number of variables, partly depending upon the properties of the building material itself and partly upon several environmental factors, acting separately or in various combinations.

Typical damage risks in historic buildings are:

- General
    - Infestation of timber components (fungus, mould, wood rot etc.). (Photo 1, Figure 4–1)
    - Moisture damage due to defect water pipes, drainage, roof covering, water installation, etc. (Photo 2, Figure 4–1)
    - Moisture damage from ground water due to missing sealing, horizontal barrier, etc. (Photo 3, Figure 4–1)
- External walls
    - Efflorescence, salt deposits. (Photo 4, Figure 4–1)
    - Corrosion of steel lintels (Photo 5, Figure 4–1)
    - Erosion of masonry joints. (Photo 6, Figure 4–1)
    - Spalling of external material layers (masonry, plastering etc.). (Photo 7, Figure 4–1)
    - Interior surface mould growth due to low insulation standard, high moisture loads, etc. (Photo 8, Figure 4–1)
    - Exterior surface algae growth e.g. due to leaking down pipes. (Photo 9, Figure 4–1)

Photo 1: Infestation of wood	Photo 2: Defect water pipes	Photo 3: Rising ground water
		
Photo 4: Damage due to salt	Photo 5: Corrosion of steel lintels (Source: Videncentret Bolius)	Photo 6: Erosion of joints
		
Photo 7: Spalling	Photo 8: Mould growth	Photo 9: Algae growth
		

Figure 4–1: Examples of how typical moisture related damages in buildings look like

On-site visit to a building serves as basis for assessing whether a building is suitable for internal insulation. If relatively new documents describing the state of the building and its usage characteristics are easy accessible, these should be studied to focus the assessment. Further documents on the renovation history of the building as well as information on local conditions and climate might be relevant at a later stage, if the visual assessment indicates that driving rain load and hidden building elements need to be studied (Section 4.3).

In the case of a listed or worth preserving building, information about restrictions concerning renovation is important as well, when an internal insulation solution is to be chosen. Information can be gathered from drawings, inspection reports, etc.

Based on case studies conducted in RIBuild and found in the literature studying the hygrothermal performance of internally insulated historic buildings (RIBuild Deliverable D3.2, 2019), the following general conclusions and recommendations can be given:

- The thinner the existing wall, the lower the possible damage-risk free thermal resistance resp. thickness of the added insulation system. A thin wall increases the condensation risk and the impact of driving rain on the construction.
- The lower the driving rain load, the more possible insulation systems. Driving rain load depends e.g. on size of roof overhang or specific location of the building
- The dryer and warmer the indoor air, the more possible insulation systems. While the performance of capillary active systems show a strong interaction with the indoor climate, the behaviour of vapour-tight systems only marginally depend on indoor climate conditions.
- A humidification potential from one side of the construction (e.g. moist indoor air or driving rain) requires an equivalent drying potential on, at least, the opposite side of the construction. This could be provided with a condensate-tolerating internal insulation system or avoided with a reduction of the moisture load (improved driving rain protection).
- The higher the built-in moisture, the higher the required drying potential of the construction. Insulation systems with a high build-in moisture should therefore at the best be vapour-open and capillary active.
- The more vapour-tight the insulation systems are, the more caution should be paid on proper workmanship at constructive details, connections, joints, etc.

4.1.2 Step-by-step assessment procedure

This guideline (Section 4) consists of three steps for determining whether a building is suitable for internal insulation, and what is required to make this decision (see Figure 4–2):

- *Visual assessment*. This first step should give an overview of the extent of cracks, wet spots, rising damp etc. Section 4.2 gives examples of what to look for and guides on possible remediation action in case cracks, wet spots, algae, mould growth, frost damage etc. are identified.
- *Collection of information about "exposed areas" of the building and its surroundings*. If no cracks etc. are identified or when those identified are treated, the building owner can move on to the next step, looking at details of the building and its surroundings that describe how robust the building is (Section 4.3). As addition of internal insulation will change the hygrothermal conditions/behaviour of the external wall, it is important to ensure/estimate that this can take place without harming the building. This step includes collection of information on the present indoor climate, the wind driven rain load, rain collection system, moisture sensitive parts, and rising ground water.
- *Measurements*. Often, measurements are needed to decide whether the façade is robust enough to be internally insulated. Relevant methods are described in Section 4.4, focusing on moisture and heat/U-value. Both on-site and laboratory measurements are described.

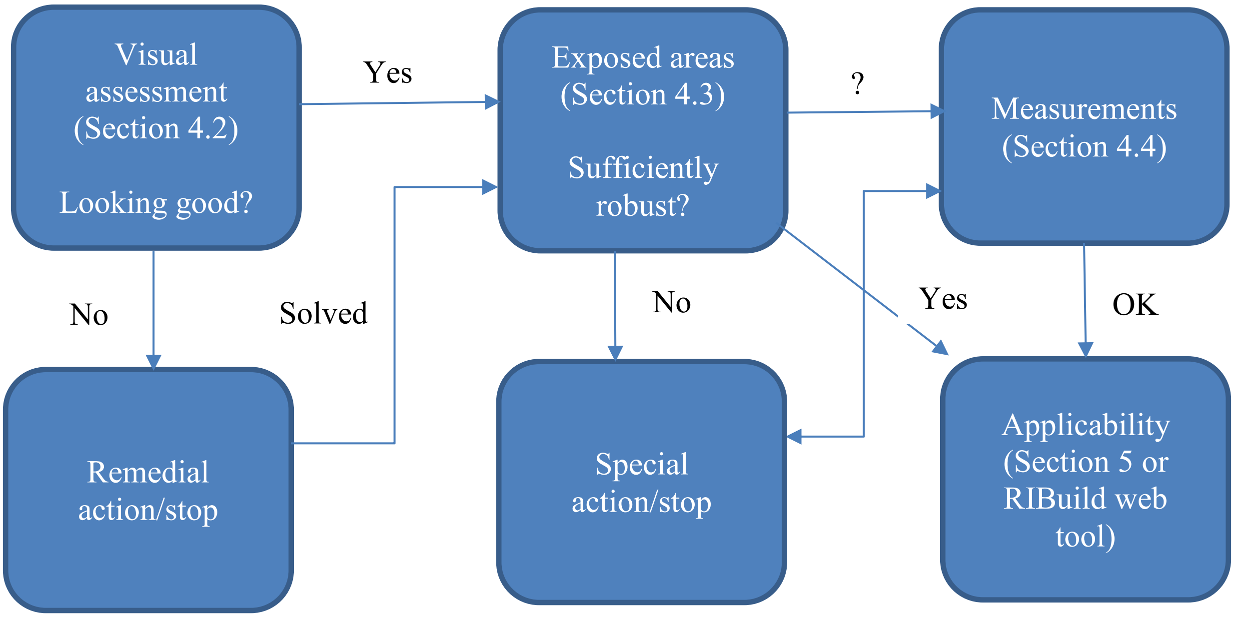


Figure 4–2: Overview of assessment procedure of the building state

If the visual assessment, the evaluation of exposed areas and possible measurements show that internal insulation is feasible, the next step (‘applicability’) is either to move further to Section 5, that introduces the different types of insulation systems and methods for calculation or simulation of heat and moisture transport, or to start collecting input data for using the RIBuild web tool (RIBuild Deliverable D6.1, Web tool including feasibility study of possible input and output data, 2020).

The user can use a link to the web tool on the website. Based on information inserted by the user, the tool will deliver a range of solutions. Input data includes location and orientation of the building, wall thickness, whether the external wall is made of brick or natural stone, and whether it is rendered at the exterior and/or interior. The present version of the web tool is a preliminary version (beta version), showing how results can be selected and presented, however not fully operational. This is mainly due to a limited number of simulations and the models for failure involved not being sufficiently exact for this kind of use.

Material properties such as capillary water uptake and density might give added information about the existing wall, and might be useful when considering to include accompanying measures like hydrophobization. However, it is much more important to repair cracks, as they have a much larger effect on moisture transport within a wall than whether one type or another type of brick has been used. Further, the location of a building seems to be much more important than the material properties of a specific wall (de Place Hansen & Møller, 2018), (RIBuild Deliverable D2.1, 2018).

The RIBuild web tool determines the risk for mould and algae growth when applying internal insulation. The guideline does not provide threshold values for safe application of internal insulation in cases where frost or wood rot might be the most likely failure mode, as models to characterize degradation caused by these are yet not advanced or precise enough to fit into a simulation tool.

4.2 Assessment of state of the building envelope

4.2.1 Visual assessment: general activities

Visual assessment of a building must be carried out to determine whether there are any fundamental limitations to application of internal insulation. The external wall and the adjoining constructions need to be in a sufficiently good state, e.g. having no cracks, and no indication of moisture damage or presence of salt, before application of internal insulation should be considered. The main goal is to assess risk factors related to the existing wall, constructive details, boundary and initial conditions, and specific aspects of internal insulation application. It is recommended that an assessment follows a certain procedure including assessment of whether and how the building has functioned in its current state and if it has been damage-free, photo documentation of the building, and finally preparation of damage report (mapping).

Several conditions have to be present before internal insulation can be considered an option for a specific historic building, as presented in Section 4.2.2 - 4.2.9. If visual assessment has identified indication of moisture damage, the moisture sources need to be identified and eliminated no matter whether it has resulted e.g. in frost damage, mould or algae growth, wood rot, salt efflorescence or is caused by rising damp. Internal insulation systems can only be applied after all measures to avoid further moisture ingress into the construction have been carried out. Further, damaged parts of the façade and the adjoining elements (e.g. wooden beams supporting the floors) should be replaced or treated as part of the renovation. Internal insulation can never be used to 'hide' previous damage.

Application of internal insulation could be performed in combination with impregnating the external surface of the wall with a water-repelling agent. In that case, the agent should be applied first, letting the wall dry out before installing internal insulation. How long the wall should dry depends first of all on the state and the thickness of the existing external wall, the location and orientation of the wall and the indoor climate. The guidelines do not go into detail with the potential of combining internal insulation and water repellent agents; more research is needed within this topic before integrating such recommendation. The potential benefits are at present studied in a number of projects, e.g. in Denmark and Belgium, being part of or connected to RIBuild, (RIBuild Deliverable D2.3, 2020) – which also includes a state-of-the-art, (RIBuild Deliverable D3.1, 2018) and (Odgaard, Bjarløv, & Rode, 2018).

Table 4-1 summarises when internal insulation is applicable, might be applicable or is not recommended, based on visible damage and material properties of the existing wall. See also Table 4-11. The indoor climate in the winter season should generally not exceed 50 % relative humidity, if it does a climate control system should be installed etc.

Table 4-1: Assessment tool for the applicability of internal insulation, based on the presence of visual damage and material properties of the existing masonry wall (Steskens, Loncour , Roels, & Vereecken, 2013).

	Internal insulation is applicable	Applicability is unknown	Internal insulation is **not** recommended
Visible damage	No visible damage (traces of moisture in the internal/external finish, such as irregularities, stains) or moisture sources	No visible damage, however, presence of moisture sources (for example rising damp) which may lead to moisture problems and damage after installing the insulation	Presence of moisture (stains, moisture ingress, efflorescence of salts, algae, cracks, irregularities)
Material properties of the existing masonry wall	Exterior finish		
	No exterior finish or an exterior finish which has a good condition, has a good quality, and is vapour-open		Exterior finish not in a good condition, and/or contains damages Vapour retarding exterior finish such as varnished bricks, tiles, mosaic, vapour retarding paint
	Bricks		
	In accordance with national standards	No visible frost damage	Visible frost damage, brick susceptible to frost damage
	Mortar joints		
	In accordance with national standards	No visible frost damage Lime mortar	Visible frost damage, mortar susceptible to frost damage (for example mortar containing sandy clay)
	Interior finish		
	No visible damage No irregularities or loose parts Smooth, non-structured surface	Irregularities and/or loose parts Very structured/irregular surface Interior finish which is susceptible to moisture (damage) Vapour retarding interior finish	Visible damage (for example cracks, paint which is flaking off, degraded plaster)

Ideally, the visual assessment takes place directly after a rain event, firstly to clearly recognize damage in the splash water zone and the roof drainage and its consequences, secondly to capture a visual impression of the capillary water absorption of the façade and thus its protective state.

First, it must be checked **whether and how the building has functioned in its current state and if it has been damage-free**. If this is not the case, the focus of the inspection is on the detection and examination of hygrothermal structural damages. This allows the consultant to recommend immediate measures for the (re)production of the functional state. In some cases, the cause of the discovered structural damage is easily eliminated, e.g. by renewal of a defective roof drainage or, initially, provisional closing of defects in the building envelope.

As part of the visual assessment, a comprehensive, clear **photo documentation** of the building should be created. It is generally used to document the condition of the building, including damages. It should be used to illustrate materials, layer thicknesses (photographs with a scale), details, etc. in detail. Often, existing plans and drawings does not represent the existing building; deviating wall constructions, materials, dimensions, etc. usually show up.

It is advisable during the inspection to proceed with a **certain systematic procedure, e.g. from outside to inside**, from the overall view to the detail, from the basement to the attic, etc., to obtain a comprehensive overview of the state of the existing constructions. In addition, describing special areas necessary for the inspection, e.g. areas where samples are taken for further investigation, holes to inspect for cavities, special structural designs not included in the design documents, location of sealing levels, imperfections and leaks, type and location of existing windows and doors, etc.

As a result, a **damage report (mapping)** is carried out during the visual inspection to map the actual condition of the building as accurately as possible. During the on-site inspection, the recognizable damage (such as moisture damage, salt contamination, rot, mould, algae, corrosion, etc.) and special features are documented, mapped in their position and shape and added to an elevation (drawing) of the facade. Damages are generally mapped together with in-situ moisture measurements (Section 4.4), as this often results in correlations. Based on the damage mapping, measures to eliminate the damage or the causes of damage are derived. These measures concern the direct structural repair, for example, the repair of joints or the replacement of damaged wooden components, and the drying of the external components.

During visual assessment special attention should be paid to number of risk factors, of which some are described further in Section 4.2 and some in Section 4.3 (in most cases indicated as a specific subsection):

1) Risk factors related to the existing wall

- Constructive details
    - External wall materials (plaster, brick, natural stone, wood, etc.)
    - Determination of wall structures (layers, thicknesses)
    - Classification of cracks (due to design or plaster)
    - Survey of the surrounding buildings (Section 4.3)
    - Detection of lintels, steel girders, elements penetrating the façade, acting as a thermal bridge
    - Damage visible at inner surface of façade, such as mould and moisture damage in external wall corners, or at connections between window and wall (Section 4.2.2)
- Walls in contact with ground / base area
    - Design and condition of the splash water area, level access
    - Groundwater situation (if applicable, groundwater depth) and surface water discharge
    - Visible waterproofing levels against rising damp (horizontal barrier, vertical waterproofing and possibly existing protective layers) (Section 4.2.8)

2) Risk factors related to installing internal insulation

- Increased condensation risk behind the existing wall due to lower outgoing heat transport through the wall
    - Increased condensation risk with increasing capillary activity / capillary suction (addresses impact of driving rain)
- Reduced inwards drying, with increased risk for frost weathering (Section 4.2.5) or mould growth (Section 4.2.3)
- Misunderstanding of the different modes of operation of insulation systems (Section 5.1)
    - Vapour-tight systems: main leakage sources are workmanship-related issues, e.g. a leakage in the foil layer, and design-related issues, e.g. a non-continuous air tightness layer. Consequences of vapour transport through gaps, cracks, connections etc. might be condensation, mould growth and increased energy consumption
- Misjudgement of the existing construction, including properties of the historic building materials (masonry)

- Underestimation of drying times before installing internal insulation, related e.g. to levelling redendering of uneven walls (Section 5.1)
- Vapour ingress due to convection because of uneven historic surfaces not prepared before installation of internal insulation

3) Risk factors related to adjoining building elements

- Thermal bridges (interruption of the insulation layer) by all embedded constructive details (partitions, windows, etc.) (Section 0), with increasing risk of surface condensation
- Floor slabs
  - Condition of the ceiling constructions (visible damage, e.g. wood rot (Section 4.2.4), corrosion, exposed reinforcement in concrete)
- Roof
  - Condition of the roof drainage system (damage to gutters and down pipes, clogged gutters, etc.) (Section 4.3.5)

4) Boundary and initial conditions risk factors

- Climatic boundary conditions
  - Temperature and humidity levels in the building, especially high humidity loads from use, and condition of ventilation system (Section 4.3.6)
  - Additional moisture inputs, e.g. from the soil or a high relative humidity at the site (e.g. near water or at high groundwater level) (Section 4.2.8)
  - Driving rain load of the building (existing constructive driving rain protection including roof overhang, roof drainage and splash water protection, external rendering, etc.) (Section 4.3.2)
- General risk factors
  - Soil moisture (groundwater, seepage water, pressing water,...) (Section 4.2.8)
  - Internal moisture load (pipe routing, damage to enveloping surfaces, e.g. defective windows or connections and rainwater in the interior due to defects (Section 0)
  - Problematic connection points (surface condensation, rot, ...) (Section 0)
  - Execution of essential component connections (component opening may be required)
  - Type and condition of the existing or former service water drainage system in the building (Section 0)
  - Recording of the overall condition and the general moisture load in the building

Evaluation of on-site assessment

Evaluation of the on-site assessment in the building report should contain the following information:

- Recording of the general building condition and the existing driving rain protection of the façade and plinth areas
- Documentation of the condition of the outer and inner walls
  - Material used, condition of the wall construction
  - Condition of plaster/joints, existing coatings
  - Flatness of the wall
  - Special structural features (steel girders, beams and coatings, condition of components, special features of ceiling integration...)
  - Documentation on position and condition of the sealing levels

- Mapping of moisture damage and loads (see example in Figure 4–3)
- Listing and location of moisture damage from
  - Ascending humidity
  - Usage features
  - Individual damage (e.g. due to waste water in the building or inadequate maintenance)
  - Defects due to defects from the enveloping surface or roof drainage
- Characterization of moisture damage
  - Visual inspection (e.g. dry rot infestation)
  - Sampling for laboratory measurement (e.g. water content)
- Documentation of the salt load

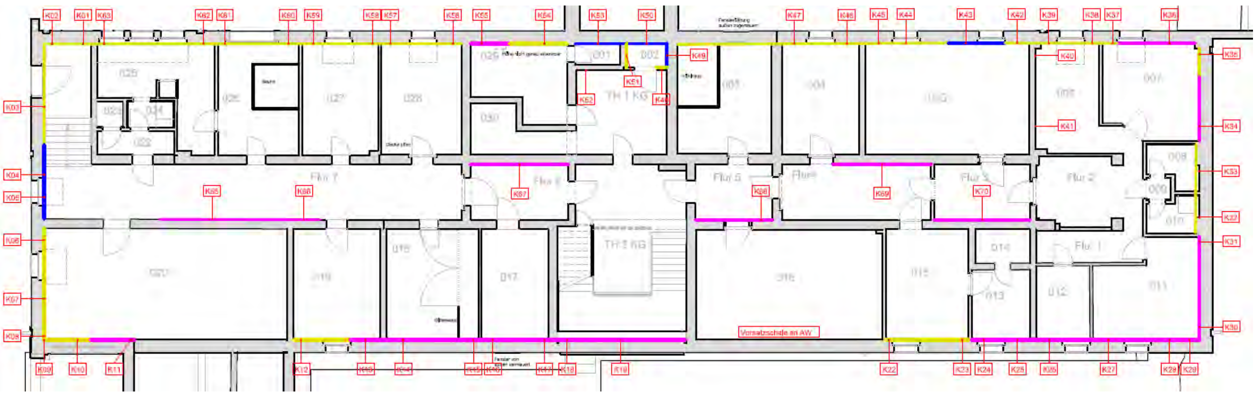


Figure 4–3: Representation and classification of the measured moisture loads in the floor plan

The results of the moisture measurements are summarised clearly and comprehensibly in a moisture status report. Its conscientious processing serves as an important basis for the calculation of the required follow-up services as well as for the further planning and execution steps.

Documentation of the façade conditions

The protective function of a façade decreases over the years due to weathering, which can be seen in changes in strength, colour or material properties. Depending on the facade material and quality, appropriate maintenance cycles must be planned. Particularly in connection with planned internal insulation, the condition of the façade must be critically examined.

In the case of plaster facades, a facade that is no longer resistant to driving rain can be well achieved by crack filling and repainting the surface and, if necessary, by partially or completely applying new plaster. These services are usually quite manageable and calculable.

The preparation of a facade renovation concept makes sense if the renovation effort cannot be easily estimated due to the existing complexity. This applies, for example, to natural stone facades or brick facades without plaster with extensive obvious damage, the comprehensive recording and assessment of which would go beyond the scope of an initial building / moisture condition analysis. For this purpose, a more detailed survey of the individual damage to the façade is mapped and classified (see example in Figure 4–4). Structural features of the façade and their effects are presented. Existing cracks are mapped and classified. On this basis a more exact calculation of the costs can be made; necessary renovation times and dependencies can be planned more concretely during the construction process.

Figure 4–4: Representation of the existing damage pattern on the façade.

Recommended measures

- Immediate or safety measures to be taken
- Recommendations for dehumidification as a function of moisture load and horizons
- Dealing with stock salts
- If necessary, display of component areas to be removed
- Explanation of necessary and recommended waterproofing measures, notes on location and overlapping of levels.

4.2.2 Moisture damage

The presence of excess moisture in building constructions can cause serious harm, and is undesirable. High levels of moisture can result in several types of deterioration, and reduce the service life of building components. Moisture induced damage include e.g. mould growth, wood decay, and frost damage, and furthermore moisture in porous materials can increase the thermal transmittance and thereby the heat loss through a wall. Moisture can appear on an external façade in the form of darkened areas indicating wet spots. Furthermore, damp areas can be revealed by the damage it causes both internally and externally, e.g. paint peeling/blistering, frost damage, salt efflorescence, mould growth, signs of fungal attacks or algae growth. Figure 4–5 illustrates examples of moisture in façades, and moisture related damages both internally and externally.

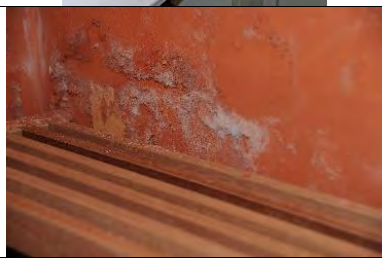
Dark, moist areas visible on external wall (left) and internal wall (right)		
Peeling of paint on external wall (left) and internal wall (right)		
Salt efflouresence on external wall (left) and internal wall (right)		
Frost damage in masonry on external wall (left) and mould growth on internal wall (right)		

Figure 4–5: Examples of moisture in constructions and related damage.

Application of internal insulation increases the risk of moisture accumulation and moisture damage as internal insulation reduces the drying potential of the existing wall, as well as the temperature. For this reason, any signs of excess moisture in the walls should be investigated and remedied prior to application of internal insulation. There are many possible moisture sources, including rising damp, precipitation, infiltrating surface water, and defective plumbing, and the remedial measures should be adapted to limiting the moisture source, where after the wall can dry out.

Table 4-2 includes what to look for and where, when determining the suitability of the building in the present state for internal insulation with regard to moisture in the walls. To identify possible defects and moisture damage in a building, a visual inspection should be conducted both internally and externally. Any signs of moisture accumulation or moisture induced issues should be registered and remedied prior to application of internal insulation.

Table 4-2: What to look for, and where with regard to moisture damage

	Externally	**Internally**
WHAT to look for	Dark (moist) areas Paint deterioration Salt crystallization on the surface Green surface coating Crumbling of bricks or mortar	Dark (moist) areas Paint deterioration Salt crystallization on the surface Mould growth Wood decay Deformation of construction elements
WHERE to pay special attention	At the plinth (rising damp) Corners of the building Around windows By installations, e.g. downspouts Northbound façade (min. solar radiation) South and Southwest façade (precipitation)	Basements walls External walls/corners Behind heavy furniture/wall decorations against external walls Wooden elements Thermal bridges (risk of condensation) North (coldest surface – risk of condensation)

Visual inspection – External façade

The external façade can provide basic information on whether a building is subjected to moisture accumulation or not. Moisture accumulation can appear as wet spots/darkened areas in a façade, as seen below in Figure 4–6. The examples illustrate that moisture accumulation in the masonry can appear anywhere on the façade or gable.

Figure 4–6: Examples of stains and wet spots. A: moist areas on rendered masonry façade, B: wet spots on masonry façade, C: moisture accumulation at top of façade gable, likely due to precipitation, D+E: local defects causing concentrated moisture accumulation, F: moisture accumulation near the plinth, likely due to rising damp

Moisture accumulation can also appear in the form of the damage that it causes. If moisture (e.g. from high internal moisture loads, rising damp etc.) is trapped behind a diffusion tight paint, the drying is blocked and causes the paint to blister, and eventually scale and peel off. The peeling of paint can also be caused by salt efflorescence. Salt efflorescence is when soluble salts from the masonry are diluted in water travelling through the pore structure of the masonry. When the moisture reaches the surface for evaporation, white, powdery salt crystals remain behind on the surface. Algae growth can appear as light to dark green coatings on a façade, if optimal conditions of moisture, temperature and lighting occur. Usually northern bound facades are more subjected to algae growth. Frost damage occurs when a moist façade is subjected to freezing and thawing cycles. As water expands up to 9% when freezing, moisture in the pore structure causes stress within bricks or mortar, and can cause spalling and crumbling of both. Furthermore, when masonry has started to deteriorate due to frost, the outer-most part of the brick/mortar is disintegrated, leaving the remaining masonry more susceptible to water absorption, and thereby the rate of frost damage is increased. Examples of visible damage caused by moisture, are shown in Figure 4–7.

Figure 4–7: Examples of visually apparent moisture induced damage of external façades

Visual inspection – Internal façade

Attention must also be given to the internal surfaces of external walls, as moisture accumulation may become visible here rather than externally. Like the case for the external inspection, moisture can appear visually as darkened areas on the internal surface. Furthermore, paint deterioration, and deterioration of internal render can be caused by moisture and salt efflorescence as the case for external paint/render. Examples are provided in Figure 4–8.

Moist areas on internal surfaces

Paint and render deterioration

Salt crystallization

Figure 4–8: Examples of visually apparent moisture and moisture induced damage of internal façades.

In addition to the moisture induced damage similar to the damage of external façades, the internal construction elements are subjected to further risk of damage caused by moisture. This includes the risk of mould growth, and wood deterioration and deformation. Mould growth can develop on internal surfaces with favourable conditions (temperature and relative humidity), and when organic material is present (e.g. wall paper but also dust). Mould growth can be hidden behind heavy furniture placed against the wall, or even wall-hanging decorations. Furthermore, the risk of development of wood-decaying fungi is present in the case of wooden elements becoming moist for a longer duration of time. Finally, some construction elements may be subjected to deformation when exposed to moisture. Thus, this is also a sign of excess moisture in the construction. Illustrations of mould, wood decay and deformation are gathered in Figure 4–9.

Mould growth

Decaying wood

Deformation of (wooden) elements

Figure 4–9: Examples of visually apparent induced damage of internal façades

Remedial actions if moisture damage is identified

Remedial actions might be complicated, dependent on the cause for moisture damage. If a broken or leaky downpipe is the cause remedial actions are quite simple (replace the downpipe), but if it is caused by rising ground water, remedial actions are complicated.

Initially the moisture source should be found, and the cause for the moisture accumulation remedied. Hereafter, potential moisture damage should be fixed, and the affected construction parts should be dried out. The sections below describe how to treat external masonry and components prior to application of internal insulation, and after the moisture source has been eliminated, following the approach given in Figure 4–10.

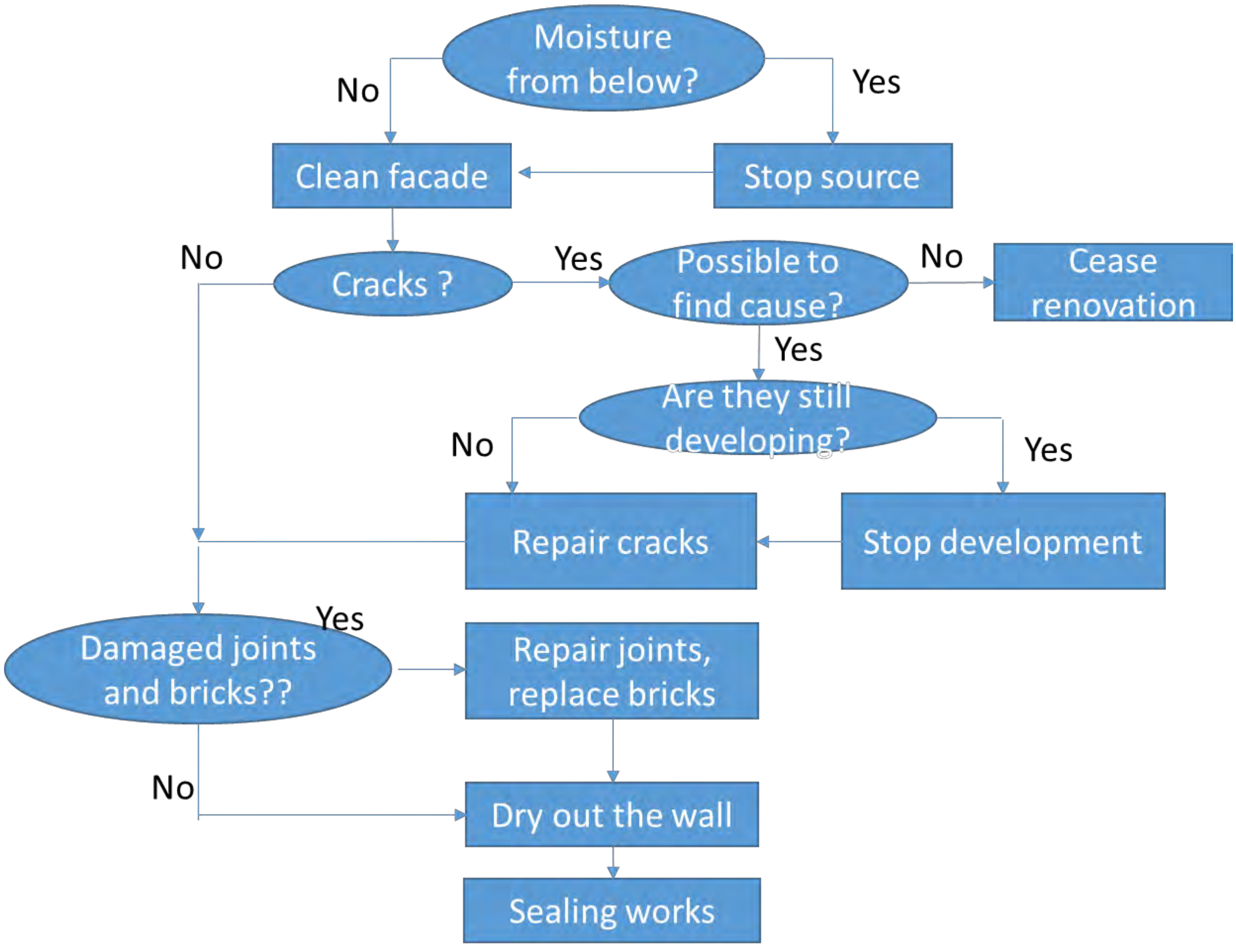


Figure 4–10. Approach for remedial action of an external solid wall. First, the cause for moisture ingress should be identified and stopped (if any), then the facade should be cleaned, removing loose facade components. If there are cracks, their cause should be identified and handled before any other measure. Dependent on the extent and size of cracks, if their cause cannot be identified, renovation of the building should not be carried out.

Stop the source for moisture damage

The first step is to locate and stop the moisture source causing damage, as described in the 'remedial actions' parts of Section 4.2.2 - 4.2.8. For instance, if the cause for moisture damage is rising damp (4.2.8), defective pipes, lack of drainage etc. should be handled before considering internal insulation.

Facade cleaning

Before facade maintenance and renovation work is carried out, or before measures are taken to provide the necessary driving rain protection (sealing work), a facade cleaning is usually necessary, during which even loose facade components are removed. The aim is to maintain a firm, cleaned facade surface, free of algae, salts, soot particles, etc. It also makes it easier to get a visual impression of the condition of the façade.

Surfaces of brick facades should be cleaned as gently as possible not to damage the burning skin. A cleaning without chemical additives is often sufficient, and therefore the use of a hot steam jet process is recommended, being also the simplest method. Depending on the conditions found, special surfactants, algae dissolvers, etc. can be used in individual areas.

The cleaning agents used must be compatible with each other and with any eventual subsequent hydrophobic impregnation. The surfactant solution must be collected and disposed of. This must be planned in the cost estimate.

It is recommended to test a suggested cleaning method on a sample area before choosing the specific method for the whole façade.

Crack repair

Cracks in the façade indicates that the protective function of the building envelope is no longer intact. If the moisture load results in cracks related to frost, serious damage can occur. If not only the facade surface is affected by cracks, but also the construction itself, static problems can also occur. Therefore, crack repair is important when preparing brick masonry for installing internal insulation.

To identify how to repair the observed cracks, their causes need to be identified; are they structural, subsurface or material-related. And are they still developing or not. This includes recording the crack depth, width, length and the course of the crack, eventually over time. Depending on the type and spread of the cracks, the proposals for repairing the cracks can range from replacing the grout to injecting and using stainless steel spiral anchors.

In the latter case, spiral anchors are dimensioned to prevent the movement of existing cracks and the formation of new cracks in the masonry according to static specifications (anchor diameter, anchor length, number and laying of anchors).

If the cause for cracks cannot be identified, no further attempt to add internal insulation should be pursued.

Repairing of joints

If the bond between brick or stone material and the joints is no longer sufficiently stable and weather-resistant with intact bricks/stones, the joints should be repaired. This is especially important if the joints show cracks and flaws and in all areas where salt efflorescence and algae deposits are visible.

The following steps are necessary:

- Removal of defective joints to a depth of approx. 20 mm, without damaging the bricks
- Re-pointing with a repair mortar adapted to the construction in terms of strength, elasticity and colour

- Post-treatment, forming of the joint
- In the splash water area (plinth are) if necessary: grouting with a mortar that is resistant to salt exposure coming from the use of salt on the pavement etc.

If the use of water-repellent agents is considered as part of repairing the joints, instead of using a mortar containing a water-repellent agent it is advisable to impregnate the whole wall. If only the joints are treated it will be become less obvious how and where moisture enters and is transported in the wall. Further, a surface treatment is much more efficient in regard to reducing water uptake than adding a water-repellent agent to the repair mortar.

Criteria for replacing parts of the existing facade

Damaged bricks/stones in the façade must be replaced with similar materials. Preferably, by using well-preserved facade materials available on-site, e.g. as a result of widening or supplementing openings as part of the renovation. Otherwise suitable replacement bricks/stones are to be used.

To select or produce suitable replacement bricks, the following properties of the existing masonry materials are recommended to be taken into account and verified:
- firmness
- bulk density
- water absorbency
- frost resistance
- content of water-soluble salts
- type of execution (solid brick, perforated brick)
- surface and colour

The replacement stone must be of the same type as the existing. If this is not considered, differences can become noticeable very fast at the façade and damage can occur because of differences in moisture absorption.

The replacement mortar to be used should also resemble the existing mortar as closely as possible, although different or changed weather conditions must also be taken into account.

Component drying

Dependent of the moisture load, especially if it is caused by leaky pipes, rising damp etc., it might take quite some time to dry the existing wall. It is advantageous if the building or the affected construction areas can dry with natural ventilation. The winter season is best suited for this, as the absolute moisture content of the outside air is lower than that of the indoor air. By means of a controlled air exchange, the warm, moist indoor air is replaced by cold, dry air. The summer months are not or only very limitedly suitable for this purpose.

Ventilation can also be controlled with simple fan units in combination with outdoor and indoor humidity sensors, so that ventilation only takes place if the external absolute humidity content is lower the internal. If necessary, additional drying devices can be used.

If sealing of areas in contact with the ground from the outside is planned, drying should be carried out from the outside by exposing the outer wall areas at an early stage. The summer season is well suited for this, as there is a good drying potential due to the warming up by the sun. In this case, drying the wall from the outside, sealing the façade at the outside should only be introduced at a later stage. The exposed areas must be protected from water.

Sealing works

Finally, it should be considered to seal the façade, e.g. by using water repellent agents (hydrophobization). It should be noted that after a sealing measure the remaining drying potential is only possible in one direction. For further information about hydrophobization refer to (RIBuild Deliverable D2.3, 2020)

4.2.3 Mould

4.2.3.1 Assessment, causes and remedial actions

Assessment of existing mould damage by visual inspection

The original external wall in historic buildings often consists of inorganic building material and may therefore be considered as robust from a mould perspective. However, there are also adjoining frames, beams, windows, doors, added insulation and surfaces containing organic compounds that needs to be inspected.

Extended mould growth on building materials may be visible to the naked eye. However, often growth cannot be seen, cf. Figure 4–11(A). Growth not visible to the naked eye and growth inside building structures may be as problematic as visible growth, as there is a risk of adverse effects on the indoor environment, which can pose health risks to those in the building. Mould can theoretically grow anywhere in a building, provided the conditions for growth are suitable. Some types of structures are more favourable than others for mould growth, and some materials are more susceptible to mould growth than others. In houses in Northern Europe, mould typically grows inside sealed building structures, e.g. as shown in Figure 4–11(B). Extensive mould growth may be present in buildings even though there are no clear visual signs. Typical indications of moisture related problems can be damp surfaces, dried out water stains and rusty nails in the construction.

(A) (B)

Figure 4–11: (A) Illustration of how the visible impression of mould growth varies. All samples shown have the same extent of mould growth, although the growth is not visbile to the naked eye in all cases. (B) Example on how mould growth may be hidden within the building structure. In this example, interior surface materials and insulation was removed before mould growth was detected.

Table 4-3: What to look for, and where with regard to mould growth

	Externally	**Internally**
WHAT to look for*	-	Discolorations on surfaces Mouldy odour Moist areas
WHERE to pay special attention	-	External walls Thermal bridges Behind heavy furniture Organic materials (wood, wall paper, etc.) Unheated rooms

* Not always visible to the naked eye

For mould to grow on a material, nutrients in the form of simple carbohydrates must be present in the material. All materials with organic compounds are therefore at risk for mould growth. However, the susceptibility for mould growth varies, some materials can withstand higher moisture loads than other. This can be described as the critical moisture value, RH_{crit}, further discussed in (RIBuild Deliverable D2.2, 2019). Also, materials may be contaminated by organic substances during production and construction, for example by dust, soil, surface treatments etc. and the susceptibility may then be changed.

Some fungi produce pigments in their hyphae and spores that can cause discolouration of surfaces on which they grow, while others lack this pigment and therefore can't be seen by the naked eye. The production of pigments by fungi is a species-specific trait, but can also be dependent on the nutrients available, or the growth phase of the fungus (Gadd G. M., 1980), (Eagen, Brisson, & Breuil, 1997), (Fleet, Breuil, & Uzunovic, 2001).

Causes of mould growth

Adding internal insulation to the building façade will make the original wall structure colder, reducing the drying potential. This in turn may increase relative humidity (RH) locally and thereby the risk for mould growth and condensation. An increased RH level increases the risk for mould growth on existing, historic materials and on new materials. The risk of high moisture levels may increase further if the internal insulation admits air leakage of humid indoor air into the wall construction, especially if the ventilation is unbalanced (internal overpressure). In time, problems with rot may also develop if access to moisture increases (Section 4.2.4).

When mould growth has been detected (e.g. if users of the building become ill), the cause of the mould growth should be found and remedied, and damaged material should be replaced or mechanically treated, e.g. by grinding, planning or blasting. Note that residues from the process must be collected and removed to minimize the risk of future mould growth.

Mould in buildings may have negative effect on the perceived indoor environment, for example, by the production of odorous substances. Also, human health may be adversely affected due to the spread of particles, toxins and volatile organic compounds from the mould fungi to the indoor air. The costs associated with this growth, i.e. due to renovation, are substantial. Therefore, both economy and health can be used as arguments for reducing the risk of mould growth in buildings.

Mould fungi are widely spread across different environments on the Earth and there is no natural place where air and materials are free from spores. When favourable conditions are present, spores (also called conidia) will germinate and a small germ tube will develop; if the favourable conditions prevail, a hypha will be formed. A hypha is a tubular cell structure which extends at the tip. By continuously branching during growth, the hyphae form a mycelium. Eventually, specialized structures (conidiophores) develop from the hyphae and from them the spores are produced and dispersed.

The main environmental factors affecting mould growth in building structures are humidity and temperature; moisture being the crucial factor. Suitable conditions for the growth and reproduction of different mould fungi vary. Some thrive at relatively low relative humidity (RH = 75%), while most fungi require higher values of RH (90-95 %) for optimal growth in room temperature. Different building materials vary in their susceptibility to mould growth; some can withstand high moisture content better than others.

Mould growth is the result of a complex interaction between all these factors; environmental factors and duration, material properties and the characteristics of mould fungi present (Blackburn, 2000). To prevent mould growth in buildings, these interactions should be considered during the design, construction and maintenance of a building.

Remedial actions if mould growth is identified

In general, specialists are needed to execute remedial actions if mould growth is identified, as it is difficult to ensure that the mould is complete removed.

When building materials have been affected by mould, various remedies or methods are used to get rid of the mould and sometimes the material is only dried without any further action. There are studies concluding that treatment with chemical agents do not stop or eliminate mould growth, and that the release of particles and toxins from mould-damaged materials even increase by drying.

In a study conducted in Sweden 2010 a number of remediation methods for removing mould were tested (Bloom, Must, Åmand, Peitzsch, & Larsson, 2010). It concluded that none of the remediation methods could eliminate viable mould growth on the tested building materials. No decontaminant eliminated the toxins completely from the damaged building material.

Primarily, the study emphasizes the importance of working preventively with moisture safety throughout the construction process and administration to prevent mould damage. If damages are found, the preferred method of remedy should be, as stated before, replacement of damaged materials or mechanical treatment of surfaces, e.g. by grinding, planning or blasting. Note that residues from the process must be collected and removed to avoid mould residues from remaining.

To treat surfaces and mix materials with mould inhibitors such as e.g. asphalt or fungicides is not recommended as these products can fortify the development of an odour and/or health hazard to the indoor air. The precautionary principle is recommended as an approach.

4.2.3.2 Mould prediction models

VTT model

This model was first presented in a version aiming to predict mould growth on wood (Hukka & Viitanen, 1999). It was later modified to handle also other materials. The latter version is often referred to as “the new VTT model” (Ojanen, et al., 2010). The model is available as a postprocessor in the hygrothermal simulation programs DELPHIN and WUFI. In this study, the partners used either DELPHIN or excel files, programmed after published version

The material susceptibility parameters to be chosen in the model are shown in **Table 4-4**. The description differ slightly between the published description (Ojanen, Peuhkuri, & Viitanen, 2011) and DELPHIN. Two additional parameters linked to material properties can be chosen in the model; Wood species (W=0 for pine or W=1 for spruce) and surface quality (SQ=0 for sawn surfaces, SQ=1 for kiln dried surfaces). In addition, a parameter (C_{mat}) is used in the model in relation to the effect of the duration of unfavourable conditions (**Table 4-5**).

Table 4-4: Sensitive classes in the VTT model. The descriptions vary some between the model as it is described in the published model (Ojanen, Peuhkuri, & Viitanen, 2011) and in DELPHIN (Bauklimat-Dresden, 2019).

Mould Sensitivity Class	Material description according to (Ojanen, Peuhkuri et al. 2011)	Material description in DELPHIN
Very sensitive	Pine sapwood	Untreated wood; includes lot of nutrients for biological growth
Sensitive	Glued wooden boards, PUR with paper surface, Spruce	Planed wood, paper-coated products, wood-based boards
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	Cement or plastic based materials, mineral fibers
Resistant	PUR polished surfaces	Glass and metal products, materials with efficient protective compound treatments

Table 4-5: Description of C_{mat}

C_{mat}	Description
1.0	Pine in original model, short periods
0.5	Significant relevant decline
0.25	Relatively no decline
0.1	Almost no decline

The outcome of the model is a dimensionless value, denominated Index. It describes the mould growth intensities, with values between 0 (no growth) and 6 (heavy and tight growth, coverage about 100%). The partners in this study used the index 1 as limit values, according to (Ojanen, et al., 2010). However, in other publications other limit values can be used.

The PJ-model

The PJ-model is a static Isopleth model. The model has not previously been described as a model. It is a part of the application of a standard test method for assessing the critical moisture level for mould growth on building materials in (SIS-TS 41, 2014). In this study, version 1.0 is used. However, the PJ-model is under development and later version may be published.

The material parameter input to the model is RH_{crit}, which is the tested critical moisture level for a material. A specific product can belong to one of five material classes, from which growth limit curves are constructed.

RH_{crit} according to the method/model has been published for some materials (Johansson, Ekstrand-Tobin, Svensson, & Bok, 2012). However, as different products have their specific RH_{crit}, according to the model, material data needs to be provided for each product through testing.

If the RH_{crit} is not known, Class A is recommended to be used. This is also in line with recommendations from the Swedish National Board of Housing (BBR 2014:3, 2014). It is recommended that the material producers provide and communicate data of RH_{crit}. Some producers in Sweden have performed tests at RISE. As this is commercial information, it is not referred to in this study. We have no knowledge about whether testing have been performed at other laboratories for other materials.

CML-method

The test was performed according to 'Laboratory method for assessment of the lowest hygrothermal conditions required for mould growth' (SIS-TS 41, 2014), also named the CML-method (Critical Moisture Level-method) (Johansson, Ekstrand-Tobin, & Bok, 2014). It is based on different standardised methods for determining the mould resistance of building materials and on laboratory testing (Johansson, Ekstrand-Tobin, Svensson, & Bok, 2012) and is validated in field studies (Johansson, Svensson, & Ekstrand-Tobin, 2013). The method is also described and discussed in (Johansson, Ekstrand-Tobin, & Bok, An innovative test method for evaluating the critical moisture level for mould growth on building materials., 2014) and is published in (Johansson, 2014).

If RH values are below the lower growth curve, no mould growth is expected. If it exceeds the upper limit growth curve, mould growth is predicted. Values in the zone between the upper and lower curve represent a "yellow-light case". However, the model also predict mould in these cases to be on the safe side (Johansson, Svensson, & Ekstrand-Tobin, 2013).

4.2.4 Wood rot

Wood rot can occur in wooden elements in constructions, in cases of excess moisture. Therefore, decayed wood is an indication of moisture problems in the building, and all moisture problems should be mitigated prior to installation of internal insulation. Wood decay is initiated by three types of rot fungi; brown rot, soft rot and white rot. Some fungal species can transport moisture over large distances, thus the moisture source feeding the fungal attack may not be located at the decayed wood. Wood rot yields reduced strength and mass loss in the wood. The consequences can be detrimental, and ultimately lead to collapse if the supporting system is attacked. Furthermore, some fungal species give off unpleasant odours, and some may even be the cause of respiratory symptoms for some residents.

Fungal attack is generally caused by a favourable combination of moisture content in the wood above the threshold value for a certain period of time with favourable temperature conditions. Furthermore, previously attacked wood is more prone to new fungal attacks when compared to new, sound wood. Figure 4–12 exhibits examples of wood rot in buildings.

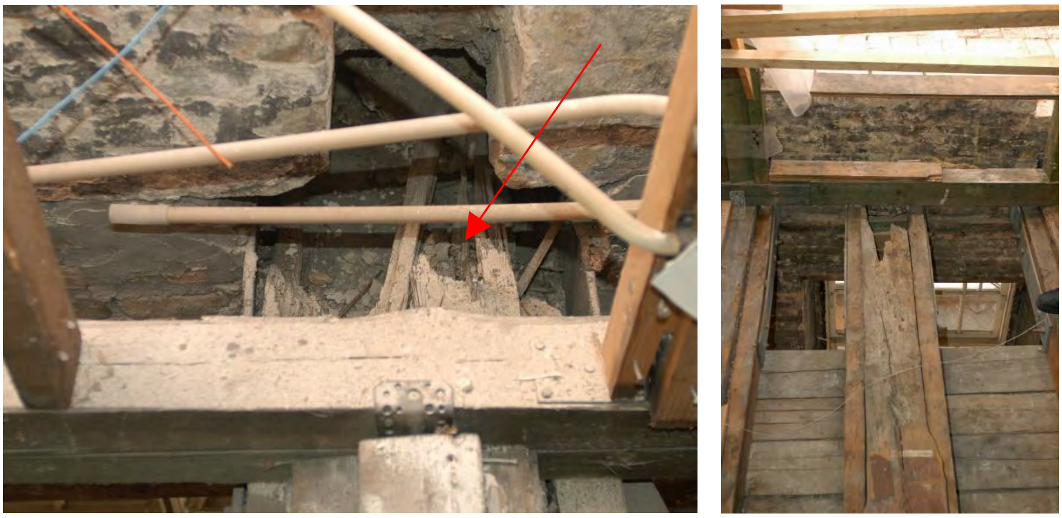


Figure 4–12: Example of wood decay in a storey partitioning beam (L), and rot fungi attack on beam near the roof (R).

As the wooden elements at risk in historic constructions are mainly embedded wooden parts, it will in most cases not be possible visibly to detect wood decay. This includes e.g. embedded wooden beam ends, half timbering and wooden framing for insulation systems. Therefore, wood in the construction and possible excess moisture in the construction should be detected. Moisture in the construction in general is described in Section 4.2.2. **Table 4-6** sums up what to look for, and where to pay special attention with regard to wood rot.

Table 4-6: What to look for, and where with regard to wood rot.

	Externally	**Internally**
WHAT to look for	Water ingress Moist areas e.g. rising damp Other visible moisture damage	Moist areas Other moisture damage Any exposed wooden elements
WHERE to pay special attention	-	Attic (e.g. water ingress through roof) At local thermal bridges Parapets with thinner walls

The critical positions in the building envelope are where wood is present and especially where the moisture load is high. This is illustrated in Figure 4–13 based on (RIBuild Deliverable D1.1, 2015). Not only the position in the envelope is critical: the moisture load on wooden constructions is highly dependent on the structural details and material composition of the detail as well as the characteristics of the materials, including also the wooden species and quality. These factors determine e.g. the drying potential.

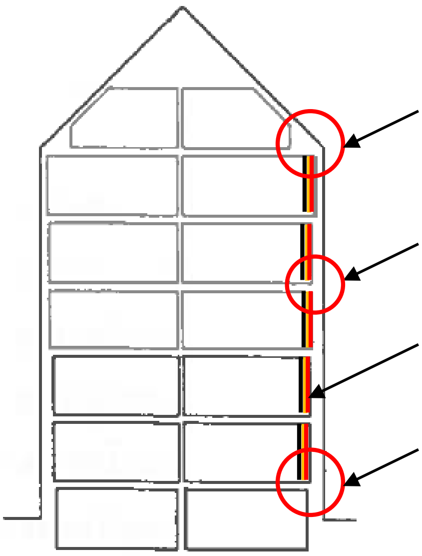


Figure 4–13: Cross section of a multi storey house with markings of areas in the external wall where there is a risk of rot. A prerequisite is the presence of wood. Water ingress or high moisture content in materials in contact with wood can cause rot.

In historic masonry facades, wood is mostly used for half-timbering in external walls. Although structural floors are not a part of the wall, wooden beam ends and supporting laths may be placed in the external walls and therefore in direct contact with bricks or stones in the external wall. Consequently, the moisture content of the embedded timber will be dependent of the moisture conditions in the wall.

When an external wall with wooden elements as half-timbering or beam ends is insulated internally, temperature and heat flux through the wall will decrease and the moisture content therefore is expected to increase in the wall including the wooden elements. Furthermore, if the building is internally insulated with systems that contain wooden materials e.g. wooden framing, there is a risk of rot if condensation can occur due to insufficient vapour barrier or if water from driving rain is trapped in the internal insulation.

Fungal growth can - depending of the species - result in unpleasant odour and emissions, which must be considered as an indoor climate problem. Depending on the exposure and the immunological reactivity of the inhabitants the inhalation of airborne micro-organisms and their metabolites of some species may cause respiratory symptoms (Singh & Singh, 2015).

A rot attack causes wood decay, resulting in reduced strength and ultimately collapse of the wooden construction. How fast a rot attack develops depends on the available moisture. If moisture supply is stopped the attack stops, but will return if moisture again becomes available. Some fungal species need long time exposure to high moisture content before the wooden construction weakens substantially, other species can weaken the wooden constructions fast if the conditions especially favours these species (Munck, Kock, & Larsen, 2003). Damage caused by the first kind of attack could be seen as lack of maintenance, as a slowly developing attack should be discovered before it becomes critical.

Water activity is a prerequisite for fungal growth, and the growth will initiate when the moisture content in wood exceeds a threshold value. The threshold value depends on different factors;

- Time of wetness, i.e. time above the certain threshold value
- Previous attacked wood has a lower threshold value than sound wood
- Temperature

For most fungal species the threshold value is in the over-hydroscopic range; condensation or liquid water sources e.g. penetrating rain are therefore usually a prerequisite for fungal growth. In general, the threshold value for wood rot is higher than for mould growth, and therefore, the threshold value for mould is more likely to be the limiting factor in critical positions where mould growth is not accepted.

Rot can attack all wooden constructions. Some species need lime as well as moisture to grow (Bech-Andersen, 1995). Lime is often used in historic buildings and therefore present for fungal growth.

There are several models for predicting rot or phenomena associated to rot (RIBuild Deliverable D2.2, 2019). Of the evaluated models in the RIBuild project, the model given by (Viitanen, et al., 2010), seems to be the most applicable for the use in RIBuild, as it describe a relevant parameter (mass loss) by using hygrothermal parameters (temperature, relative humidity) in a nuanced way, instead of e.g. defining a general critical value for moisture content independently of temperature. Material parameters describing e.g. water uptake in sound and damaged wood respectively, would be relevant as well, but difficult to determine. In case of simulations where these parameters are relevant, general assumptions must be made.

Remedial actions if wood rot is identified

Some remedial actions are quite simple, such as repairing joints and leaks from downpipes, while others are more complicated, ensuring that sufficient parts of damaged wooden beam ends are replaced.

The most important measures to minimize or prevent rot attacks are:

- Controlling the moisture, ensuring the moisture level will not exceed the threshold value, coupled with a temperature threshold
- Prevent water ingress into the wall; e.g. make sure joints in brick walls are filled, and with no leaks from rainwater drainage systems or through roofs

- Limit the use of wood in critical parts of the envelope, especially less robust species

Moisture is the most important factor in limiting the risk of wood decay in existing constructions containing wood. If parts of the original structure are renewed e.g. due to rot attack in the existing construction is it possible to choose other materials. Replacing wooden beam ends with concrete beams is one possibility. When parts of the construction are replaced, not only the damaged wood is removed; sound wood must also be removed to create a safety zone. How much sound wood that should be removed depends on the fungi species.

4.2.5 Frost damage

Frost damage in porous building materials such as bricks and mortar can originate from a variety of physical frost impacts, of which the volume increase of the water-to-ice phase change is the most widely known. Three conditions must be fulfilled for frost damage to occur:

- The material must be sufficiently wet
- The temperature must be sufficiently low, so that water in the material can freeze
- The material must be sensitive to frost damage.

Frost damage is commonly solely related to aesthetical problems, particularly scaling of the exterior surface of the masonry wall, which normally not lead to structural problems except for very extreme cases. However, by adding internal insulation, the risk for structural damage may rise if the material is significantly sensitive to frost damage.

Figure 4–14 exhibits examples of scaling due to frost attack on masonry. **Table 4-7** sums up what to look for, and where to pay special attention with regard to frost damage.

Figure 4–14: Example of scaling due to frost in masonry

Table 4-7: What to look for, and where with regard to frost damage.

	Externally	**Internally**
WHAT to look for	Crumbling of bricks and joints (or other porous building materials in façade) Scaling of external brick surfaces	-
WHERE to pay special attention	Where moisture accumulates Plinths, corners, defect installations Southwest (highest moisture load from wind driven rain) North (coldest surface)	-

Adding internal insulation to solid masonry may influence the first two conditions for frost damage to occur (wetter and colder existing wall). The wall becomes colder and conditions for freezing of water become more frequent and more intense. Furthermore, freezing will take place deeper into the wall. Secondly, it will be more difficult for the wall to dry inwards because of the internal insulation, especially in the case of using a vapour-tight insulation system, increasing the risk of critical moisture levels. However, only if the brick material is sensitive to frost damage, a colder and wetter wall will have impact.

Porous building materials experiencing high moisture contents and low frost temperatures are at risk for frost damage. Relevant examples are ceramic brick, natural stone and mortar joint for facades of historic buildings, but frost damage may equally occur in concrete facades, roof tiles etc.

Frost damage in porous building materials can originate from a variety of physical frost impacts, of which the volume increase of the water-to-ice phase change is the most widely known. The risk of frost damage is normally highest in the outer millimetres of historic masonry walls, typically shown as scaling of the outer surfaces. Both moisture and temperature levels of porous building materials depend on the wall orientation. The prevailing direction for wind-driven rain in Europe is South-West while the lowest facade temperatures occur in North-faced facades. It is subsequently difficult to predict which is the most exposed orientation with respect to frost damage.

If there is no clear visual evidence, a direct or indirect evaluation of the masonry material could be considered, based on CEN/TS 722-22 for ceramic brick (CEN/TS 772-22, 2006) or EN 12371 for natural stone (EN 12371, 2010). If these (extreme) evaluations give a negative result, it should finally be considered to judge the sensitivity to frost damage at milder conditions with the methodology put forward by (Feng, Roels, & Janssen, 2019); one should keep in mind though that this requires an extensive experimental effort, wherein a large number of material samples has to be available.

Remedial action if frost damage is identified

In short, if the visual assessment reveals evidence of frost damage from the past, application of internal insulation is not recommended, as it implies that the wall is not sufficiently robust for this type of renovation.

Three conditions must be fulfilled to induce frost damage:

- The material must be sufficiently wet
- Phase change must happen in the material
- The material must be sensitive to frost damage.

The first and second condition can primarily be affected by the type and thickness of the insulation material, but in general only a very low thermal resistance will not affect the moisture and temperature conditions, nullifying the desired impact of the thermal retrofit with internal insulation. The third condition cannot be altered in the design or the application of the internal insulation thermal retrofit. However, it can be evaluated whether it applies for the masonry material involved. As a first step, a visual inspection of the existing facade material may reveal evidence of frost damage from the past, which logically is an indicator of potential future frost damage. In these cases, the application of internal insulation should not be recommended.

4.2.6 Algae growth

Microorganisms, plants, algae, or small animals can accumulate on wetted surfaces. It is shown as appearance of stains, readily recognizable on the material surfaces, since they form patinas varying in extent, thickness, consistency, and colour. Depending on the type of microorganism and on their life cycle phase, dark green, brown, grey and pink coloured patinas may occur (Figure 4–15).

The biological colonization of external façades by microorganisms can change the aspect of the surfaces and can even compromise the durability of materials. Algae and cyanobacteria are the main colonizers of building façades, and later they can favour the growth of mould, lichens, fungi and other microorganisms.

(a) (b) (c) (d)

Figure 4–15: Examples of algae growth on external walls: a) and b) façades exposed to wind driven rain; c) and d) fed by drain water from windows overhangs.

Table 4-8 sums up what to look for, and where to pay special attention with regard to algae growth.

Table 4-8: What to look for, and where with regard to algae growth

	Externally	**Internally**
WHAT to look for	Green and black stains Different-coloured patinas	-
WHERE to pay special attention	North and Northwest façades Facades where free water is available, i.e. due to wind driven rain, damaged waste-water pipes, roof drains, etc.	-

Algae and cyanobacteria are the main colonizers of building façades, and later they can favour the growth of mould, lichens, fungi and other microorganisms (Maury-Ramirez, Muynck, Stevens, Demeestere, & Belie, 2013)

Algae and cyanobacteria can develop on a large variety of façades (i.e. on stone, brick, plaster and mortar), whenever suitable combination of relative humidity, temperature and light occurs. The presence of water is fundamental for algae growth. The main causes for wetting of façades are mainly given by wind driven rain, leaks from rainwater drainage systems and dew water (Flores-Colen, Brito, & Freitas, 2008).

In addition to the aesthetic deterioration, algae and cyanobacteria may also cause a biochemical and a biophysical deterioration of the substrate (Tiano, 2001). The production of organic and inorganic acids by the microbial layer and the mechanical pressure exerted by the growing microbial structures, caused by the shrinking/swelling phenomena during the cycles of drying and moistening, induces different types of damages:

- aesthetical (coloured patinas and encrustations);
- physical (mechanical stress and loosens mineral grains especially on stone surface);
- chemical (solubilisation of essential minerals, excretion of organic acids or enzymes, pH reduction, change of the electrical conductivity).

Algae and cyanobacteria are often widespread on façades, and several are the factors that influence their growth, such as climate, building design and façade materials. Considering that building envelope is characterized by extreme fluctuations of temperature, repeated desiccation and high UV-radiation, algae and cyanobacteria can tolerate these variations, maintaining a metabolic activity. Different algal species have very different life-styles and tolerance of variations in temperature, moisture etc. and they are metabolically active only when appropriate combinations of relative humidity, temperature and light are present. Temperature and free water availability are the most important environmental conditions that affect the growth of these microorganisms (D'Orazio, et al., 2014), (Ortega-Calvo, Ariño, Hernandez-Marine, & Saiz-Jimenez, 1995).

For most algae and cyanobacteria an optimal temperature for growth is estimated within the range 20 °C - 30 °C, while the range of suitable growth is usually considered between 5 °C and 40 °C (Singh & Singh, 2015).

Wind driven rain, leaks from rainwater drainage systems and dew water are the main causes for wetting of façades, providing liquid water for algae. However, algae and cyanobacteria can survive in dry periods and can restart their growth when enough water is available. Therefore, the drying of façades during the day is not enough to prevent algae colonisation. Hence, the presence of algae and cyanobacteria on the surface indicates a high moisture content of the substrate (Miller, Dionísio, Laiz, MacEdo, & Saiz-Jimenez, 2009).

The growth of algae and cyanobacteria is also influenced by the orientation of the façade. Indeed, the north-facing walls, which are wetter for longer time and less irradiated by the sun, are faster colonized. Similarly, a façade exposed to dominant winds could be colonized more easily than the other sides of the same building: the wind could transport both rain and biological contaminants. A façade which is often wet by rainfall promotes the growth of algae. However, a high temperature caused by direct irradiation induces water evaporation by heating the material surfaces (Ortega-Calvo, Ariño, Hernandez-Marine, & Saiz-Jimenez, 1995).

The geometry of the building may offer preferential routes, where water could stagnate after a rain event, creating the ideal conditions for the proliferation of algae and cyanobacteria. If balconies or roof overhangs reduce the wind driven rain on the walls, a light inclination of the façade increases the surface exposed to the water. Once the algae have grown, the run-off rain water contributes to replace the old cells with new cells and favours the spread of algal spots to further building components not already contaminated. External parts of building, which are often moistened for long periods or easily covered by biological propagules, are highly sensitive to the biological colonization. Biofouling often increases at the foot of walls, junctions of different coatings, and overhanging elements (cornices, mouldings, balconies, etc.) (Barberousse, 2007).

The biological colonization on building surfaces is also highly dependent on the material substrate: porous building materials (e.g. bricks, stones, mortar) can contain a large quantity of water, which becomes available to the microorganisms. Since historic masonry walls are generally built by porous bricks and natural stones, they can contain high quantity of moisture, and thus be greatly exposed to algae colonisation. Moreover, roughness affects the flow of water on the surface and favours the adhesion of organic material blown by the wind or brought by water flow on the substrate. Consequently, rough building façades are more subject to biofouling than smooth ones (Tran, et al., 2014). Finally, the influence of pH of the substrate on algae is not well known, but, like most microorganisms whose growth is satisfactory between pH values equal to 6.0 and 9.0, algae and cyanobacteria found on building façades can normally develop at a pH equal to 8.0 (Singh & Singh, 2015).

To date, only few mathematical models are able to describe and predict algae and cyanobacteria biofouling on building surfaces.

A main algae failure model, recently developed based on the Avrami's Theory, predicts the algae coverage of a certain surface, depending on specific material properties and boundary conditions (Quagliarini, u.c., 2019). Material properties are related to the porous structure of the material: indeed, open porosity and pore distribution affects the retention of water and nutrients important for the growth of algae. A relevant effect is also given by the roughness, which is not an intrinsic property of the material, but depends on the production process (surface smoothing procedure). Environmental conditions, as temperature and relative humidity, are considered in the model and affect the growth rate of algae and cyanobacteria over the time when exposed to optimal and non-optimal environmental conditions.

As a result of the failure model assessment, a specific index expresses the percentage of the surface area covered by the microorganisms.

An in-situ evaluation of the deterioration caused by the proliferation of algae on façades can be made with both quantitative and qualitative analyses (Graziani, u.c., Evaluation of inhibitory effect of TiO2 nanocoatings against microalgal growth on clay brick façades under weak UV exposure conditions, 2013), by measuring:

- the chromatic variation of the materials' surface
- the extension of the covered surface during the time.

Qualitative analyses consist on chromatic investigations on façades. Colorimetric measurements for the evaluation of the chromatic variation (*ΔE*) can be carried out using a spectrophotometer, in accordance with UNI EN 15886:2010 (UNI EN 15886, 2010) and UNI 1602371:2018 (UNI 11721, 2018). On each investigated area, measurements should be periodically repeated on the same points. Results are expressed in CIELab colour space and averaged to obtain a representative value for each investigated area. Colour variations is calculated in terms of total colour difference ΔE, following Eq (4.1):

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (4.1)$$

where L_0^*, a_0^* and b_0^* indicate the colour coordinates of samples at the first measurement, and L^*, a^*, b^* the coordinates periodically measured during the monitoring. According to standard methods (UNI EN 15886, 2010), (UNI 11721, 2018), a total colour difference $\Delta E<1$ is considered not visible by naked human eyes, while a ΔE ranging between 1 and 2 is detectable only with a close observation. From an engineering point of view, a $\Delta E=1$ can be assumed as the acceptable lowest limit for algae growing. In case of average *ΔE*>1, the term $a_0^*-a^*$ should be evaluated to verify if the colour change is due to the presence of algae. In fact, the variation *Δa* indicates a colour difference in a red/green scale. That way, it permits to associate the colour variation to the appearance of algae as green stains: the amount of red is indicated by positive values (*Δa>0*), while a green toning by negative values (*Δa<0*).

The colorimetric analyses should be associated to the quantification of the biofouling extension, evaluated by a (quantitative) Digital Image Analysis (DIA) of the growth rate of algae (Graziani, et al., 2014). To calculate the extension of colonized area in-situ the so-called "threshold method" can be adopted (Tiago & Wayne, 2011). The colonized surfaces need to be periodically digitalized with an adequate image resolution, and elaborated to calculate the algal coverage, expressed as a percentage of the total sampled area. Once set the threshold values in CIELab colour space, the acquired images are binary converted to consider only the pixels related to the contaminated surface by algae (Figure 4–16). The covered area by microalgae is represented as the percentage of the black pixels on the total area of the sample (Muynck, Ramirez, Belie, & Verstraete, 2009). Measurements should be carried out periodically in accordance to the estimated growth rate. Results are averaged on at least three samples for each investigated area.

Figure 4–16: An example of binarization process; from left to right: acquired images of a colonized brick are elaborated by a filtering process (threshold method) to obtain binary images

Remedial actions if algae growth is identified

Remedial actions should be performed by specialists to avoid damages of the material surfaces and to ensure that a specific treatment is feasible.

Once a façade is deteriorated by the presence of algae and cyanobacteria, mechanical, physical and chemical measures can be adopted to face the problem. Mechanical methods can be used to remove stains and patinas from contaminated elements either by hand or with tools, and a preliminary biocide treatment (applied before the mechanical intervention) is advantageous to facilitate the removal of biofilm. The most widespread physical interventions against algal and cyanobacteria growth is surface treatment using ultraviolet (UV) radiation. Furthermore, chemical methods can give satisfying results, but it should be remembered that the use biocide agents of synthetic origin like pesticides and disinfectants, have a side problem related to the use of pesticides that persist in the soil or water.

After the removal of biological contaminations, a hydrophobic treatment on the material surface is recommended to prevent or minimize a future algal development. Operations should be performed by specialized practitioners to avoid damages of the material surfaces, and experts should evaluate case-by-case and test the products on small portions of the building before the application (Tiano, 2001).

4.2.7 Salt efflorescence

Salt efflorescence is an expression for the deposits of salts on the surface of masonry. Salt efflorescence is formation of powdery, usually white, crystals or coating on masonry surfaces. The deposition occurs when soluble salt is present, and dissolved in moisture within the wall. The moisture and diluted salts move towards the surface for evaporation, causing the salts to form superficial crystal formations. Salt efflorescence can appear both internally and externally, and examples of salt efflorescence in both cases are shown in Figure 4–17. As the salt migrates with moisture, the presence of salt efflorescence can be an indication of moisture problems in general, and often rising damp can be the driving factor for the salt depositions.

Salts in masonry can originate from the original building materials themselves, or from atmospheric pollutants in the surrounding air. The buildings may be constructed on saline soil, or the soil may have become saline from agricultural fertilizer. The history of a historic building may also yield information on salt origins, if it has been used for e.g. manure, salt or gunpowder storage. Finally, nowadays a major contributor to salty masonry is road salt for removal of ice and snow on roads and pavements.

Figure 4–17: Examples of salt efflorescence in masonry walls; top row: externally, middle row: internally, bottom row: façade with salt attack.

The location of a building furthermore influences the salinity of soil, air and masonry, and thus there are salt exposure classes based on location. Buildings located in coastal areas, or adjacent to roads that are salted in winter, are therefore classified as being exposed. Red bricks usually have a higher porosity when compared to yellow bricks, and thereby attract more moisture and salt. For this reason, red bricks are more prone to salt damage compared to yellow bricks.

The previous use of the building can also have an impact of the quantity of salt inside the masonry, e.g. if the building has been used to store gun powder (RIBuild Deliverable D1.1, 2015).

Table 4-9 sums up what to look for with regard to salt efflorescence, and where on the building to pay special attention.

Table 4-9: What to look for, and where with regard to salt efflorescence.

	Externally	**Internally**
WHAT to look for	Salt crystallization on the surface Paint deterioration Scaling of masonry	Salt crystallization on the surface Paint deterioration
WHERE to pay special attention	At the plinth (rising damp) Corners of the building Red bricks	Basements walls

As removal of the cause for salt efflorescence is difficult if not impossible, it is recommended not to proceed with internal insulation if salt efflorescence is detected.

Salt migrates with moisture, and the efflorescence occurs at the surface. Often the salts will migrate with rising damp, so basement walls, or the façade near the plinth are often good indicators for presence of salt. Visible salt deposits in masonry often appears as white, crystal-like, powdery substance, or merely as a white coating. Note that loose external salt efflorescence may easily be weathered away by the climate, and therefore may not be visible at the time of inspection.

Sub-florescence is the accumulation of salt crystals beneath the surface of the masonry. Due to expansion of the salt, and crystallization pressure, the salt can cause serious damage to masonry. Similar to frost damage, sub-florescence can cause scaling of the surface. The presence of salt becomes apparent if the outer layer detaches. Salt efflorescence is an indication of the presence of moisture. Therefore, the moisture source should be located and remedied prior to installation of internal insulation.

Moisture damage to facades can be often be associated with presence of salt. Moisture damage is often caused by a lack of horizontal and vertical sealing, insufficient protection in the splash water area, incorrect material selection, damage to the roof drainage system, leaking roofs, window connections or damage to building services. The water dissolves the harmful salts from the wall and transports them to zones with lower humidity (surface), where favourable crystallization conditions are present. Walls containing salts may even be more susceptible to moisture, as the salts can absorb moisture from the surrounding air (osmosis).

For a complete diagnosis of salt content in masonry, the salinity can be measured in drill dust samples, and should not exceed 0.5 % by weight. As salt has hygroscopic properties, it will in itself attract moisture from the air in high relative humidity conditions, and bind this moisture. Thus, the moisture level is kept rather constant with the presence of salt, which will crystallize where the moisture level is not constant, i.e. at the surface.

Frequent damage patterns of salt efflorescence are e.g.

- Efflorescence of salts, crust formation on surfaces
- Damage due to salt crystallization (spalling, shell formation and attrition), also within the stone structure due to volume increase and high crystallization pressure with insufficiently resistant facade material.
- Hygroscopic water damage, visible by damp stains, often already with attacked surface; moisture from the environment is bound by salt-loaded areas in the material in this case.
- For plastered surfaces: Flaking on paint with efflorescence (often in the base area, at the eaves, under window parapets)
- Damage in pedestal areas caused by frost-thaw salts

As part of a renovation measure of a salt-loaded facade, the causes of the moisture and salt load must first be checked and measures taken to eliminate them (e.g. blocking, drying, etc.). The degree of salinity should be determined to derive the necessary steps.

Salt complicates DELPHIN simulations by affecting the moisture content, and the characterization model does not include a parameter to describe salt storage capacity. Furthermore, it was not possible to get a clear picture of the number of damages related to presence of salt or locate it to specific types of buildings (RIBuild Deliverable D2.2, 2019). Therefore, to be on the safe side, the RIBuild guidelines recommend not to apply internal insulation if visual inspection could detect (unwanted) presence of salt. And presence of salt is not part of the simulations behind the RIBuild web tool.

Remedial actions if salt efflorescence is identified

As removal of the cause for salt efflorescence is difficult if not impossible, it is recommended not to proceed with internal insulation if salt efflorescence is detected.

There are different methods for salt remediation.

- With a planned drying, the salts will also reach the facade surface with the moisture transport. These must always be removed dry on the surface.
- In the case of brick facades, the joints must be completely renovated up to at least 50 cm beyond the affected areas.
- In the case of partial high salt contents, the salt-loaded areas are removed, i.e. contaminated plaster or stones are removed and new plaster or stone replacement is applied, resulting in a natural reduction of the salt content.
- Chemical processes, in which easily soluble salts are converted into poorly soluble or insoluble salts.
- Physical processes in which salts are dissolved and transported to a defined location where they crystallize. This is achieved, for example, with compresses that are applied to the wall surface and removed again after the salt has been added.
- Coatings and plaster systems are frequently used. However, this depends on the surface design of the façade (plaster façade). The best known of these are pore-hydrophobic restoration plasters with high water vapour permeability and reduced capillary conductivity. After the plaster has been saturated with salts, the restoration plaster has fulfilled its function and must be removed.

4.2.8 Rising damp

Rising damp is when water migrates in porous building materials, e.g. masonry, from below ground level, into and through the construction, and up above ground level. The pore structure and porosity allow these materials to transport liquid moisture. Moisture accumulation in walls due to rising damp can appear visibly by discoloration (darkening) of the wall to a certain level above the ground. Examples of rising damp in external façades are seen in Figure 4–18.

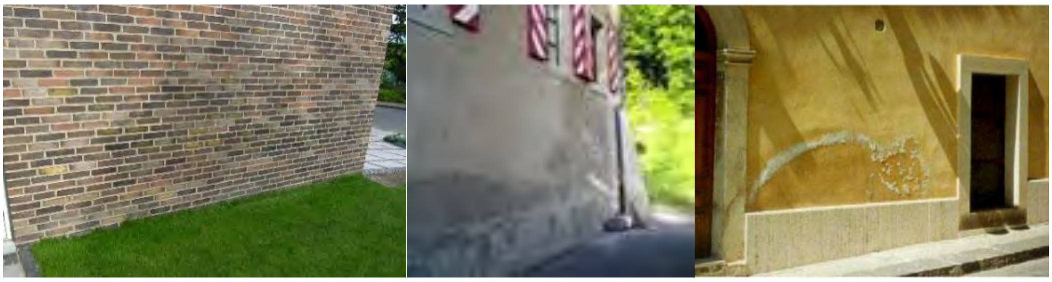


Figure 4–18: Examples of rising damp in external masonry, appears as darkened/moist areas (Left and center), and an example also showing salt efflorescence (right). Source (center): CSC Sárl https://conservation-science.ch/

Accumulation of moisture in masonry facades can yield several deterioration mechanisms, why it is undesirable (Section 4.2.2). Moisture accumulation in the wall can cause damage to surface treatments; peeling of paint, damaged render, deterioration of brick and mortar due to frost damage, or the appearance of salt efflorescence. If moisture accumulates behind a diffusion open paint, the evaporation of moisture is inhibited, and in time will cause the paint to bubble and peel off. Examples of damage from moisture accumulation in walls can be seen in Figure 4–19.

Figure 4–19: Examples of rising damp and damages caused by moisture in the walls; left: darkening of masonry and salt efflorescence, middle: frost damage in masonry, right: peeling of paint due to moisture accumulation and too diffusion tight paint (Source: Morten Hjorslev Hansen).

Rising damp can appear in both external and internal walls. Internally the problems will most likely be noticeable in the basements. Damp walls and moisture in general are always considered problematic and issues to be addressed. Moisture in the façade is undesirable as it can lead to e.g. frost damage (Section 4.2.5), mould growth (Section 4.2.3) and general deterioration (Section 4.2.2), especially of embedded wood (Section 4.2.4).

When adding internal insulation, the risk deterioration processes increases, as the existing wall becomes colder, and furthermore the drying potential is reduced. **Table 4-10** summarizes where one should pay special attention when visually inspecting the building, and what to look for.

Table 4-10: What to look for, and where with regard to rising damp.

	Externally	**Internally**
WHAT to look for	Dark/moistened areas on walls Salt crystallization on the surface Paint deterioration Scaling of masonry	Dark/moistened areas on walls Salt crystallization on the surface Paint deterioration
WHERE to pay special attention	At the plinth	Basements walls

With regard to rising damp, there are several possible moisture sources, including ground water, infiltrating surface water, damp soil, defective piping and surface water combined with terrain sloped towards the building. Some of the possible moisture sources in basements are illustrated in Figure 4–20. Walls affected by rising damp, can even become more susceptible to moisture, as the risen ground water contains salts that furthermore absorb moisture from the surrounding air (osmosis). Rising damp can sometimes be mitigated according to the moisture source; e.g. repair of defective piping and wrongly sloped terrain may alleviate the moisture source, while moisture from damp soil can be reduced by installation of a drainage system on the external side of the walls below ground. To prevent moisture from migrating upwards via porous materials in the construction, physical damp-proof moisture barriers can be installed in the perimeter of the wall.

Figure 4–20: Possible moisture sources in basements (https://gi.dk/Publikationer/Standsning%20af%20Grundfugt_web.pdf)

Moist areas in façades due to rising damp can appear when the porous masonry is in contact with moisture, and absorbs water by capillary forces and due to water pressure. There are several sources from which the water in a moist façade can originate, including;

- Ground water, infiltrating water (seepage of surface water through the ground) or damp soil surrounding the foundation or basement walls
- Defective piping (either underground plumbing or external drainage systems)
- Surface water (precipitation in the case of the terrain being sloped towards the building)

Remedial actions if rising damp is identified

The typical remedial action, to insert horizontal moisture barriers in the external wall, is complicated and requires experts.

Initially the moisture source should be identified, and the cause of moisture appearance should be addressed. Depending on the moisture source, there are several options for remedying the moisture accumulation due to rising damp. Obvious physical damage and problems, e.g. in the case of leaky drainage or piping, these systems should be repaired properly, or if surface water appears to be an issue due to the terrain being sloped towards the building, the slope should be reversed if possible. A slope of minimum 1:40 away from the building for the first 3 m next to the building is preferred (Brandt, 2013). Heating of the basement is generally a good idea, but especially if the internal moisture sources are high, as it improves the drying potential of damp walls. Furthermore, to not impede drying of a moist façade, diffusion open paint (e.g. silicate paint) is advisable for the internal surface. This allows more drying than in cases of diffusion tight paint and can prevent peeling of paint. Ventilation of the basement will remove moisture in the winter, however, in the summer ventilation with hot moist outdoor air may cause high relative humidity or even condensation on the colder basement walls.

With regard to moisture penetration from damp soil, it may be beneficial to implement a drainage system around the building, which can relieve some of the moisture load on the wall. The drainage system can be combined with external thermal insulation of the basement wall; a warmer basement will improve the drying potential. If the risk of moisture penetration from the outside is small, insulation with hydrophobic mineral wool or loose aggregates (coated) can be used, thereby the external surface will be diffusion open, allowing the wall to dry to the outside. If the risk of moisture penetration from the outside is high, the thermal insulation could typically be a lining of plastic sheets combined with a cellular foam with drainage grooves (Brandt, 2013). These plates are mounted and shaped in a manner that carries the water away from the construction to the drainage system. Another option is to roughcast the external basement walls, including two layers of asphalt to ensure water tightness.

Traditionally rising damp in basement walls is inhibited by damp-proof courses, which are continuous moisture barriers. Physical moisture barriers can be of steel plates that are vibrated into mortar joints in the depth of the masonry construction if the joints are continuous. It is also possible to saw through the wall thickness, a section at a time, and place either steel sheets or reinforced roofing felt as moisture barrier. Examples of these measures are seen in Figure 4–21.

Sawing of facade for placement of steel sheets

Corrugated steel sheet vibrated into mortar joint

Principle of rising damp and application of physical damp proof course

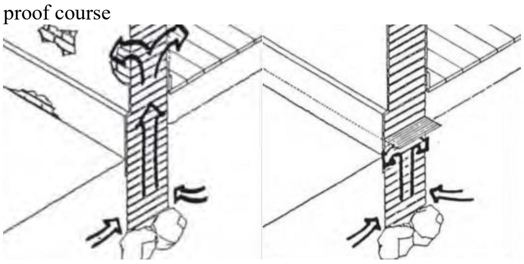


Figure 4–21: Examples of continuous moisture barriers (Source: Morten Hjorslev Hansen (left and middle),* (BYG-ERFA, 1997) *(right)).

4.2.9 Graffiti on building facades

Although graffiti on building facades does not hinder the installation of internal insulation, it should be considered to remove it. At least, it should be removed in the case it is decided to protect the façade from external load by adding a water-repellent agent. This agent might also make it easier to remove future graffiti from the façade.

Remedial actions if graffiti is present

It is recommended to make use of specialists to remove graffiti as the condition of the wall and the materials involved defines the most suitable method.

The removal of unwanted graffiti from the facade usually is expensive, but to make it easier to remove graffiti in the future anti-graffiti protection can be applied to the cleaned facade. This consists of a special coating of the façade to prevent deeper penetration of graffiti paint layers. Thus the graffiti remains on the surface and can be easily removed by suitable cleaning procedures. In case the building includes grounded surfaces, e.g. made of marble, removing graffiti can result in stone damaging, while leaving the graffiti is safe although keeping the ugly look.

The systems are classified according to their removability and durability:

- *Temporary system*: a system based on silicone that dissolves during cleaning together with the graffiti. It must be renewed and is open to water vapour diffusion
- *Semi permanent system*:
    a. Single layer system: The protective layer is partly removed during cleaning, and should be partly renewed after cleaning. It makes use of hydro- and oleophobic systems and is open to diffusion
    b. Two-layer system: Includes a permanent primer and a temporary protective layer. Only the protective layer dissolves during cleaning together with graffiti and has to be renewed. The system is open to water vapour diffusion
- *Permanent system*: A system with several layers that remain permanently on or in the substrate (the brickwork), resistant to cleaning, increases the diffusion resistance of the façade and delays the drying behaviour. The coating system is usually based on polyurethane. As delaying the drying behaviour might be a problem when adding internal insulation, one has to be careful by using a permanent system in this case.

Some types of water-repellent agents might also work as anti-graffiti protection, especially if they mention oil repellence in their data sheets, but in general a water repellent agent cannot be considered an anti-grafitti measure on its own.

4.3 Collection of information about the building and surroundings

4.3.1 Summary – applicability of internal insulation

While the first part of the visual assessment (Section 4.2) focused on visible moisture damage, further assessment is needed to evaluate whether the building envelope is sufficiently robust to meet the changed hygrothermal conditions caused by adding internal insulation. Although the building envelope in its present state might seem OK, or a plan is made to take the needed measures to improve the condition, this is not necessary sufficient to ensure that internal insulation will work with regard to moisture safety. Both the weather, especially the driving rain load (Section 4.3.2) and the indoor climate (Section 4.3.6) can affect the building's ability to function after adding internal insulation. Especially if the building contains moisture sensitive or frost sensitive parts (Sections 0 and 4.3.4) or has a defect rain water collection system (Section 4.3.5).

If more details are needed, additional material parameters have to be obtained via measurements either on site or in the laboratory (Section 4.4). This will serve as input data for a realistic prediction of the hygrothermal behaviour via simulation models. The more detailed and precise the information about the state of the building before renovation, the safer is the application of internal insulation.

Table 4-11 summarises when internal insulation is applicable, might be applicable or is not recommended. The indoor climate in the winter season should generally not exceed 50 % relative humidity, if it does a climate control system should be installed etc. See also **Table 4-1**.

Table 4-11: Assessment tool for the applicability of internal insulation, focusing on moisture load, frost damage and indoor climate, adapted from (Steskens, Loncour , Roels, & Vereecken, 2013)

	Internal insulation is applicable	Applicability is unknown	Internal insulation is **not** recommended
Moisture load and frost damage	Typology of the existing facade and exposure to rain		
	Solid masonry wall at last two stones thick Solid masonry wall maximum 1½ stone thick exposed to a relatively small (wind-driven) rain load	1½ stone thick solid masonry wall (exposed to a moderate/high rain load)	Solid masonry wall, maximum one stone thick (exposed to a moderate/high rain load)
	Floor construction		
	Concrete floor or wooden floor, not connected to the facade	Undamaged wooden construction which is connected to the facade	Moisture damaged wooden construction, connected to the facade
	Technical installations		
	Water pipes or ducts, which are susceptible to frost or frost damage is not present Technical installations which do require penetration of internal insulation are not present		Water pipes or ducts susceptible to frost or are frost damage is present
Indoor climate	Indoor climate		
	Indoor Climate Class 3 according to ISO EN 13788 or Indoor Climate class B according to EN 15026 (corresponding to a humidity load in buildings with unknown/high occupancy)	Indoor Climate Class 4 according to ISO EN 13788 (corresponding to a humidity load in sports halls, kitchens, canteens, etc.) or	Indoor Climate Class 5 according to ISO EN 13788 (corresponding to a humidity load in laundries, breweries, swimming pools etc.)

		Higher moisture load than defined by Indoor Climate Class B according to EN 15026	
	HVAC system		
	Well-controlled and efficient ventilation, climate control and heating system		Insufficient ventilation

Aspects of weather that causes degradation of building components:

- *wind effects on buildings*: internal-external pressure difference (convection), highest load at corners of buildings and roofs where flow separation occurs;
- *ambient air temperature*: chemical and biological degradation usually accelerate at higher temperatures, freezing and thawing are especially harmful for porous materials as brick;
- *solar radiation*: has a great impact on the material surface temperature but can also change the atomic structure of a building material (destroys the bonds between the atoms);
- *moisture*: air humidity, condensation, precipitation, groundwater, higher vapour content of the ambient air in summer and lower in the winter, driving rain (horizontal component of rain during windy conditions, part of the rain is absorbed, part may penetrate into cracks and joints), freezing, deterioration by decomposition, corrosion of reinforcement.

In addition to the large-scale classification of the location, it may be useful to investigate the local climate more closely. Risk factors result from local differences in driving rain, the humidity level of the outside air and the drying potential due to solar radiation. Risk factors and associated possible causes are illustrated in **Table 4-12**. Other aspects are also relevant, listed in **Table 4-13**.

Table 4-12: Location and local climate. Risk factors and associated possible causes

Risk factor	**Possible causes**
High driving rain load	Wind-exposed location (high building, limited amount of greenery and surrounding buildings, no kind of windbreak, exposed orientation) Limited roof overhang
High ambient humidity	Located close a forest Surrounding and facade greening Low degree of sealing of the environment
Low drying potential	Strong shading due to surrounding buildings, trees or location in a valley
Low temperatures at winter	Located in a valley (cold air lakes, shading) Exposed position or altitude

Table 4-13: Other possible risks related to the building and the surroundings

	Possible risks
Moisture sensitive parts	Hidden construction details (esp. wooden beam ends or leaky pipes) might contain moisture damage Moisture damage could be a result of adding internal insulation
Frost sensitive parts	Piping embedded in walls may be subjected to freezing, as the temperature in the walls is reduced with internal insulation. Embedded piping should be drained and plugged, and replaced with frost resistant solutions Porous building materials may be subjected to frost damage if the material is sensitive to frost and sufficiently wet. The risk increases with internal insulation, as the temperature in the wall decreases.
Condition of rain water collection	Leakages in the water collection system can lead to wet spots/areas on the facade around the collection system after heavy rainfalls Rainwater can accumulate on horizontal surfaces (e.g. friezes) and be absorbed into porous building materials (e.g. masonry) and cause damage Formation of icicles in winter, may indicate clogged gutters
Indoor climate	High internal moisture load, mainly due to high moisture production (many inhabitants etc.) and low air exchange with outdoor environment (limited ventilation and/or opening of widows)

Aspects related to driving rain load, moisture sensitive parts, frost sensitive parts, rain water collection systems and indoor climate are described in more detail in section 4.3.2 - 4.3.6.

If easy accessible and relatively new, drawings, inspection reports etc. can help when preparing a more detailed building assessment, looking for causes to moisture damage seen at the exterior (Section 4.2), as it often is necessary to open constructions to identify causes. Useful planning documents and data sources are listed in Table 4-14. If no plans are available, it is recommended to carry out a building survey covering the necessary constraint and connection points.

Table 4-14: Possible planning documents and data sources

Data	**Source**	**Purpose**
Floor plans, cross sections, facade views	Building application documents, archives, measurements, photos, information on year of construction	Information on construction (dimensions, superstructures) and areas of use
Construction details	Documents on statics, building descriptions, detailed plans, photos	Detailed structures, information on statically relevant components penetrating the building envelope (supports, beams, girders)
Constructions and materials	In addition to above mentioned documents: building material remnants from previous renovation, invoices, literature sources	Determine the composition of the building envelope

Previous renovation	Planning documents for renovation, photos, invoices, construction diaries, etc.	Changes to the building envelope (superstructures, statics, materials)
Other documents	Expert opinions, e.g. subsoil reports, wood preservation reports, usage history	Observance of special boundary conditions

In most cases, energy efficiency renovation of a building goes hand in hand with system technology renewal. The planned improvement of the building envelope will reduce the final energy requirement of the building. In the case of planned further use of installations or at least parts of thereof, existing components must be suited for this. This includes:

- heating systems (boilers, pumps, additional chimney?)
- ventilation system (supply and return air, heat recovery, only return air?)
- distribution and transfer system
- hot water preparation.

The type and location of the heating system (radiators or surface heating, pipe routing, temperatures etc.) as well as the presence of a ventilation system can influence the effect of a planned internal insulation measure and thus limit or expand the selection of potential insulation materials. For example, critical design points can be mitigated by well thought-out positioning of the heating pipes. It should also be borne in mind that special fasteners are required when installing radiators to the internally insulated outer wall.

Building services and connection details to pay attention to:

- building services: cold water pipes (no laying in or outside of the insulation level, otherwise high risk of frost)
- building services: hot water pipes (drinking water, heating pipes) are problematic, especially energetically, but can contribute to local heating (drying).
- avoid leaks, e.g. due to airtight sockets and switch inserts, cable lines free of empty conduits
- wooden beam ceilings : material and constructive thermal bridge in the area of the ceiling supports, with internal insulation the beam head becomes colder than before, possible insulation, elimination of leaks,
- lower/uppermost floor slabs
- jamb (sides)
- non-insulated floor slabs

Particularly in the case of listed buildings, the existing situation is such that it is often difficult to carry out a sensibly designed internal insulation measure due to structural constraints. In addition, there are requirements under monument protection law that, for example, window face widths cannot be changed, that historic valuable facades must not be painted (and thus protected against driving rain) or that no changes are permitted to brick face facades (e.g. sheeting in the area of projections). Sometimes compromises have to be made here, which may also have planning consequences.

4.3.2 Driving rain load

A good assessment of the driving rain load on the façade is a decisive step when designing an internal insulation system. The driving rain load in combination with the façade materials and façade thickness are the key elements that determine the risk for moisture and frost damage. The rain load on the façade is dependent on the surrounding environment, orientation of the façade, the height of the building and protection of the façade by overhangs and/or exterior finishing. There exist no strict guidelines related to driving rain load, but as general rule, caution should be exercised when the rain load is high.

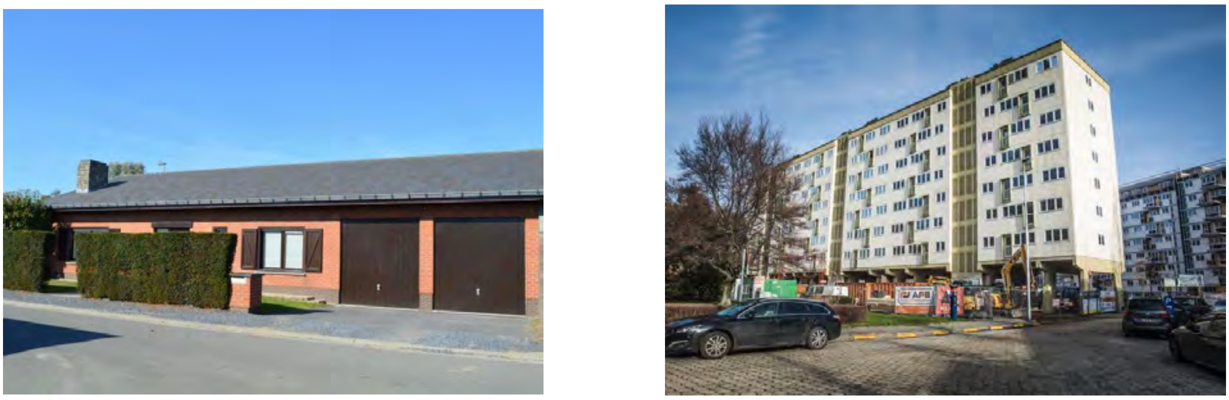
In general, a façade will have a higher rain load if (see Figure 4–22):

- it is oriented towards to the main driving rain direction in an open region with hardly any surrounding buildings
- it is a relatively high building (e.g. a multi-storey apartment building)
- the building is located in a region with high precipitation, e.g. the coastal area or on a hill side
- hardly any protection is provided by cover stones, sills, roof overhangs, etc.

If a high driving rain load is to be expected, care should be taken when designing the internal insulation system. In this case it is advisable to ask the opinion of an expert or to perform a more in depth study to evaluate whether additional protection of the façade is necessary.

a)

b)



c)

Figure 4–22: Driving rain load on a façade will in general be higher for a) a free standing building in an open region compared to terraced houses in the city, b) a high rise building compared to a low rise building and c) facades without physical protections due to overhangs etc.

Wind driven rain is one of the most important moisture sources affecting the hygrothermal performance and hence, durability of building facades. Wind driven rain is rain that is given a horizontal velocity component by the wind, which drives the rain drops against the windward façade of the building. The amount of wind driven rain impinging upon building facades is governed by different parameters such as wind speed and direction, rainfall intensity, environmental topology, the building geometry, and the position on the façade. As a result, data on wind driven rain impinging upon a building façade is typically not available. Standard meteorological data measured by weather stations only provide wind speed, wind direction and horizontal rain fall. To quantify the amount of wind driven rain on a specific façade of a specific building semi-empirical quantification methods can be used, such as the European Standard EN 15927-3 (EN-ISO 15927-3, 2009). In specific cases, more precise, but also more expensive numerical quantification methods such as computational fluid dynamics can be used.

To get a first idea of the driving rain load on a building façade, checking the location of the building, the orientation of the façade and the protection of the façade often provides a first evaluation of the applicability of internal insulation. Weather data of a nearby weather station is important information to get an idea of the driving rain load in the region of the building. Typically this weather data is collected in the free field and local terrain roughness and obstructions (surrounding buildings, trees,…) highly influence the final driving rain load on the façade. Nevertheless precipitation and wind load data from a nearby site will be decisive information to determine the most susceptible wall orientations.

Figure 4–23 shows an example of mean wind speeds for Bremen, Stuttgart and Magdeburg. A slightly higher mean wind speed from the west and south-west sector is recorded for all locations. To evaluate the driving rain load for a building, it is not only the wind speed itself that is decisive, but also the amount of precipitation that strikes the façade together with the wind from a given direction. Figure 4–24 illustrates that if the precipitation is summed up over the different points of the compass, the dominating wind driven rain comes from south- and south-west directions for the three given locations.

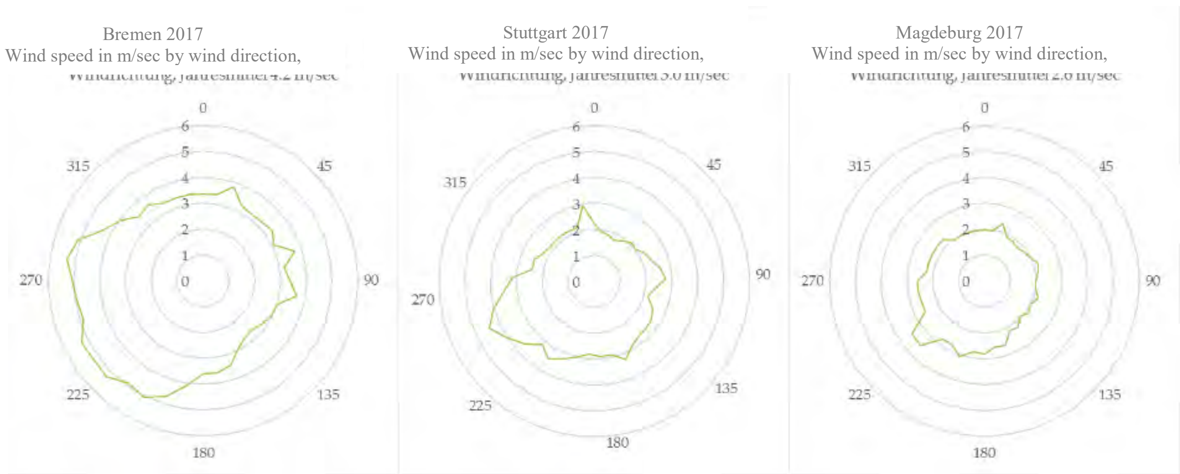


Figure 4–23: Mean wind speeds by wind direction for the locations Bremen, Stuttgart, Magdeburg in 2017. Data source: FTP-server of the DWD (ftp://ftp-cdc.dwd.de/pub/CDC)

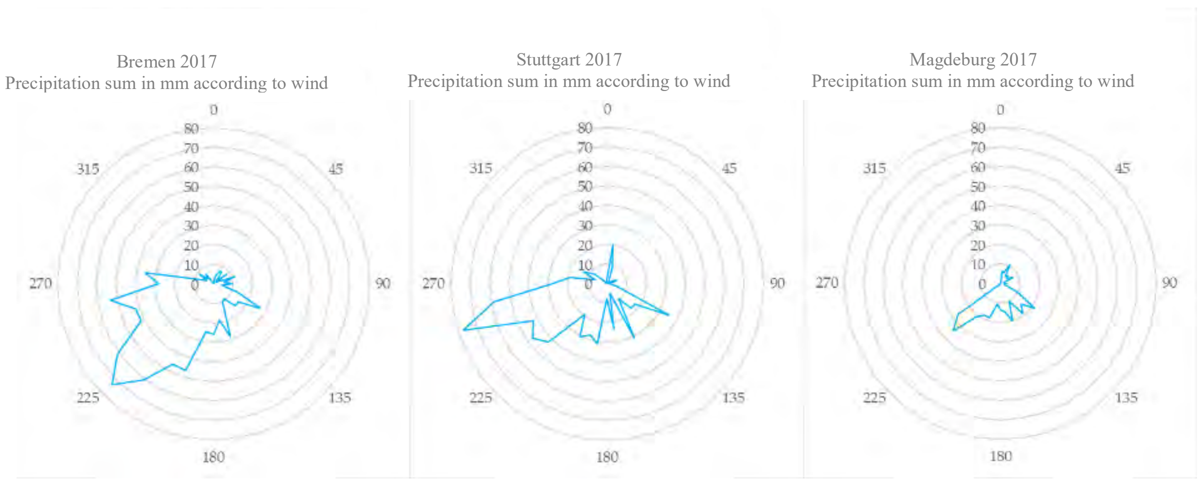


Figure 4–24: Precipitation totals by wind direction for the locations Bremen, Stuttgart, Magdeburg in 2017. Data source: FTP server of the DWD (ftp://ftp-cdc.dwd.de/pub/CDC)

In addition to the local driving rain load, protection on the façade may strongly influence the impinging and absorbed rain. Constructive elements such as large roof overhangs, correct window sills, etc. strongly reduce driving rain loads (see Figure 4–25). The water absorption of the driving rain load can be further reduced by finishing renders, paints or hydrophobic treatment of the walls.

Figure 4–25: Visualisation of rain trajectories on a façade in case of a roof overhang. For small droplets in a low velocity wind field (left figure) the roof overhang shields the façade completely for impinging rain droplets. For larger droplets in a high velocity wind field (figure at the right) shielding is less, but still larger than the geometrical shielding.

If a first check reveals the façade will suffer from high driving rain loads and has insufficient protection against it and no possibility of strengthening it, hygrothermal simulations are advisable to check whether the use of an internal insulation system is nevertheless possible and whether it can be applied without problems.

Knowledge on the wind driven rain load impinging on the building facade is essential as a boundary condition for reliable hygrothermal simulations. Determining the wind driven rain load on the building facade is complex, though, due to the large number of parameters that determine the load: wind speed and wind direction, rainfall intensity and raindrop size distribution, building geometry and local topology, orientation of the facade and position on the facade. To assess the moisture load impinging on the building facade semi-empirical models or catch ratio charts predicted by numerical simulations based on computational fluid dynamics can be used.

Semi-empirical models are based on a combination of theoretical formulae with coefficients that have been obtained from wind driven rain measurements. The best known and widely used illustration is EN-ISO 15927-3[2] (EN-ISO 15927-3, 2009), but other approaches are available as well. In the standard, hourly measurements of rainfall, wind speed and wind direction are first cumulated in an airfield annual index I_A [l/m²]:

$$I_A = \frac{2}{9} \frac{\sum v \cdot r^{8/9} \cdot \cos(D - \Theta)}{N} \quad (4.2)$$

with v [m/s] hourly mean wind speed, r [l/m²] hourly total rainfall, D [°] hourly mean wind direction from North, Θ [°] wall orientation, and N [-] is 8760, the number of hours in a year. The summation is only taken over all hours for which the cos(D-Θ) is positive, hence only when wind is blowing onto the wall.

[2] Parts of the following tekst have been verbatim adopted from the standard.

The airfield index is then transformed to a wall index I_{WA} [l/m²], via:

$$I_{WA} = I_A \cdot C_R \cdot C_T \cdot O \cdot W \tag{4.3}$$

with C_R [-] the roughness coefficient, C_T [-] the topography coefficient, O [-] the obstruction factor, and W [-] the wall factor. The roughness coefficient accounts for the variability of mean wind velocity at the site due to 1) the height above the ground, and 2) the roughness of the terrain in the direction from which the wind is coming. The topography coefficient accounts for the increase in mean wind speed over isolated hills and escarpments (not undulating and mountainous regions) and is related to the wind velocity upwind to the hill or escarpment. More information on how to quantify these can be found in the standard.

The exposure of the wall should be assessed by determining the horizontal distance to the nearest obstacle, which is at least as high as the wall, along the line of sight from the wall. When the obstructions are being assessed, account should be taken of possible changes such as the felling of trees in the development of a housing estate. **Table 4-15** below lists possible values of the obstruction factor.

The amount of rain incident on a wall depends on the type of wall, its height and other factors such as overhangs or the orientation of bricks etc. within the structure. In addition the amount of incident rain varies significantly over the surface of a wall due to the flow of air around corners, over the roof etc. The wall factor W for the appropriate position on the wall is illustrated for a two storey gable, a two storey eaves wall, and a two storey building with flat roof in Figure 4–26.

Table 4-15: Values of obstruction factor depending on the distance of obstruction from the wall.

Distance of obstruction from wall, m	Obstruction factor *O*
From 4 to 8	0,2
Over 8 to 15	0,3
Over 15 to 25	0,4
Over 25 to 40	0,5
Over 40 to 60	0,6
Over 60 to 80	0,7
Over 80 to 100	0,8
Over 100 to 120	0,9
Over 120	1

It should be noted though that the obstruction can vary significantly at different points along a long wall.

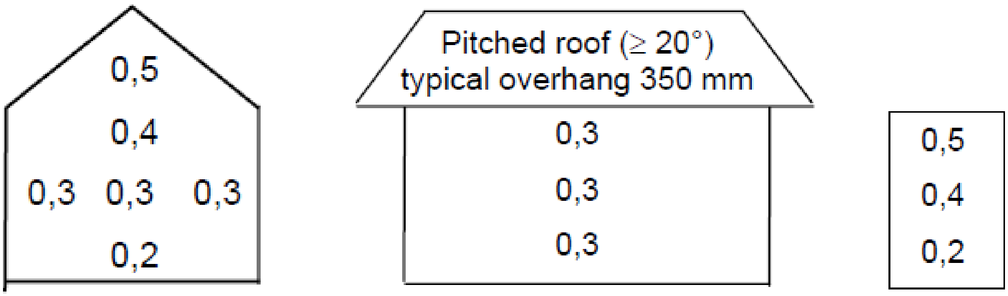


Figure 4–26: Wall factor dependent on the building design.

Semi-empirical models are attractive because they are relatively simple to use. Their accuracy, however, is limited. More detailed information on the driving rain load can be obtained with numerical simulations based on computational fluid dynamics. In these simulations (Blocken, 2004), the wind flow around buildings and the resulting wind-driven rain on buildings is calculated and then translated to a catch ratio description:

$$r_{wdr} = \eta . r \qquad (4.4)$$

with r_{wdr} [l/m²] the wind-driven rain and η [-] the catch ratio. The catch ratio depends on rainfall, wind speed (and wind direction), and is typically obtained through catch ratio graphs, examples of which are shown in Figure 4–27.

These simulations are however quite time-consuming, and can hence not be performed for each and every configuration. A restricted spectrum of catch ratio graphs for different buildings and building clusters is available in literature.

Assessment of the degree of exposure to WDR is summarised in **Table 4-16**.

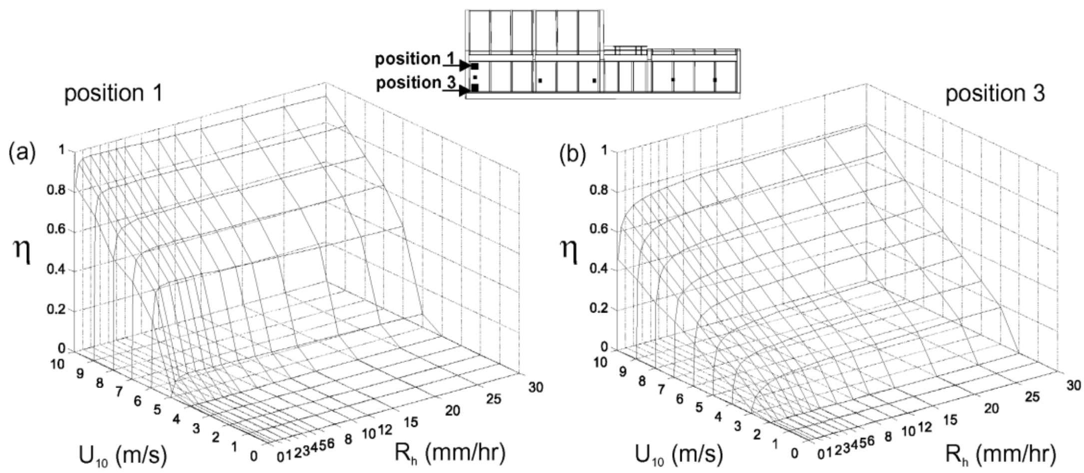


Figure 4–27: Catch ratio graph. Catch ratio (η) as a function of wind speed (U_{10}), amount of precipitation (R_h) and position on a wall **(Blocken, 2004).**

Table 4-16: Summary of assessment of the degree of exposure to WDR

Establish if the building / facade is exposed to large WDR loads			
	Influencing factors	**More exposed**	**More protected**
Location and surroundings	Location and topography	Free standing in open region Coastal area or hill side	Close buildings, e.g. city Wind shielding by e.g. surrounding trees
	Orientation	Predominant wind direction	Other wind direction
Physical building	Height	Tall building	Not tall building
	Constructional rain protection	Little or no roof overhang Defect/incorrect window sills	Large roof overhang Correct window sills
Facade	Surface treatments	No surface treatment	Surface treatment (e.g. render, paint, hydrophobization)
	Type of brick	Brick type with higher sorptivity	Brick type with lower sorptivity

4.3.3 Moisture sensitive parts

A fundamental part of the planning for application of internal insulation is the examination of the existing structure. In particular, this includes locating and documenting the condition of wooden beam ends. At the beginning of the last century, square section floor joists were the most widespread construction method for floor slabs. They were used on all floors and consisted of floor joists (wooden beams), with floor boards or similar on the top and grooves and lining boards or similar as ceiling towards the floor below. Pugging and pugging boards or similar were fixed to the wooden beams to ensure fire resistance and sound insulation. The floor joists were supported either directly by the brick masonry or a wall plate (wooden beam) placed within the wall. An example is seen in Figure 4–28.

Installing internal insulation will expose floor joists and wall plates to lower temperatures and higher relative humidity. I.e. increasing the risk of mould growth.

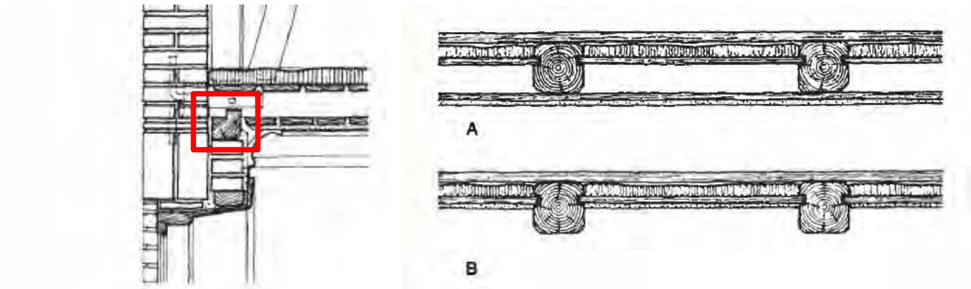


Figure 4–28: Joint between external wall and floor joist supported by a wall plate (marked by red box) (left). Cross-section of floor joists in normal floors (right, A) and above basement (right, B) **(Engelmark, 1983).**

If available, the location of beam ends in the building can be determined from old drawings. If they are not available, detailed investigation should be carried out by qualified experts.

Damage at wooden beams can have different causes and they have to be eliminated prior to application of an internal insulation. In many cases an increased moisture content can be identified. The cause of damage can be due to poor maintenance or due to a single event.

Damage can be caused by:

- The external wall not sufficiently being dimensioned for the existing driving rain load or having damage, in both cases causing moisture penetration due to driving rain (Section 4.3.2)
- Water leaking or condensation taking place in the area of water pipes on the façade or within the external wall. This can lead to permanent or event-based moisture exposure of the wall (Figure 4–29b).
- The wall being salt-loaded and constantly moist as a result of the hygroscopic effect of the salts (Section 4.2.7).
- The beam end covered with vapour-tight materials, e.g. tar board or bitumen sheeting, not being able to transfer moisture from the inside to the surrounding masonry.
- The beam head being filled with air. If the air gap is connected with the indoor climate, infiltration can cause high humidity loads.
- A diffusion-tight coating of the facade. This can lead to an accumulation of moisture in the masonry coming from the inside which cannot dry to the outside.
- Anchors acting as a thermal bridge. Condensate occurs on the cold iron, the outermost point of which is usually further outside than the beam end (see Figure 4–29a).

- Damage events that have led to a long lasting moisture penetration of the masonry or the wood, e.g. accidents with washing machines, leaking baths, tap water or fire-fighting water, broken or blocked gutters and downpipes, leaking eaves connections and/or leaking roof coverings.
- Consequences of war damage, as some buildings have been exposed to the weather unprotected for years or inadequate, improvised repairs persist.
- Earlier insulation measures.
- High relative humidity in the masonry or the wooden beam itself and inadequate rain protection during the construction period.
- Addition of internal insulation can yield excess moisture at the interface due to condensation, as internal insulation creates a steep temperature gradient, and there is a risk of the temperature reaching dew point temperature at the interface.

a)

b)

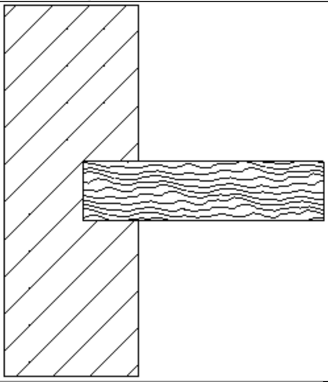
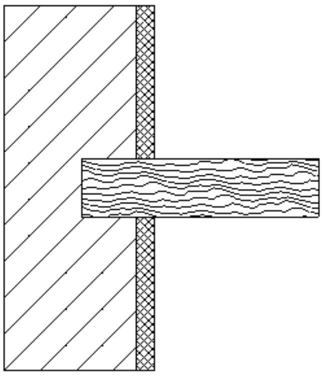
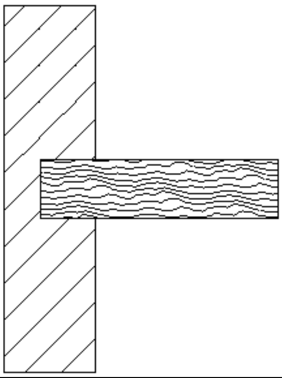
Figure 4–29: Possible damages as a result of a) an anchor or b) a damaged water pipe.

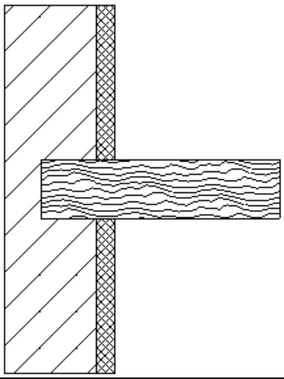
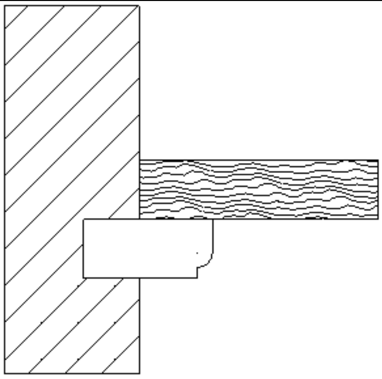
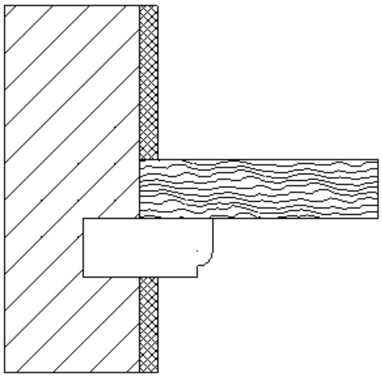
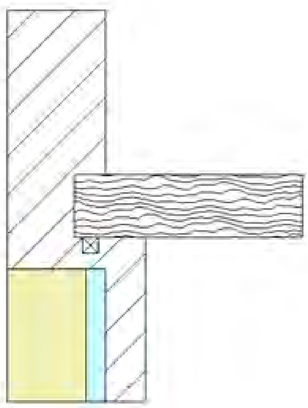
In addition to the aforementioned causes of moisture damage to wooden beam ends, the following points must be observed by a suitable expert:

- Assessment of the ceiling structure (e.g. by uncovering or endoscopy), determination of dimensions and all materials
- Assessment of the bearing
- Assessment of existing insulation measures
- Assessment of weak points in the wall construction: hollow masonry, recesses, etc.
- Assessment of the existing wall construction - materials and their properties
- Checking for infestation with wood-destroying organisms (e.g. fungi, insects). Search on any wood preservation measures carried out earlier.
- Localisation of damaged beam ends incl. condition mapping

The bearings can be evaluated with regard to their hazard potential using **Table 4-17**. For each type of situation, both the original condition (uninsulated) and the condition after adding internal insulation is listed.

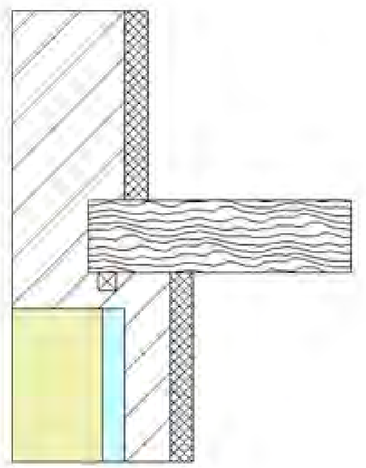
Table 4-17: Bearing types for wooden beam ends in masonry (WTA 8-14, 2014). Bearing can either be by the external wall itself, by a bracket bearing, or a combined bearing (wall plate and the external wall)

<table>
<tr><td colspan="2">Beam end with sufficiently driving rain-proof masonry</td></tr>
<tr><td>Bearing</td><td>Remark</td></tr>
<tr><td></td><td>Tendentially uncritical</td></tr>
<tr><td></td><td>Temperature of the wall construction decreases
Possible moisture accumulation between internal insulation and existing wall
Degradation of the moisture situation in the existing wall
Less favourable drying behaviour of the component
Tendentially critical when exposed to driving rain
Hygrothermal pre-dimensioning required</td></tr>
<tr><td colspan="2">Beam end with insufficient driving rain proof masonry
Whether the masonry has insufficient driving rain protection or not, is more dependent on the masonry properties, estimated by capillary water uptake and the condition of the masonry (e.g. cracks between brick and mortar)</td></tr>
<tr><td>Bearing</td><td>Remark</td></tr>
<tr><td></td><td>Moisture load of the beam end due to driving rain
Possible accumulation of moisture on the inner surface of the outer wall</td></tr>
</table>

<table>
<tr><td></td><td>Temperature of the wall construction decreases
Possible moisture accumulation between internal insulation and existing wall
Degradation of the moisture situation in the existing wall
Less favourable drying behaviour of the component
Internal insulation should be avoided in case of high driving rain loads
Hygrothermal pre-dimensioning required</td></tr>
<tr><td colspan="2">Bracket bearing</td></tr>
<tr><td>Bearing</td><td>Remark</td></tr>
<tr><td></td><td>Beam end in indoor climate
Bearing is made of natural stone</td></tr>
<tr><td></td><td>Temperature of the wall construction decreases
Possible moisture accumulation between internal insulation and existing wall
Degradation of the moisture situation in the existing wall
Less favourable drying behaviour of the component
Tendentially critical when exposed to driving rain
Hygrothermal pre-dimensioning required</td></tr>
<tr><td colspan="2">Beam end on wall plate</td></tr>
<tr><td>Bearing</td><td>Remark</td></tr>
<tr><td></td><td>High risk of moisture and fungal decay due to natural stone (yellow signature) having a higher thermal conductivity than brick

In case of moisture ingress into the outer natural stone layer (one brick width thick), the air layer (light blue signature, 50-100 mm deep) hinders the moisture to be transported to the inner brick masonry layer. The outer and inner layer are fixed to each other using anchor of natural stone, brick or steel.

This solution is also seen without the air layer. It is also seen with brick mansonry in stead of natural stone.</td></tr>
</table>

	Temperature of the wall construction decreases Possible moisture accumulation between internal insulation and existing wall Degradation of the moisture situation in the existing wall Less favourable drying behaviour of the component Tendentially critical when exposed to driving rain High risk of moisture and fungal decay Hygrothermal pre-dimensioning required See the description of the case without internal insulation, regarding the setup of the existing wall.

The application of an internal insulation system changes the temperature conditions in the existing construction. The temperature level in the wall decreases and this leads to a reduction of the drying potential. This is illustrated in Figure 4–30. For the beam end itself as well as for the surroundings, the relative humidity eventually increases. For critical constructions, this increases the risk of destruction of the wooden beam end by wood-destroying fungi.

a) b)

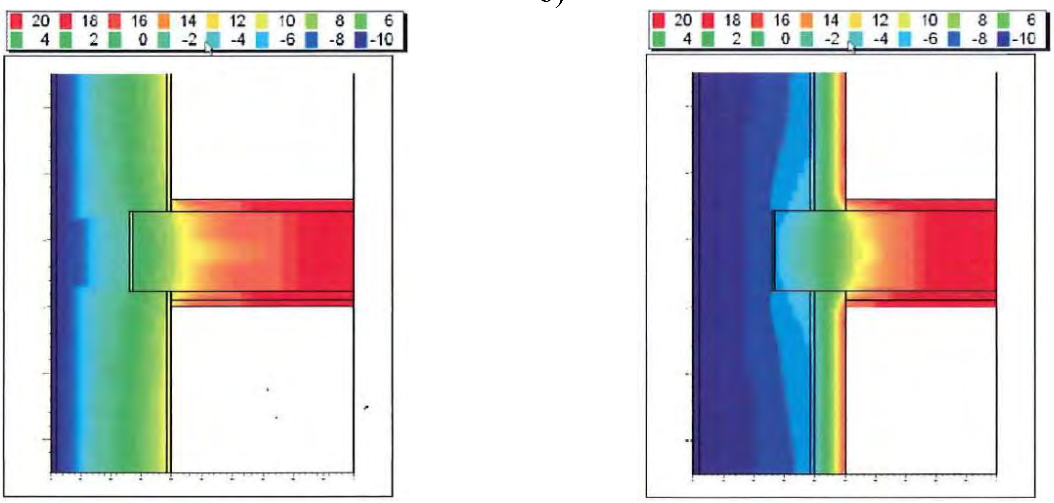


Figure 4–30: Beam end before (a) and after (b) application of internal insulation **(WTA 8-14, 2014)**

To reduce the risk of destruction, planning and executing the installation of internal insulation must done carefully. At the beginning of the refurbishment, defective beam ends have to be replaced or repaired. All anchors, if present, should be removed due to their thermal bridge effect and replaced by statically suitable measures. The same applies to wall plates that are no longer intact. Before installing new wooden beam ends and the subsequent application of internal insulation, depending on the condition of the wall, drying may be needed (see also Section 4.2.2).

Driving rain protection:

Buildings with a low driving rain load usually have a low risk of damage to the wooden beams. The same applies to buildings for which a suitable protection against driving rain is guaranteed due to constructive measures and/or an intact continuous external plaster.

Brick-faced façades have a lower resistance to driving rain. Therefore, the material properties of the bricks and the joint material must be examined prior to the refurbishment. If necessary, a joint refurbishment and in some cases a hydrophobic treatment has to be carried out. Their effect on the construction should be checked by means of hygrothermal simulations. It is advisable to first depict the actual situation to then compare it with the refurbished construction. The evaluation of the results requires an experienced planner. At the construction site, the success of the hydrophobization measure also has to be checked.

Driving rain load is further described in Section 4.3.2.

Sealing layer:

A sealing layer underneath the bearing ensures hygric decoupling of the wooden beam end and prevents capillary moisture from the masonry from entering the wooden beam end. If a permanently dry masonry can be ensured, no barrier layer is necessary.

In case of a high moisture content it is important that not all sides are sealed, as this will hinder the moisture to be transported away from the beam.

The sealing layer have to be designed to in such a way that protrusions are avoided. Furthermore, the sealing layer should be protected from damage by ensuring a smooth mortar bed.

Airtight connection of the beam:

According to practical experience and the current state of European research, beam ends should be walled in in such a way that there is no contact between the beam flanks, the beam top and the end grained wood and the mortar or surrounding masonry (WTA 8-14, 2014). To avoid moisture damage due to convection of air from the inside, a convection-inhibiting connection must be provided. This can be achieved, for example, with pre-compressed sealing tapes, plasterable adhesive tapes or other suitable adhesive tapes, as shown in Figure 4–31. It is also possible to fill the gaps with frayed insulating material. In addition, larger cracks in the wooden beam have to be closed. In most cases, a convection-tight design is not necessary.

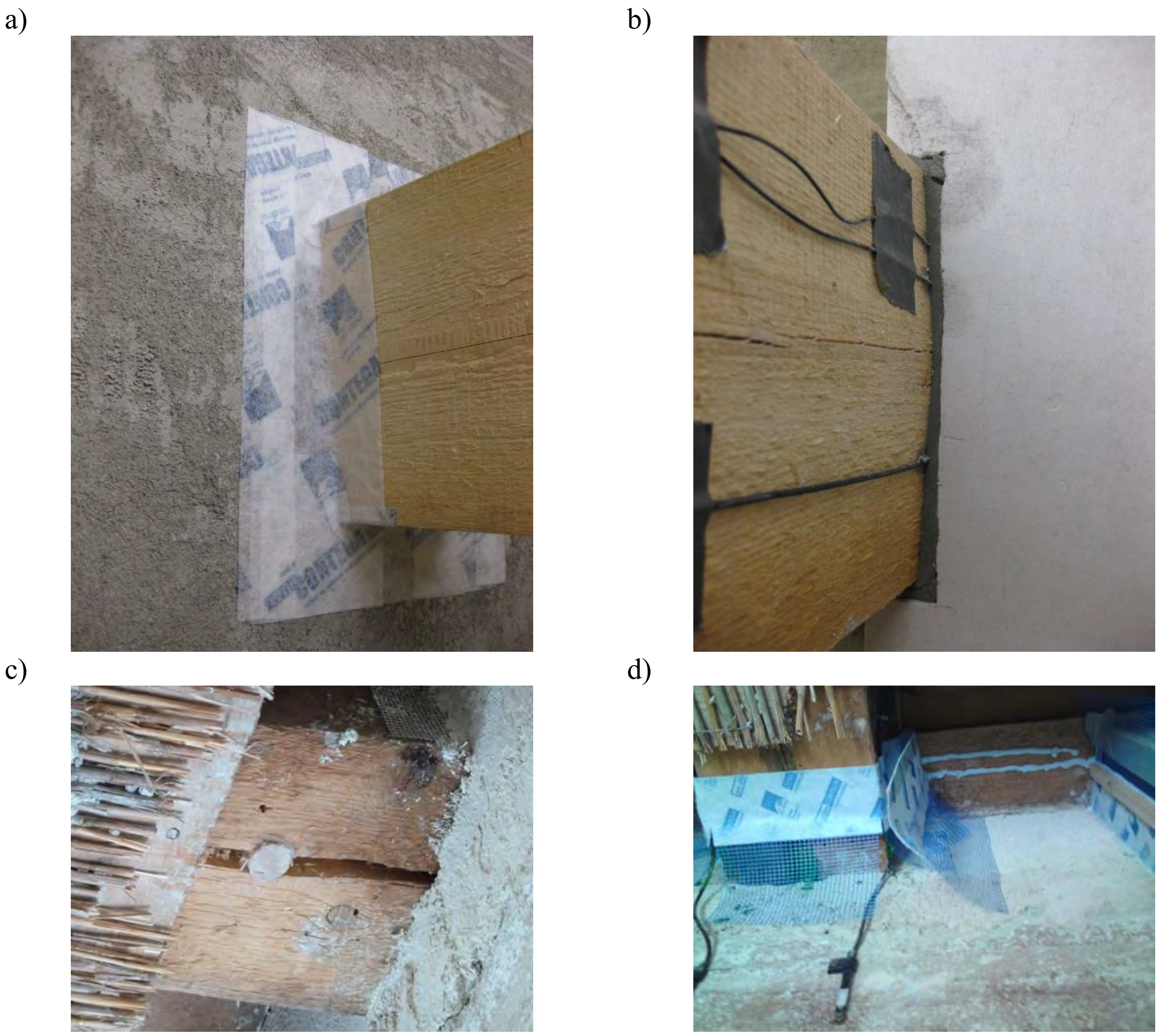


Figure 4–31: Suitable sealing variants a) plasterable adhesive tape, b) pre-compressed sealing tape, c) wood plug in crack* (Kautsch, et al.)*, d) plasterable adhesive tape with a mesh embedded in the plaster* (Kautsch, et al.)*. a) and b) are from a laboratory setup, with the connections made according to specifications of the manufacturer. In c) and d) the beam is seen from below.

If the ceiling is not opened and the intermediate beam area remains uninsulated, a convection-inhibiting connection to the ceiling layers should be made. The hygrothermal conditions at the beam end itself are slightly improved by the thermal bridge effect. In addition, the intermediate beam area acts as a heat and moisture buffer between the interior and bearing.

All types require detailed planning. Their careful implementation has to be checked during the construction process. In the case of very critical construction details, monitoring can ensure safety in subsequent years.

As with hydrophobization, it is advisable to verify the construction details by means of a hygrothermal simulation. At this point, the wood moisture with the limit value of 20 M-% (DIN 68800-1, 2012) is often mentioned as the evaluation criterion. Below this a degradation of wood by fungi or other organisms can be excluded. However, the temperature dependence cannot be represented with this rigid limit value. For this reason, there were investigations in the past that consider the dependencies of temperature, humidity and time with wood degradation (Viitanen, et al., 2010). Based on this, a boundary line was derived in (Kehl, Ruisinger, R., & Grunewald, 2013), which can also be used for the evaluation of the hygrothermal simulation (WTA 6-8, 2016). Below a relative pore air humidity of 95 % (26 M-%) at 0 °C and 86 % (20 M-%) at 30 °C no wood degradation takes place (WTA 6-8, 2016). In individual cases, exceeding can be tolerated if it is ensured that the construction does not tend to humidify in long term. Crossing the boundary line in the first year after refurbishment is to be named here as an example. In the following years, the construction has to have a sufficiently large drying potential so that a long-term moisture condition occurs below the limit line.

Even before the start of the simulation, the wood moisture content of the existing structure can be checked using the measurement methods listed in **Table 4-18**. A detailed method description can be found in Section 4.4.

Table 4-18: Moisture measurement. Classification and accuracy of different procedures.

Procedure	Destructive	Method	On-site measurements	Accuracy
Darr weighing method	yes	gravimetric	no	very accurate (+/- 0,5 %)
CM method (calcium carbide method)	yes	chemical	yes	low, compared to Darr (+/- 3 %)
Capacitive measurement	no	electronic	yes	inaccurate, only qualitative comparison
Resistance humidity measurement	no	electronic	yes	inaccurate, only qualitative comparison
Microwave moisture measurement	no	electronic	yes	relatively accurate

4.3.4 Frost sensitive parts

Both porous building materials as well as installations embedded in the external walls, can be highly sensitive to frost. In order to assess frost sensitive parts in the construction such as piping embedded in the wall, it is preferable to locate drawings of the construction at an early stage in the investigation. If no drawings are available, an on-site investigation is highly important. This would also reveal whether the external surface of the building is already subjected to frost damage (see the consequences of frost damage on external surfaces in section 4.2.5). In this case, internal insulation is not recommended without further assessment. Installation of internal insulation decreases the temperature of the existing wall, and the risk of frost damage in the masonry and embedded installations increases.

When installing internal insulation, it is recommended to replace embedded piping with a frost resistant solution and ensure that the old piping system is drained and plugged. If it is not possible to do changes in the piping system, it is recommended to use heating coils to ensure that the pipes do not crack due to frost.

To reduce the risk of destruction of the porous building materials, it should be considered to improve the driving rain protection (Section 4.3.2), if possible, or to impregnate the wall (section 4.2.2). In both cases to reduce the external moisture load.

Frost problems related to a defect water collection system are described in Section 4.3.5.

If no frost damage is detected in the existing wall and the general state of the wall seems OK, it is assumed that the risk of frost damage after adding internal insulation is limited. However, if frost damage is detected during the visual assessment or if the building façade contains elements deviating from a plane surface, e.g. façade ornamentation, frost damage after installing internal insulation might be expected. Likewise, if embedded piping has shown problems with frost prior to internal insulation, one should assume a worsening of the situation after decreasing the wall temperature.

Frost damage occurs when the volume expansion of water during water-to-ice phase change, in cases where building materials or piping are sufficiently wet or water filled, leads to pressure that exceeds the tensile strength of the material. Essentially this leads to micro cracks and spalling/crumbling of materials, or bursting of pipes, which in turn can cause even more moisture damage.

The outer surface layers of historic masonry walls are normally exposed to the highest risk for frost damage, mainly manifested through scaling of the outer surfaces. An example is shown in Figure 4–32. Both the moisture and temperature levels of porous building materials depend on the wall orientation. The prevailing direction for wind-driven rain in Europe is South-West while the lowest facade temperatures occur in North-faced facades. It is subsequently difficult to predict the most exposed orientation with respect to frost damage.

Table 4-19 presents a summary with regard to determination of frost sensitive parts, and possible mitigation.

Figure 4–32: Frost damage in outer layers of historic masonry

Table 4-19: Summary for determination of frost sensitive parts with regard to internal insulation and possible mitigation.

Detect if there are frost sensitive parts	Possible mitigation
Examine existing construction drawings and establish whether piping is installed in the walls. If drawings are not available, pay special attention at on-site inspection.	Replace embedded piping with a frost resistant solution. Ensure that the old system is drained and plugged. Install heating coils to avoid cracked pipes due to frost, if not possible to change the system.
Evaluation of type and location of heating and ventilation systems.	Critical design points can be mitigated by good planning.
Evaluation of the existing wall; any existing frost damage could get worse with application of internal insulation	Frost damage occurs due to the presence of moisture. The moisture source should be remedied.

Frost damage in porous building materials can originate from a variety of physical frost impacts, of which the volume increase of the water-to-ice phase change is the most widely known. Three conditions must be fulfilled for frost damage to occur in porous building materials:

- The material must be sufficiently wet
- Phase change must happen in the material
- The material must be sensitive to frost damage

The two latter also applies to embedded piping, which can burst when sufficiently filled with water, for the expansion to rupture the pipe. The application of an internal insulation system changes the temperature conditions in the existing construction as illustrated in Figure 4–33. The temperature level in the wall decreases, potentially increasing the frequency of freezing point passages and the duration of temperature below 0°C. Depending on the moisture load and the state of the external wall this increases the risk of frost damage at the external surface.

Embedded piping that was previously kept warm by internal heat loss through the wall, may become in risk even if it is located close to the internal side of the existing wall, as the temperature decreases significantly in the entire wall. Different materials have different sensitivities to frost damage, and hence respond differently when exposed to the same climatic exposure. Consequently, to predict and prevent frost damage in real world situations, both the climatic exposure and the mechanical resistance of the material should be considered.

To eliminate the risk of damage to embedded piping or other installations in the walls, these should be replaced. Water pipes should be drained and plugged. If that is not an option, heating coils should be used to ensure safe temperatures around the piping systems.

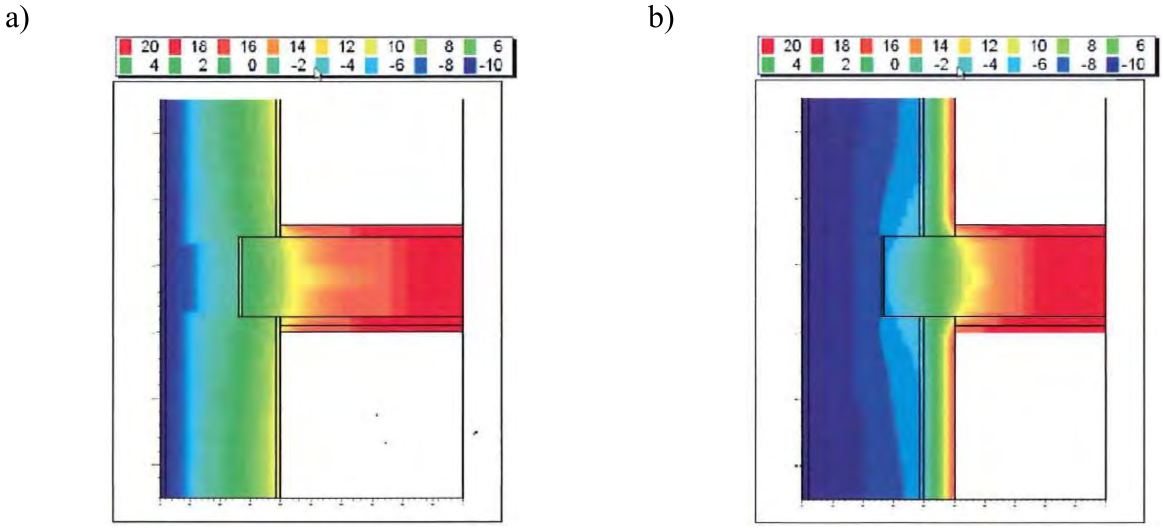


Figure 4–33: Beam end before (a) and after (b) application of internal insulation **(WTA 8-14, 2014)**

4.3.5 Rain water collection system

It is important to do an overall inspection of the rain water collection system shortly after heavy rains. This is to capture all leakages in both vertical and horizontal rain water piping on the façades and above. Horizontal chutes can also be inspected during dry periods by filling them with water, to control that the inclination is sufficient to drain the water and that there are no flaws or blockages.

Things to observe and details to inspect after a heavy rainfall is for instance (**Table 4-20**):

- Wet spots/areas on the façade around water collection systems; see examples of poor water collection systems and water sensitive areas and details in Figure 4–34 to Figure 4–37.
- Areas on the façade where rainwater has been accumulating. It can appear as water stains on the façade, usually in conjunction with water collection systems and water chutes where water can spray both below and above these. Signs are usually obvious if the problems have been ongoing for some time.
- Icicles from eaves, chutes and piping when the temperature is below 0 °C. Icicles are usually a sign of poorly insulated roofs or congested pipes, which can result in further blockage of the rain water collection system during cold periods.
- Locally damaged joints close to the water collection system, indicating high water load on the facades. Damaged joints increase the risk for further leakages into the construction.

It is recommended to regularly assess the building façades to avoid future problems with rain water collection systems.

If damaged joints are found (see Figure 4–35), they should be repaired and filled with a mortar suitable for the type of masonry used once the water collection system has been repaired or maintained.

Check around friezes. Friezes often have horizontal surfaces and joints in which rain water can be collected and stay.

Table 4-20: Summary for determination of problems and possible mitigation for rain water collection systems

Detect if the rain water collection system is defect (examples see Figures)		**Cause**	**Possible mitigation**
Inspection after heavy rain fall	Wet spots around water collection system (horizontal and vertical pipes)	Leakages in the piping system	Locate and fix the leakage /blockage
Inspection in frost	Icicles from eaves, chutes and pipes	Can be congested pipes	Clean the piping system
General inspection	Regular assessment of entire building facade – especially joints	Water can stand still and accumulate on horizontal surfaces, e.g. around friezes	Locally damaged joints close to water collection system should be filled in

Figure 4–34: Example of frieze on a brick façade with extensive damaged joints.

Figure 4–35: Brick façade with a distinct frieze which has collected water leading to joint and frost damage.

Figure 4–36: Frieze with steel cladding. Water can be transported behind the steel plate, be absorbed and lead to frost damage.

Figure 4–37: A clear sign on a blocked water collection system. Water that cannot be transported through the vertical pipe is absorbed to the bricks (the darker areas around the vertical pipe).

4.3.6 Indoor climate

Installing internal insulation increases the thermal comfort and reduces the risk of mould growth on the interior finishing as the indoor surface temperature increases in winter. This can increase the use of the area closest to the external wall by those present in the building. Further, the indoor climate will react faster to heat inputs. This means that the indoor temperature will increase faster when the heat is turned on and less energy is needed to increase the temperature in spring and autumn, where heating is not needed all the time. However, there is also a significant increase in risk of overheating in summer, which might result in thermal discomfort.

It is well known that the exterior climate strongly determines the heat and moisture response and hence the durability of the building façade, and this both before and after thermally upgrading the wall. Examples of degradation and impact of the driving rain load are given in Section 4.3.2. But there is also a strong interaction between the building walls and the indoor climate. So will indoor insulation strongly reduce the thermal capacity of the building elements itself (Hens, 1998) and hence decrease the reaction time of the indoor climate to heat inputs. This occurs due to the fact that external walls no longer serve as heat storage after internal insulation is installed. The reduced thermal inertia of the building has some advantages, e.g. lower heat requirements in intermittent heating period and quicker reaction time when the heating is switched on, but drawbacks as well, e.g. a significant increase of overheating risks in summer (Al-Sanea & Zedan, 2001), which might result in thermal discomfort.

On the other hand, the internal insulation will increase the indoor surface temperature in winter, rising the thermal comfort and in general reducing the risk on mould growth on the internal finishing. Finally, depending on the type of internal insulation, the temperature and relative humidity of the indoor climate to a large extent determines the risk of interstitial condensation. Interstitial condensation is an important issue for internal insulation. Previous insulation systems mainly focused on avoiding interstitial condensation by a vapour tight barrier. Nowadays also vapour tolerant systems are available on the market. The different types of insulation systems will be discussed in Section 5.1. But, as the indoor climate is a decisive parameter when designing all systems, this section focuses on the assessment of the indoor climate itself and more specifically on moisture sources in the indoor environment and their impact on the indoor humidity.

Assessment of internal moisture sources and corresponding climate classes

Indoor air always contains moisture in the form of water vapour. The indoor air moisture content is dependent on the air exchange with the outdoor due to ventilation and/or infiltration, moisture exchange via the building envelope, moisture buffering in indoor materials and internal moisture sources. Usually, the moisture generated by inhabitants is the most important moisture source in the building. Humans release moisture by respiration and perspiration. In addition moisture is released to the indoor air due to various activities such as bathing, showering, cooking, dish washing, and cloth washing and drying. The balance between moisture production and removal by ventilation determines the indoor conditions: a high moisture release with a poor ventilation will result in a high indoor humidity and hence a larger risk on interstitial condensation, but also a higher change of possible other problems such as mould growth at thermal bridges. A good balance between moisture release and ventilation is hence crucial.

The indoor heat and moisture load can vary significantly from building to building depending on its use, the buildings properties and the outdoor climate. However, a rough division can be made between residential and commercial buildings. The moisture generated in residential buildings by the inhabitants usually varies over time: more moisture is generated in the mornings and late afternoons due to cooking, cleaning, showering etc. Previous studies (IEA Annex 14, 1991) estimated the average moisture release of a typical family (two adults and two kids) to be more than 13 kg per day. In office buildings loads are concentrated during office hours and also often coincide with solar gains. Similarly, for commercial buildings, moisture production is high during daytime. In most office and commercial buildings the ventilation system compensates for the moisture production and the excess moisture is removed. However, in naturally ventilated buildings, often the case for historic buildings, the indoor humidity level is a constant balance between indoor moisture production, air exchange with the outdoor environment and vapour stored and released by condensation/evaporation and buffering in materials.

On average, the indoor relative humidity can be calculated from the following equation:

$$RH = 100\,\frac{\mathrm{p}_i}{\mathrm{p}_{sat,i}} = 100\left(\frac{\mathrm{p}_e}{\mathrm{p}_{sat,i}} + \frac{\mathrm{RT}_i}{\mathrm{p}_{sat,i}nV}\,G_{vp}\right) \qquad (4.5)$$

with p_i, $p_{sat,i}$ en p_e respectively the indoor, the indoor saturation and the outdoor vapour pressure, R the gasconstant of air (462 [J/kg/K]), n the number of air changes per hour, V the indoor volume and G_{vp} the moisture production rate in the indoor. This equation states that if moisture is released in the building, the indoor vapour pressure is on average always higher than the outdoor vapour pressure. The difference between both increase with increasing moisture release and decreasing ventilation rate. Note that, although the vapour pressure is higher indoor than outdoor, the relative humidity often is not as the saturation vapour pressure is highly temperature dependent.

Even though a lot of data is collected on typical indoor moisture sources and their corresponding moisture release (see e.g. IEA ECBCS Annex 41 (IEA Annex 41, 2007)), most of the time no information is available on the exact moisture release inside a specific building. Therefore, simplified empirical models have been developed in the past to assess the humidity levels of the indoor environment. These models are based on large-scale field measurement data of various buildings, mostly collected in North and West Europe on natural ventilated buildings. Typically relationships between indoor-outdoor vapour pressure difference and outdoor temperature are found, subdividing buildings in different indoor climate classes. This concept is also incorporated in the informative annex to the European Standard ISO 13788 on hygrothermal performance (ISO 13788, 2012). Buildings' indoor humidity environment is classified as very-low, low, medium, high or very high (Figure 4–38). Also the informative Annex of EN 15026 (EN 15026, 2007) presents a simple way to assign indoor conditions to buildings in the absence of more precise measured or simulated data. In this model, indoor temperature and relative humidity are assigned according to the daily mean outdoor air temperature (Figure 4–39).

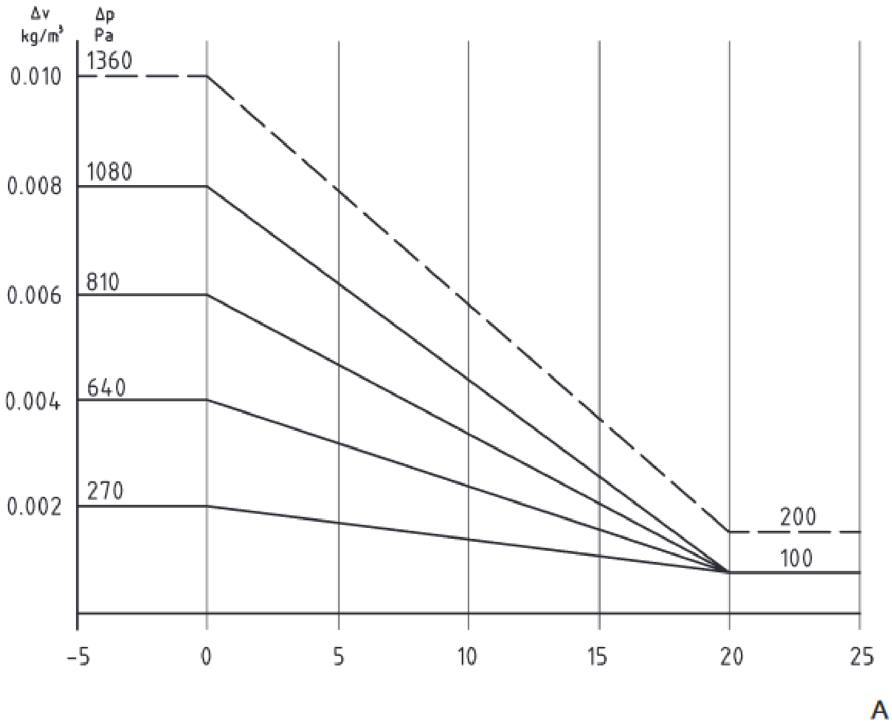


Figure 4–38: Simplified approach to determine the internal humidity class of a building as proposed in Annex A of EN ISO 13788* (ISO 13788, 2012)*: the indoor outdoor vapour pressure difference (Δp [Pa]) and difference between outdoor and indoor moisture content (Δv [kg/m³]) is given as a function of the monthly mean outdoor air temperature (A) for different classes of buildings, ranging from very dry storage buildings (class 1) to very wet special buildings such as breweries, swimming pools etc. (class 5).

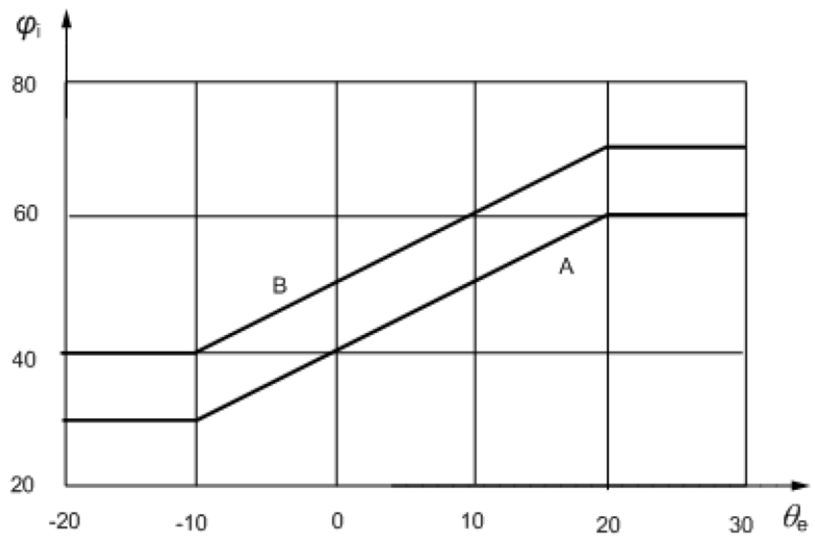


Figure 4–39: Simplified approach to determine the internal boundary conditions, proposed in Annex C of EN ISO 15026* (EN 15026, 2007)*: the daily mean humidity is presented as normal (A) and high (B) occupancy humidity levels depending on daily mean external outdoor temperature (θ_e).

Most building energy simulation software allow calculating the moisture balance of the indoor space in addition to the thermal balance. At that moment, much more detailed information can be included in the models compared to the commonly used empirical relationships of incorporated in ISO 13788 (ISO 13788, 2012) or EN ISO 15026 (EN 15026, 2007). Note though, that the moisture balance is a continuous equilibrium between moisture release, air exchange, moisture buffering and hence requires not only a more precise description of the moisture production, but also a reliable assessment of the moisture buffering capacity, ventilation system and air tightness of the building.

Some general guidelines concerning indoor climate

Apart from lowering the energy losses through the building fabric, applying an internal insulation system typically also increases the thermal comfort as cold surface temperatures are avoided. Combined with a proper detailing of all junctions, this might also reduce the risk of mould growth on the interior finishing, depending on the specific circumstances. Despite all benefits, there might be some drawbacks with respect to the indoor climate that have to be taken into account. The most important ones are listed below:

- When applying internal insulation in historic buildings one has to be aware that the thermal inertia of the building façade is no longer available from the inside. Depending on the overall heat storage capacity of the building (concrete floors versus wooden floors), this might result in a higher overheating risk in summer. Installing appropriate solar shading devices might be advisable in that case.

- Vapour open or vapour tolerant internal insulation systems are only recommended in buildings with a low indoor air moisture content. For buildings corresponding to high indoor moisture classes, such as swimming pools, an in depth hygrothermal study by experts is anyway advisable.

- When internal insulation is part of an overall renovation, one has to be aware that the overall hygrothermal response of the building may change. A renovation, including e.g. installing windows with a better thermal performance, often results in a more airtight building. At that moment, introducing a ventilation system might be crucial to maintain a healthy and moisture safe indoor climate.

Table 4-21: Summary table for indoor climate and mitigation of elevated RH.

Indoor air moisture content depends on	Mitigation
• Outdoor air (ventilation and infiltration) • Moisture exchange via building envelope • Moisture buffering in internal materials • Internal moisture sources: Moisture generated by humans is usually considered the most important moisture source (respiration, perspiration, activities (e.g. bathing, cooking, laundry)	• Ensure a balance between moisture production and removal by ventilation • Ventilation systems may be vital in cases where renovation measures yield more air tight buildings

4.4 Measurements

4.4.1 Introduction

Depending on the task, the renovation objective and the scope of measures, it may be necessary to determine properties of the building materials in the existing wall structure as a prerequisite for selecting an internal insulation system. Measurements are required if the building as a whole cannot be classified as uncritical (showing no cracks, indication of presence of salt or indication of moisture related damage) (section 4.2). This is also the case if the assessment described in section 4.3 is not sufficient to regard the external wall and adjoining building elements (esp. wooden beams supporting suspended floors) as sufficiently robust to let the external wall be internally insulated.

Such an evaluation might require measurements either on-site or in a laboratory (Figure 4–40 and Section 4.4.2 and 4.4.3), although it might be possible to use simpler aids to obtain some basic values (Section 4.4.4). Measurements cost from approx. EUR 2.000 for simple, basic parameters to EUR 9-10.000 for an extensive investigation. Measurements needed to perform a simulation using DELPHIN (Section 5.2) on a specific building material cost approx. EUR 5-6.000.

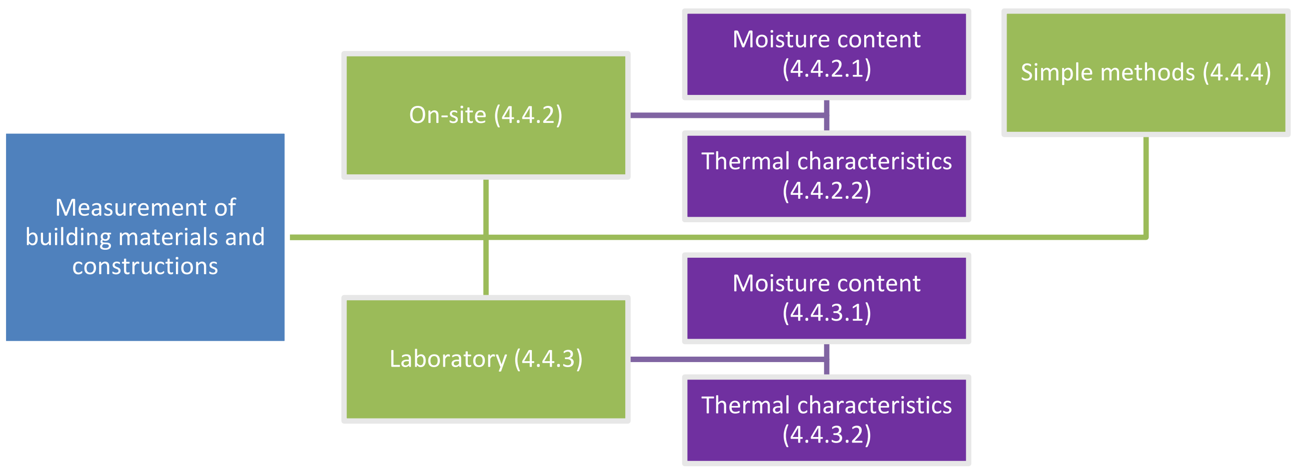


Figure 4–40: Measurements to assess current state of the building wall construction and materials

Many damages in buildings are caused by moisture, e.g. by leakages at the roof, at the facade or in the ground area (Figure 4–41). The moisture load causes existing salts in the building material/component to dissolve and to be transported in the direction of the drying area. The hygroscopic properties of many salts can cause water accumulation, which are often accompanied by an extensive increase of the volume. Thus, even after the construction has dried, damage is unavoidable if the cause and extent of the damage is not clear. Therefore, moisture measurements on walls to determine the moisture content and distribution and knowledge of the salt content are necessary prerequisites to consider further measures, especially in the case of planned renovation.

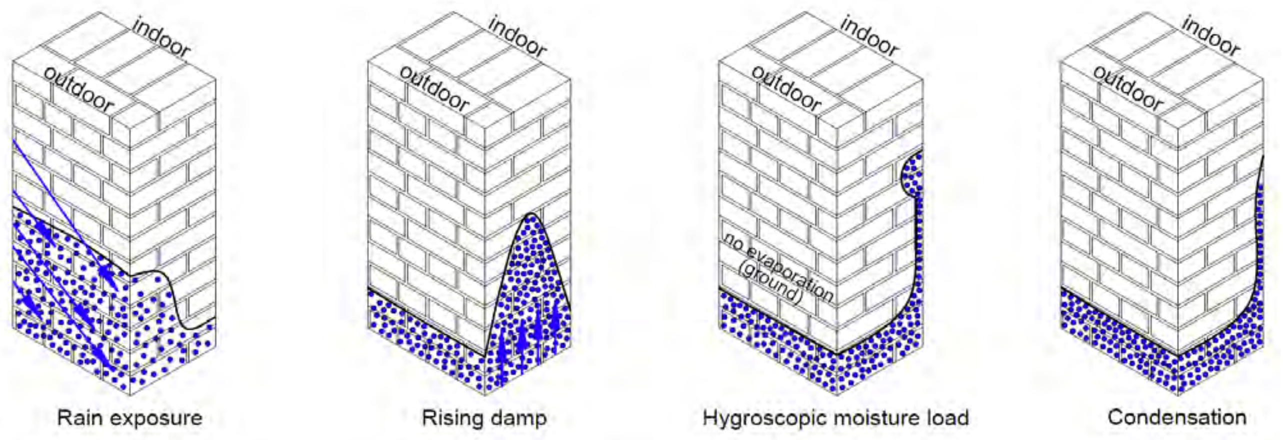


Figure 4–41: Schematic representation of moisture distributions in masonry (Translation from German version found at: https://slideplayer.org/slide/13942388/)

The most important parameters are:

1) **Water vapour permeability (μ-value)**

   Knowledge of this value is important, for example, for structures at risk of driving rain, to be able to assess the vaporous drying potential through the existing structure and, on this basis, to shortlist or exclude certain insulation systems for internal insulation. The value can only be determined by means of a laboratory measurement.

2) **Water absorption capacity (w or AW) of the facade material**

   It is always necessary to determine the water absorption capacity of the façade material if it is not possible to ensure that the façade is sufficiently resistant to driving rain.

   Option 1: Laboratory measurement of capillary water absorption

   Option 2: In-situ tests, e.g. Karsten's test tube, test plate according to Franke, or Water Absorption measuring instrument (WAM)

3) **Thermal resistance (R) or U-value**

   This value results from the type of materials used, the material thicknesses and their thermal conductivity. There are different ways of determining or estimating these values.

   Option 1: Laboratory measurement of thermal conductivity

   Option 2: In-situ testing

   Option 3: Use of characteristic values from databases

RIBuild deliverable D3.2 (RIBuild Deliverable D3.2, 2019) presents the hygrothermal performance of a number of internally insulated case study buildings, either RIBuild-cases or published monitoring projects. And it gives a description of material testing methodologies that can be done on-site with a minimum destruction of the buildings (Section 4.3.1 in deliverable D3.2). Laboratory testing methodologies are described in (RIBuild Deliverable D2.1, 2018).

Building material properties can be differentiated into storage and transport characteristics. The heat storage capacity is a simple characteristic value which is described by the mass-related storage capacity (specific heat storage capacity) and the bulk density. The thermal conductivity results from the conductivity of the material itself and, if it is a porous building material, from the conductivity of the material enclosed in the pore space (water or air). The water present in the pore space is mapped via the moisture storage function.

The moisture transport property of a building material is in turn subdivided into the transport function for vapour and for liquid water. Both components, as well as the thermal conductivity, depend on the water content of the brick, i.e. on its storage properties. This storage property is measured in the form of the equilibrium moisture content (sorption isotherm) for specific values of relative humidity.

4.4.2 On-site measurements

Moisture penetration through existing structures is not always visible. If, for example, the outer surface of the external wall has dried after a period of sunny weather, it may be difficult to determine whether the wall core has become moist. On the other hand, in unused, cold basement rooms in summer, surface condensation may be visible, which does not necessarily indicate moisture penetration from outside, but can be summer condensation. On-site measurements (if possible in combination with sampling) can be used to make sufficiently accurate statements. The scale of on-site measurement activities depend on:

- available time
- non-destructive vs destructive method
- cost
- derivable material properties
- measuring accuracy (high, medium, low)
- measurement prerequisites/flexibility

Fundamental different types of methods are used for measurement of moisture properties (Section 4.4.2.1) and heat transport (Section 4.4.2.2).

4.4.2.1 On-site moisture measurements

In practice, there are many on-site moisture measurement methods with different requirements and accuracies. A distinction is made between indirect (or non-destructive) and direct (or destructive) methods as presented in Figure 4–42.

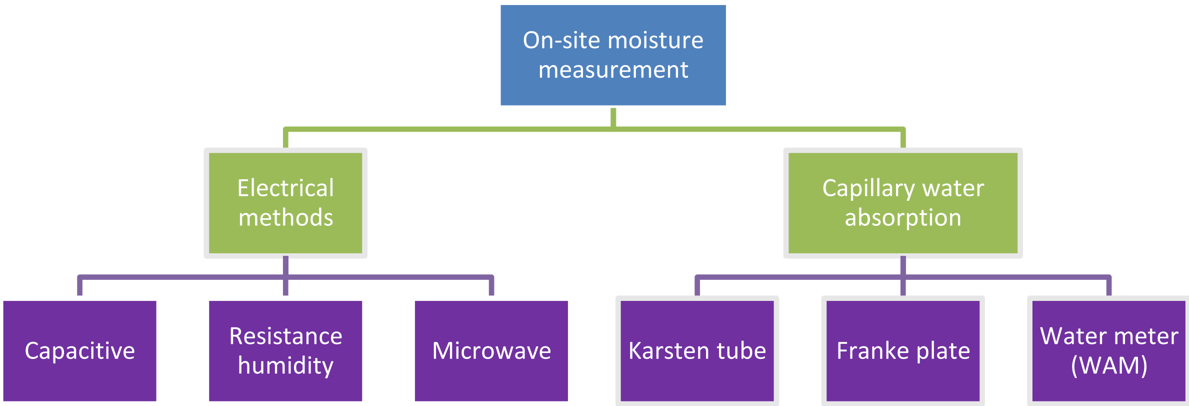


Figure 4–42: Types of on-site moisture measurement methods for analysis of existing buildings.

Indirect or non-destructive electrical measurement methods

There is a multitude of indirect or non-destructive measurement methods (electrical, optical, thermometric, hygrometric, acoustic...), many of which are not relevant or usable for construction practice. Only the most common procedures in the construction industry will be dealt with here; the electrical procedures, listed in **Table 4-22**.

Table 4-22. Overview of indirect moisture measurement methods

Method	Building material	Suitable for	Unsuitable for
Capacitive measurement	Brickwork, concrete, etc. Wood	Detect wet areas of surfaces (2-4 cm depth) Relative / comparative measurement	Measurement of specific values for humidity / moisture measurement
Resistance humidity measurement	Wood	Measurement of moisture content (converted from electrical conductivity)	Other materials than wood
Microwave moisture measurement	Brickwork, concrete, etc. Wood	Detecting of damage from rising damp or leaks Detecting of wet areas until 80 cm behind surface Relative / comparative measurement	Measurement of specific values for humidity / moisture content Building components with a number of (thin) layers (e.g. timber frame walls)

Capacitive measurement

This method allows non-destructive moisture measurements in near-surface areas, up to approx. 2-4 cm depth of material depending on the building material density (Figure 4–43). It is well suited for comparative measurement to detect differences between wet and dry areas in mineral building materials and wood, but is considered unsuitable for qualified humidity measurements. It is suitable as a pre-tester for destructive measurement methods (Laboratory measurements, Section 4.4.3).

The capacitive humidity measurement is based on the functional principle of a capacitor. The procedure exploits the different dielectric constants of dry, non-conductive substances (about 2-10) and water (about 80). Depending on the dielectric constant, the capacitance of the capacitor changes. The higher the humidity, the higher the electrical conductivity and at the same time the increase in the dielectric constant of the substance to be measured. The complex relative dielectric constant is a material-specific quantity. One factor to be considered is the raw density of the test product. With increasing density, the display value increases with dry and moist material.

The measuring field is formed between the active probe on the upper side of the device and the material to be evaluated. The change in the electric field due to material and moisture is recorded in the meter, converted to digital (output, for example, as a digit unit or also as a conversion in % by weight). The measurement is a relative measurement. The difference between the dry and the wet building material is displayed. Dissolved salts can turn the building material into an electrolytic conductor, resulting in higher capacitance values.

Figure 4–43: Examples of a measuring instrument for capacitive humidity measurement (Source: left: www.gann.de, right: www.trotec24.com)

Resistance humidity measurement

The resistance measurement method can be used to measure the moisture content at the material surface, but also in deeper component layers. However, drilling is required to allow longer electrodes to be inserted. It is well suited for wood based materials (see Figure 4–44).

In this method, the electrical resistance is measured as a function of the electrical conductivity between two electrodes that are hit, rammed or drilled into the material. In dry building materials the resistance is very high, as they conduct the power poorly. Thus, a low reading is displayed on the meter. As the moisture content of the material increases, so does the conductivity, as water contained in the material conducts the current well. This displays a higher reading. The displayed measurement results can be converted into moisture percentages taking into account different building materials.

Falsifications of the measurement results are possible due to unequal moisture distribution and inhomogeneity in the material, to other conductive materials in the wall (e.g. cables or wires), salts in the building material, surface treatment, or poor contact of the electrodes to the material. However, such incorrect measurements can be corrected somewhat by performing several measurements.

Figure 4–44: Examples of a resistance moisture meter (Source: left: testo.com, right: www.gann.de)

Microwave moisture measurement

With this method, moisture measurement can be carried out from near the surface to a penetration depth of 800 mm, through the use of different measuring heads (see Figure 4–45). The method is well suited for the usual building materials. Non-destructive, systematic, multi-layer raster moisture measurements can be carried out and graphically displayed as both areal and depth-resolved moisture distributions. Thus, a distinction in near-surface moisture and moisture in the core of components is possible. Moisture damage can be clearly classified and multi-dimensionally characterized with the area-based grid moisture measurements, since different patterns of moisture distribution are produced depending on the type of moisture damage. In particular, damage from rising damp and leaks can be easily identified with volume measurements (at various depths). Material-specific calibration curves of various building materials are integrated in the sensors.

The measuring principle is the radar reflection method. The waves are reflected as they pass through the material and detected by a meter. The method belongs to the dielectric measurement methods, i.e. the measurement is based on the determination of the permittivity of a medium to be examined. Since the dielectric constant of water is significantly higher than for dry building materials, the measured value of building materials increases significantly with the moisture content.

Figure 4–45: Example of a microwave moisture analyser with different measuring heads (Source: hf-sensor.de)

The influence of ionic conductivity on the measurement results is low in high frequency engineering, i.e., saline independent measurements can be made. The measuring accuracy depends on various disturbing factors such as thickness, density and grain size of the material to be examined.

Non-destructive measurement of capillary water absorption

Introduction

One of the most important criteria for the planning and dimensioning of internal insulation measures is the assessment of the driving rain load and the local driving rain protection of the individual facades of the building.

By installing internal insulation, the existing wall becomes colder and wetter, as the heat transport from the room side and through the wall, is reduced due to the insulation layer.

For a general assessment of the condition of the façade, a visual inspection should be supplemented by information on maintenance measures carried out during the use of the building. For a rough overview, ideally a first on-site inspection takes place directly after a rain event to visually record the capillary water absorption of the façade and, above all, to clearly identify and document damage to the splash water area and the roof drainage system.

However, for the on-site measurements of the capillary water absorption of the façade, which serve as an important criterion for classifying the driving rain protection of the façade, the following weather conditions are required:

- The temperatures are above 5°C for a long time.
- There has been no rain event for several days, i.e. the facade must be dry. A measurement in the late afternoon hours is ideal here, since then a falsification of the measured values can be excluded also by any existing impact of nocturnal surface condensate on the facade.

In the following, some on-site non-destructive measurement methods are presented, starting with the most simple, fast and inaccurate (wetting the façade), gradually becoming more precise and time consuming, with the water absorption measuring device (WAM) as the most advanced. All methods are suitable for brick masonry, however it must be ensured that a sufficient number of measurements (on all sides of the facade, at different heights) are carried out to achieve representative results. The smaller the suction surface, the more measurements are necessary. The accuracy of the measurements increases with the size of the test surface or with the complexity of the investigations.

Wetting the facade

An easy way to get the first impression of water absorptivity of building materials is to simply wet the facade with water. With a squirt bottle one can generally determine whether the facade is strongly absorbent or rather water-repellent and whether there are serious differences in the different façade orientations and heights or in certain areas. On this basis, the location of inspection points can be determined for the measurement of capillary water absorption.

Karsten's test tube

The Karsten water penetration test tube is a simple proven method for the on-site measurement of capillary water uptake of building materials and components. For exposed brickwork facades, this method is suitable as a coarse estimation. The test is very simple. The water penetration tester is applied to the test surface with a contact material (putty) (Figure 4–46). After pouring a specified amount of water into the test tube, the absorbed amounts of water and the associated penetration times are read off and documented at specific time intervals.

Figure 4–46: Test tube according to Dr. Karsten, placed on a brick

Due to the small cross-sectional dimensions of the tube and the strong edge influence, however, only very limited statements are possible, especially in brick-faced facades with joints. The correct determination of the water absorption coefficient in the laboratory requires a one-dimensional transport, but this cannot be achieved with the Karsten test tube. In addition, in this in-situ measurement method, the water is brought through the water column in the tube with a hydrostatic pressure on the facade, thus resulting in increased values. Further measurement errors can result from the strength and shape of the putty.

More detailed information about Karsten's tube method can be found in RIBuild deliverable D2.1, Section 5.3.5 (RIBuild Deliverable D2.1, 2018).

Test plate according to Franke

The design of this measurement setup is a further development of the Karsten test tube. The measuring principle is the same. Again, the test plate is applied with a putty to the test area (Figure 4–47). The quantities of water absorbed and the associated penetration times are likewise read off and documented at specific time intervals to obtain a water absorption coefficient by evaluating the measurement curve. Due to the larger wetting area with a rectangular structure in the size dimension of a normal format brick plus the horizontal joint and vertical joint (25 x 8.3 cm), the entire system can be recorded here as a combination of brick and joint share.

Also in this method, a multidimensional liquid transport takes place. Due to the larger test area, the edge effects are less influential here than with the Karsten test tube. This allows more accurate statements about the capillary water absorption of the entire system as an average of brick and joints. Also in this in-situ measurement method, the water is brought to the facade with a hydrostatic pressure, resulting in increased values. Further measurement errors can be due to the strength and shape of the putty, as with the test tube.

Figure 4–47: Test plate according to Franke, detection of brick and joint content

Water absorption measuring device (WAM)

A new and more elaborate process is the measurement with the water meter WAM 100 B according to (Stelzmann, 2013) using a wetting area of 30 cm x 40 cm. This makes it possible to measure an integral water absorption over several stone and joint layers for brick-faced facades (Figure 4–48). Here, the façade area is pressurized with a superficial water film, which is produced with a constant and closed water cycle. The measuring principle is based gravimetrically on the determination of the mass differences. Depending on how absorbent a surface is, the water is absorbed by the facade or flows back into the circulation. This allows a more accurate non-destructive measurement of capillary water absorption on the facade.

Especially after the implementation of measures for the production of impact protection (for example, subsequent hydrophobing), the effectiveness of the measure in the combination of brick and joint layers can be checked well (Stelzmann, Berg, Möller, & Grunewald, 2016) (Stelzmann, 2013).

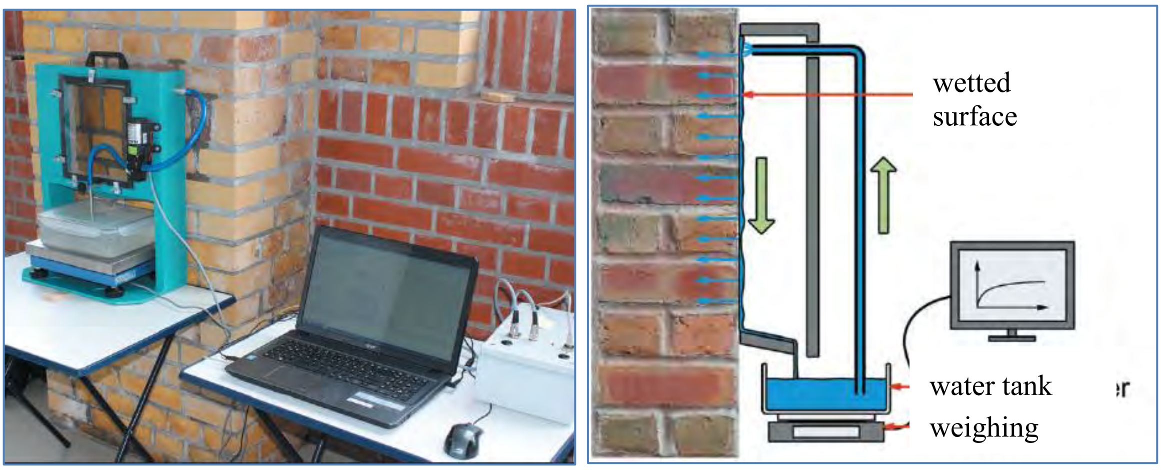


Figure 4–48: Water absorption measuring device WAM 100 B, construction and measuring principle [Source: hf-sensor.de]

More detailed information about the water absorption measuring device can be found in RIBuild deliverable D2.1, Section 5.3.6 (RIBuild Deliverable D2.1, 2018).

Direct measurement methods

Direct measurement methods are destructive measurement methods in which material samples have to be taken. This means that new samples must be taken for any subsequent measurement.

CM method (calcium carbide method)

In this method, which is a chemical method, only small material samples (5 g – 20 g) are taken, wet weighed, carefully crushed and mixed with calcium carbide in a pressure vessel with steel balls and a glass ampoule.

The amount of acetylene gas produced, which is determined by measuring the increase in pressure using a manometer (Figure 4–49), is a measure of the water content of the sample with reference to the sample mass. This procedure is applied directly on the spot, but requires some experience.

The accuracy of this method is low compared to the Darr weighing method (approx. ±3%). Nevertheless, it is frequently used in building practice, as it allows the moisture content for the investigated building materials to be determined quickly on-site at individual measuring points.

Figure 4–49: Example of a CM measuring instrument for moisture measurement (Source:radtke-messtechnik.com)

4.4.2.2 On-site heat flow measurements

Thermal resistance R or thermal transmittance of a building element U-value

The most important thermal characteristic value in this context is the thermal conductivity or, derived from this, the thermal resistance R or thermal transmittance of a building element U-value. An approximate U-value of the specific existing structure can be obtained by non-destructive on-site measurements.

This is done by means of heat flow measurements. Since these values are determined transiently and are always subject to the fluctuations of the boundary influences on-site, the results can also only be used as orientation guidance. Measurements should preferably be taken on a day when the outside temperature remains approximately constant for at least 24 hours to maintain a stable and appropriate indoor temperature. In addition, the temperature difference between the inside and outside should be as constant as possible, at least 15 K. The construction to be measured must not be exposed to direct sunlight, as this would falsify the measured values. Thus cold winter days or cloudy days are well suited for the measurements. The measured values must be recorded over a sufficiently long period of time to determine a stable mean value. A thermographic image taken beforehand can be used to determine representative points for the U-value measurement. Thermography is described in the following section.

ISO 9869 (ISO 9869, 2014) provides a guide about heat flow meter measurements for the determination of U-values. The heat flow through a wall depends on the thermal conductivity of the individual layers, the area and the temperature difference between the two sides of the component (inside and outside). With a heat flow meter sensor directly applied to the hot side of the wall surface, the density of heat flow rate is quantitatively measured (see Figure 4–50). If air temperatures are detected on the room side and on the outside, the U-value or heat transfer resistance can be calculated from this. In this case, the same boundary conditions and a sufficiently long measuring time must be observed. The same boundary conditions and a sufficiently long measuring time must be observed as for temperature measurement.

$$R = \frac{\theta_i - \theta_e}{q} \tag{4.6}$$

where

q - density of heat flow rate [W/m²]

R - thermal resistance [m²K/W]

Θe - temperature outside [ºC]

θ_i - temperature inside [ºC]

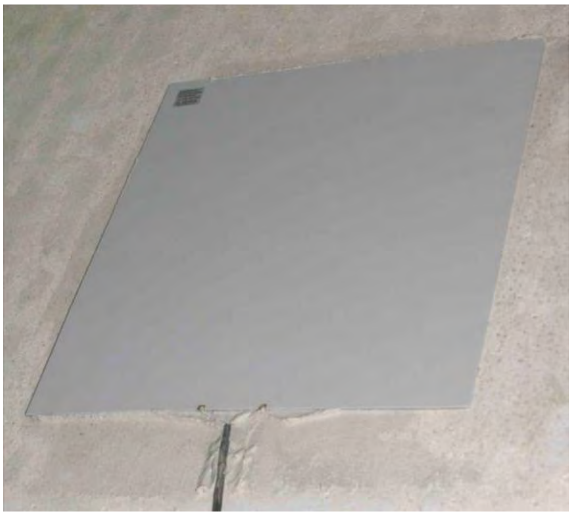


Figure 4–50: Example of a heat flow meter sensor applied to the wall surface

The larger the U-value of a component, the smaller the influence of measurement errors. This means that these measurements can give a good indication for uninsulated constructions, while the influence of measurement errors is more significant for insulated constructions.

Thermography

Thermography is a non-destructive measurement method that can be used to identify local heat loss (thermal bridges, air leaks, gaps in the construction) (see Figure 4–51). Although it is not possible to measure the moisture content on building components, the method is well suited for leakage location. A higher moisture content increase the heat transfer within the component and lead to a temperature reduction at the component surface. Thus a temperature difference between dry and humid areas is recognizable. However, the results must be interpreted correctly, as the procedure does not discern between temperature change due to moisture and due to a thermal bridge.

The method is to be seen as a supplementary method for recording the actual condition and analysing damage and represents a snapshot of the surface temperature distribution on components.

Care must be taken to ensure that the temperature differences between inside and outside are as large as possible (heated building on a cold winter day). Environmental influences such as wind, rain and solar radiation can lead to a warming or cooling of the building envelope and thus falsify the heat flow-induced temperatures at the component surface. Therefore, it should preferably be carried out in the early morning or late evening hours in calm and dry weather.

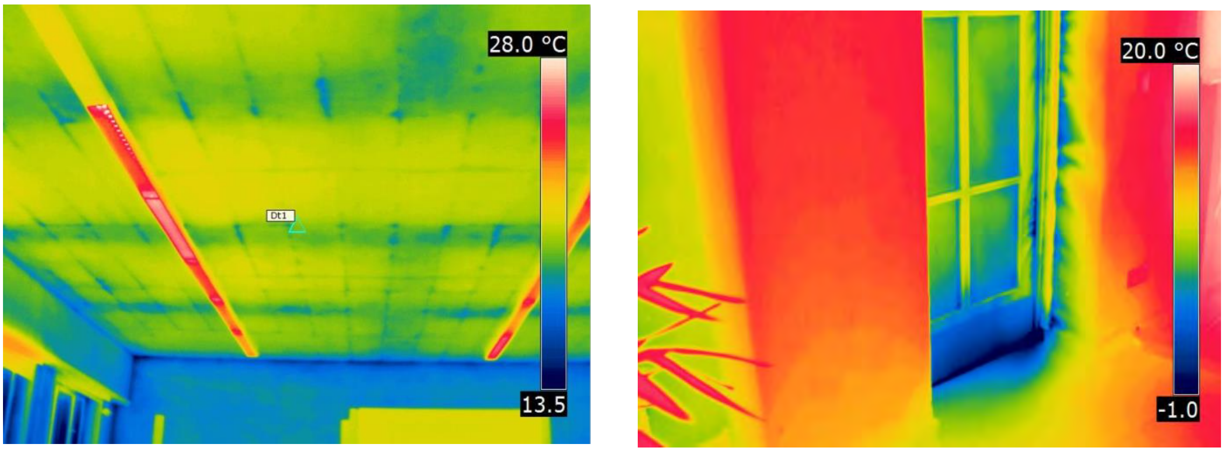


Figure 4–51: Example of thermography images from Willers-Bau (Germany): Thermographic images on the upper floor (left) and on an outer door (right)

4.4.3 Laboratory measurements

Laboratory measurements offer significantly higher measurement accuracy than on-site tests. In addition, some characteristic values, such as equilibrium moisture content (sorption isotherms) or water vapour permeability (expressed as a μ-value) can be determined exclusively by laboratory measurements. These laboratory measurements require samples to be taken, e.g. in the form of core drillings or stone samples. Finding possible tapping points in the existing structure is sometimes a challenge and must be done very carefully. The number and size of the samples to be taken vary depending on the measurement method.

4.4.3.1 Laboratory measurements of moisture

Darr weighing method (gravimetric method)

In this classical, destructive method for determining the moisture content of materials, the mass difference between moist and dried material samples is determined in the laboratory. This is a very accurate method (up to ±0.5%). Material samples are taken on-site from the existing structure, weighed moist, packed airtight, brought to the laboratory and dried in a drying cabinet until the mass remains constant (drying temperature usually 105°C for mineral building materials). The dry material is then weighed again. The mass difference between moist and dried material samples represents the water content.

This method is calibration-free and can be used to calibrate other measurement methods. It is used when precise humidity values are required.

When taking drilling samples, the drilling time must be kept as short as possible to avoid excessive heating of the sample, as this can cause water to escape from the sample. In addition, it is more advantageous to take larger samples instead of drill cores with small diameters or, if possible, to take whole stones without significant heat exposure.

Salinity measurements

Salinity measurements are made to determine the salt content or salt composition. Material samples are taken on-site, either as a drill core, or as drill dust.

In accordance with WTA Leaflet 4-5-99 (WTA 4-5, 1999), a classification of salts is given, from which the required order of magnitude of measures can be deduced. For simple conclusions about the total salt content, the determined highest content of salt ions, independent of whether chloride, nitrate or sulphate, and the evaluation shown in **Table 4-23** is decisive according to (WTA 4-5-99).

Table 4-23: Assessment of the damage-causing effect of different salt ions in masonry bodies (data in M-%) (WTA 4-5, 1999)

Load	low	medium	high
Chlorides[1]	< 0,2	0,2 – 0,5	> 0,5
Nitrates	< 0,1	0,1 – 0,3	> 0,3
Sulphates[2]	< 0,5	0,5 – 1,5	> 1,5
Assessment	Measures required in exceptional cases	Further investigations of the total salt content (salt compound, cation determination) necessary, measures required in individual cases	Further investigations on total salt content (salt compound, cation determination) necessary, measures required

[1] In the case of structural safety measures, such as the installation of anchors/needles, a selection of special steel grades and specially formulated grouting mortar and backfilling mortar must be used for chloride loads.
[2] Assessment based on readily soluble sulphates; building materials containing sulphates are to be assessed in particular.
[3] The results of the salt analyses are not the only decisive factor for the decision on the need for measures.

Water vapour diffusion resistance

At low relative humidity of up to approx. 30%, moisture is transported in a building material exclusively by water vapour diffusion (vapour transport). This diffusivity can be measured with the aid of the so-called "dry cup method". At higher air humidity of up to about 95 %, vapour and liquid water transport occur simultaneously. This combined transport is measured by the wet cup method and the extraction of the vapour component.

The water vapour diffusion resistance provides a measure of how much water vapour is transported through a porous material in the presence of a vapour pressure gradient. The building material characteristic value is the μ-value (water vapour diffusion resistance factor). This indicates the factor by which the building material in question impedes water vapour transport in comparison with air.

When considering to apply internal insulation, it is crucial to know the drying potential of the wall construction to the exterior as only limited transport to the indoor can take place, depending on the characteristics of the insulation system.

More detailed information about water vapour diffusion resistance method can be found in (RIBuild Deliverable D2.1, 2018), Sections 5.1.5 and 5.2.2.

Water absorption capacity and water absorption coefficient

In historic wall constructions, the choice of suitable materials was partly used to prevent the wall from absorbing too much water. This applies mainly to basement walls or plinth areas where dense sandstones, granite, diabase or basalt were used. Diabase, for example, has a water absorption capacity of less than one percent by volume. The water absorption capacity of a material depends on how large the pore volume is, on the one hand, and on which pore structure is accessible to water, on the other. Therefore, the water absorption capacity of a building material can at most reach the value of the total pore volume, but is usually lower.

In contrast to these materials often used for the lower part of external walls (including basements), other natural stones (sandstone, travertine, tuff, etc.) have a porosity of up to 30% and are correspondingly more absorbent. They are therefore not used for components which are exposed to liquid water for a longer period of time.

The water absorption capacity of building materials is meaningful for the foundation or basement construction, as these can be exposed to groundwater.

When liquid water (e.g. driving rain) acts for a short time, a building material absorbs considerably less water. This short-term water absorption capacity of a relatively dry starting material can differ greatly from the maximum possible water absorption. It is therefore recorded as a separate characteristic value (water absorption coefficient) and is an important criterion for external wall materials. The corresponding water absorption test indicates how much the water absorption of a building material slows down over time. It is therefore expressed as water mass per square metre of contact area (between building material and liquid water) and per root second. The higher the water absorption coefficient, the faster the material can absorb liquid water.

The water absorption coefficient for a material exposed to the weather provides a decisive parameter for the dimensioning of an internal insulation measure, since the damage potential depends strongly on the rainwater input.

To obtain an exact statement on the capillary water absorption of facade materials and in the case of obvious or emerging necessity for further investigations and measures to reduce the capillary water absorption, it is often necessary to take material samples and have them examined in the laboratory, especially for brick facade without plastering.

In the case of plastered facades, the water absorption coefficient for the facade can be sufficiently fulfilled with a suitable facade coat applied to the intact facade as part of the renovation, so that in this case the water absorption coefficient does not necessarily have to be determined in the laboratory.

More detailed information about water absorption coefficient test method can be found in (RIBuild Deliverable D2.1, 2018), Section 5.1.6 and 5.2.3.

Equilibrium moisture content

The equilibrium moisture content (or practical moisture content) is the moisture content in a building material after prolonged storage in a room with constant relative humidity and temperature. The equilibrium moisture content is typically measured in the laboratory for several levels of ambient moisture. A constant moisture level is created with the help of saturated salt solutions. The choice of salt determines the moisture level in the measuring vessel (e.g. 75.4% for saturated saline solution). If all measured equilibrium humidity are applied over the ambient humidity applied, the so-called sorption isotherm is obtained.

The equilibrium moisture content at a certain relative humidity thus represents a single characteristic value from the moisture storage curve of a material. From the equilibrium moisture content and the porosity of a building material, for example, it can be concluded how high its practical thermal conductivity is. For bricks it can be assumed that an increase in moisture content of one percent by mass produces an increase in thermal conductivity of 10%. Since the practical moisture content of a brick lies between 0.5 (vertically perforated brick) and 1.5 % by volume (other bricks), a tolerance of 5 (vertically perforated brick) to 15% (solid brick) is therefore required for the thermal conductivity of the dry building material. If the brick is completely moistened, the characteristic value increases accordingly.

More detailed information about equilibrium moisture content test method can be found in (RIBuild Deliverable D2.1, 2018), section 5.1.8 and 5.2.4.

Moisture storage function

Depending on the measurement method used, moisture storage is divided into a hygroscopic and a suphygroscopic portion. The moisture storage function is made up from sorption isotherms and pressure plate measurements.

More detailed information about moisture storage function test method can be found in (RIBuild Deliverable D2.1, 2018), Section 5.1.9 and 5.2.5.

Saturated moisture content

The saturation moisture is the moisture content that results after storage in water until saturation of all pores. For this purpose, the dry sample is weighed and reweighed after storage in water.

Saturation of samples is also used when determining the porosity, described in (RIBuild Deliverable D2.1, 2018), Section 5.1.2.

Degree of moisture penetration

The degree of moisture penetration describes the ratio of moisture content to maximum water absorption in building materials. The degree of moisture penetration is determined indirectly by measuring the moisture content and the maximum water absorption, both as mass percentages. The degree of moisture penetration allows evaluation of moist building materials. On this basis, the degree of moisture penetration of a material can be indicated after a moisture measurement.

Other methods for determination of material parameters are presented in (RIBuild Deliverable D2.1, 2018), Section 5.3.

4.4.3.2 Laboratory measurements of U-value/heat

Bulk density

The bulk density describes the density of a porous building material based on the gross volume (including pores). It also serves to determine the heat storage capacity. Conclusions on other characteristic values, such as thermal conductivity, can also be drawn conditionally from the bulk density.

More detailed information about bulk density test method can be found in (RIBuild Deliverable D2.1, 2018), Section 5.1.1 and 5.2.1.

Porosity

Porosity is the ratio of the pore volume to the total volume of a building material.

In general, a decreasing porosity is associated with a lower thermal insulation capacity (higher thermal conductivity) and higher storage capacity (higher bulk density) of the building material. However, when comparing different types of building materials, this conclusion is not always correct.

In addition to the porosity itself, it is also decisive which pore structure is present. Pores that are accessible to water contribute to a high water absorption capacity while other pores are inaccessible to water in liquid form. No pores are inaccessible to water vapour although it takes time to get access to them. In addition, the composition of the solid matrix is also important. The derivation of further building material properties such as liquid water and steam conductivity is therefore only possible to a limited extent even with this basic characteristic value.

More detailed information about porosity test method you can find in (RIBuild Deliverable D2.1, 2018), Section 5.1.2 and 5.2.1.

Thermal conductivity

Thermal conductivity can be specified both as dry thermal conductivity and in the form of thermal conductivity with a standardised equilibrium moisture content. The thermal conductivity thus depends on the water content of the porous building material and increases with it. The lower the thermal conductivity and layer thickness of a building material, the lower the heat losses through the outer wall. Thermal insulation materials have characteristic values of less than 0.10 W/mK, porous natural and brick stones have values of around 0.50 to 2.50 W/mK.

More detailed information about thermal conductivity test method can be found in (RIBuild Deliverable D2.1, 2018), Section 5.1.4 and 5.3.1.

Specific heat capacity

The heat capacity represents the ability of a building material to retain thermal energy. The specific heat capacity indicates how much heat energy per kg of building material and degree Kelvin temperature difference can be stored and is given in J/(kgK). It is between 800 and 1000 J/kgK for standard building materials and between 800 and 900 J/kgK for brickwork. Wood-based materials have higher values of approx. 1500 J/kgK. For the actual storage capacity, however, the density is decisive. Wood and wood-based materials have a density that is about one third of that of solid building materials. Thus bricks and natural stones are still clearly better heat accumulators despite the lower specific characteristic value of the heat storage capacity in comparison to wood.

More detailed information about specific heat capacity test method can be found in (RIBuild Deliverable D2.1, 2018), Section 5.1.3 and 5.3.1.

4.4.4 Alternatives to determining the characteristics of the existing structure

The building owner can carry out do-it-yourself (DIY) material tests and assess dry density, porosity, specific heat capacity, water uptake, and moisture content. The following tools will be needed:

- Ruler or caliper (if the samples are irregular, a measuring cup can be used instead) [cm]
- Scales, [g]
- Oven, capable of maintain constant temperature at +105 °C
- Thermometer for measuring room temperature [°C]
- Thermometer for measuring water temperature [°C]
- Graduated container (large enough to fit the sample inside) if the sample is irregular
- Container (large enough to fit the sample inside) with low heat conductivity walls e.g. ice box
- Thin rope (strong enough to lift the sample)
- Waterproof marker, for writing on brick samples.

The test should be carried out in the following steps:

1. Before the test, brick sample(s) should be taken out from the masonry wall, cleaned from the mortar and if possible cut into a regular pieces.
2. If more than one sample is tested, a unique number to each sample is assigned and written on the sample.
3. Ruler or caliper is used to measure dimensions of regular samples. Measured dimensions of these samples (height (h), width (w) and length (l)) should be written down in Table 4-24. After that calculation of volume V_r [cm^3] should be carried out as in Eq 4.7 and written in Table 4-24:

$$V_r = h \times w \times l, \qquad (4.7)$$

where
h - height of the sample [cm]
w – width of the sample [cm]
l – length of the sample [cm]

Table 4-24: Volume ...

Sample No.	Height, h [cm]	Width, w [cm]	Length, l [cm]	Volume, Vr [cm^3]	Volume, V_i [cm^3]
...	...	...	...	...	...

4. If samples are not regular, graduated container can be used to determine their volume (Step 14).
5. The oven should be preheated as close as possible to +105° C (t_1 [°C]).

6. Sample(s) are inserted in the oven, and dried until the dry mass of the sample(s) is reached. Dry mass is determined by weighing sample(s) approximately every 24 hours until the weight is stable. At this point the sample is dry. Small decrease of weight (up to 2 % of sample mass) can be neglected. Percentage of weight reduction during drying [%]:

$$\text{Reduction of weight} = \frac{weight\ before\ drying - weight\ after\ drying}{weight\ after\ drying} \text{ x } 100\ \% \qquad (4.8)$$

7. Dry mass of sample(s) (m_d [g]) and t_1 should be written in Table 4-25.

Table 4-25: Weight of sample(s) and drying conditions

Sample No.	Saturated weight m_s [g]	Drying temperature t_1 [°C]	Dry weight m_d [g]
…	…	…	…

8. After sample(s) are weighted, they should be placed back in the oven to heat they up to the 105 °C while carrying out steps 9 – 11.

9. Container with water (mass of the water (m_w [g]) should be measured) is prepared. The container should be large enough to fit sample(s), well insulated and if possible with lid (e.g. ice box).

10. To measure the mass of water in the container, scales or measuring cup can be used. When using scales:

- the weight of empty container is measured (m_c [g]) and container filled with water (m_{cw} [g]) is measured
- the mass of water in container (m_w [g]) is calculated as

$$m_w = m_{wc} - m_c \qquad (4.9)$$

When using measuring cup, the mass of the water is calculated from the volume, by using water density (in general water density in room temperature is 1 g/cm^3 (1 cm^3 of water is 1 g of water)).

11. The value m_w should be inserted in Table 4-26.

Table 4-26: Specific heat capacity

Sample No.	Water mass m_w [g]	Brick temperature t_1 [°C]	Water temperature t_w [°C]	Water temperature t_2 [°C]
…	…	…		…

12. The container filled with water is kept in the room while it reaches the room temperature (can be done while drying samples), the water and room temperature are measured and when both temperature are equal, water temperature (t_w [°C]) is written down in Table 4-26.

13. The sample(s) is taken out from the oven and inserted in the container with water. Temperature of the water should be monitored (water can be stirred for better heat exchange) until the temperature doesn't change or starts to drop. This is temperature t_2 [°C]. The temperature t_2 is written down in Table 4-26.

14. When temperature t_2 is reached, leave the sample in the water until the saturated weight (m_s [g]) of the sample(s) is reached. To determine saturated weight weighing of sample(s) are made approximately every 24 hours. When the weight stops increasing, the sample is saturated. Small increase of weight up to 2 % of sample mass can be neglected (see Eq. 4.10). Determination of weight increase during sample saturation [%]:

$$\text{Increase of weight} = \frac{weight\ now - previous\ weight}{previous\ weight} x100\ \% \qquad (4.10)$$

15. The saturated weight of the sample m_s is inserted in Table 4-25 .

16. When the sample is saturated, measuring cup can be used to determine volume of the sample(s) (V_i [cm^3]) (Figure 4–52) (not necessary if the volume is determined in step 4):
- o The measuring cup is filled with water and the reading of the measuring cup (V_1 [ml]) is written down
- o The saturated sample is submerged in the cup and the resulting reading of the measuring cup (V_2 [ml]) is written down
- o The volume of the sample (V_i [cm^3]) is calculated as

$$V_i = V_2 - V_1 \qquad (4.11)$$

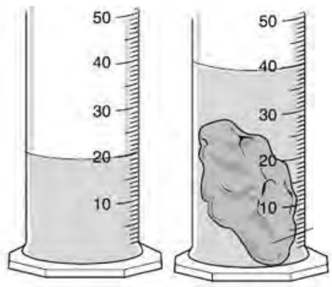


Figure 4–52: Determine volume with measuring cup.

17. V_i is written down in Table 4-24.

Sample density [g/cm^3] is calculated as:

$$\text{Density} = \frac{m_d}{V_r\ or V_i} \qquad (4.12)$$

Sample porosity [%] is calculated as:

$$\text{Porosity} = \frac{m_s - m_d}{V_i or\ V_r}\ x100\ \% \qquad (4.13)$$

Sample specific heat capacity C [kJ/(kg K)]:

$$C = \frac{C_w \cdot m_w \cdot (t_2 - t_w)}{m_d \cdot (t_1 - t_2)}, \quad (4.14)$$

C_w – specific heat capacity of water (4.1844 [kJ/(kg K)]).

Guideline for selecting an internal insulation system

5 Guideline for selecting an internal insulation system

The main goal of this guideline is to provide information to the consultant on how to select an internal insulation system.

5.1 Insulation systems – characteristics and preconditions for installation

Internal insulation systems are generally composed of several materials (layers) ensuring the necessary functions, such as insulation, structural stability and finishing. In many cases, the manufacturer delivers all the needed components (insulation material, fixing layers etc.).

The installation procedure usually includes the following phases:

- i) decide the type of insulation system, thickness and installation method;
- ii) remove everything fixed to the walls to be insulated (e.g. plug sockets, light switches, curtain rails, radiator, etc.);
- iii) clean and prepare the wall surface (i.e. knocking off old plaster if damaged);
- iv) install the insulation system according to the instructions of the manufacturer;
- v) eventual reinstallation of previously removed items.

Concerning phase iv), in general, there are two main installation methods, i.e.:

- directly fixing the thermal insulation to the wall. This method is generally adopted in case of sufficiently rigid insulation boards;
- creating a new internal stud. This method is usually adopted in case of not sufficiently rigid insulation materials.

Since installing an internal insulation system requires removal and re-fixing of several items, such as switches, radiators, etc., it is important to consider the best insulation solution/material for each specific case, also taking into account the possible occurrence of moisture-related problems, such as frost damage, interstitial condensation, mould growth and other damage patterns that may occur when an internal insulation system is applied. In this case, it is advisable to ask the opinion of an expert or to perform a more in-depth study to evaluate the possible occurrence of moisture-related issues and, then, to select the insulation system suitable for the specific case.

As a rule, the surface of the existing wall has to be clean, sustainable and dry (phase iii). Unsustainable plastering, barrier layers, paint and wallpaper have to be removed. Gypsum components in the existing wall construction have to be removed depending on the planned internal insulation system. If board-shaped internal insulation materials are applied, an even surface is required. This means that depending on the condition of the existing surface, the application of a base or levelling plaster may be necessary.

5.1.1 Preparation for installation

As part of deciding which type of insulation system to install (phase i), it might be relevant to clarify e.g. the bearing capacity of the existing wall (cf. some systems are glued directly to the existing wall), and possible material incompatibilities between materials in the existing wall and layers in the insulation system. Provided that the existing masonry is intact and the moisture load can be assumed normal, measurements of moisture properties in the specific case are not required, as most properties in historic brick material don't differ that much. If this is not the case, knowledge about the drying potential and moisture resistance of the existing wall, as well as capillary and diffusive transport and storage properties is needed. Potential increase of internal moisture loads should also be considered, especially if the use of the building is changed after the renovation. Finally, also fire and noise protection requirements should be considered, cf. Section 3.8.

Phase iii) includes the following items:

- Wall texture: The substrate of the existing wall must be clean, dry, dust-free and free from other contaminants.
- Bearing capacity of existing plaster surfaces. Non load-bearing concealed plasters, barrier layers, paints and wallpaper must be removed in order not to hinder moisture transport after the internal insulation has been applied.
- Flatness of the wall: Gypsum components in the existing wall construction must be removed. If panel-shaped internal insulation materials are to be applied, a flat surface is required. This means that, depending on the condition of the existing plaster, it may be necessary to arrange a base plaster or level out.
- Prepare a new base plaster to be applied: It should have the following properties: (1) Compressive strength: 3-5 N/mm^2 , (2) high porosity, (3) vapour diffusion resistance $\mu < 15$, (4) sufficient capillary activity ($Aw > 1\ kg/(m^2h0,5)$), e.g. NHL plaster, lime plaster with a low content of cement or special base plaster.
- The drying of the base plaster (if required) must be observed until internal insulation can be applied.

If a sufficiently rigid insulation material is adopted (e.g. EPS, XPS, PUR, cork, etc.), the insulation layer can be directly fixed to the wall by using a specific adhesive or, when necessary, mechanical fixing (screws). If the retrofit intervention concerns an uneven wall, fixing battens can be used to provide a flatter surface for the insulation installation. The installation is then finished at the interior by using a specific rendering system or through gypsum plasterboards directly glued to the insulation material.

In the case of more flexible insulation material, a new stud wall is generally built, leaving a ventilated cavity between the existing wall and the stud wall that is finished with gypsum plasterboard.

Non-rigid internal insulation systems

They can be deformed during paving and can therefore be applied to uneven surfaces without further preparation. If insulating plasters are to be applied, make sure that the surface is moisture-resistant. Highly absorbent surfaces have to be prepared accordingly with a suitable primer.

Board-shaped internal insulation systems

Even with board-shaped systems, the absorption behaviour of the surface has to be adjusted according to the manufacturer's specifications. Unevenness has to be evened out with plasters suitable for the system. The size of the permissible unevenness depends on the manufacturer's specifications. Internal insulation systems with vacuum insulation panels tolerate only very small deviations up to 5 mm.

Pre-walled shells

They do not require any levelling plaster. The resulting cavity has to be completely filled with a suitable backfilling mortar to ensure capillary coupling of the facing layer.

5.1.2 Characteristics of internal insulation systems

Various internal insulation systems and products are available on the market. They mainly differ in terms of material properties, installation method, environmental impact, durability and costs. Based on the hygrothermal properties of the insulation material, the internal insulation systems can be subdivided into two main groups: *vapour-tight* and *vapour-open* systems. Table 5-1 includes a selection of the main insulation systems subdivided according to this classification.

A *vapour-tight* internal insulation system prevents the warm, moist indoor air from penetrating the insulation. It can be obtained by using a *vapour-tight* insulation material (e.g. PUR, XPS, cellular glass, etc.) or, alternatively, by coupling a vapour barrier (i.e. a foil that does not permit the vapour to pass through) to a vapour-open material (e.g. mineral wool). Particular caution is always required when a vapour barrier is adopted, as any disconnection or perforation of the barrier determines a possible vapour penetration, thus a potential significant decrease in the system performance. The installation of a vapour barrier requires proper workmanship ensuring an air tight layer and careful use by the residents avoiding perforation of the vapour barrier. In some countries, e.g. Switzerland, internal insulation of mineral wool is also used together with a smart vapour retarder, able to modify its vapour diffusion resistance depending on the relative humidity of the indoor environment. This kind of solution has not been studied as part of RIBuild.

A *vapour-open* internal insulation system is generally obtained by using a vapour-open insulation material that also enables capillary suction (*capillary-active* insulation material). The capillary activity of the material, in fact, allows the moisture transport through the insulation material towards the indoor air if the inner surface of the existing wall gets wet, for instance due to interstitial condensation.

Table 5-1. Examples of internal insulation systems classified based on water vapour diffusion resistance of the composing materials.

Vapour-tight internal insulation systems		Vapour-open (capillary active) internal insulation systems
Vapour-tight insulation materials	**Vapour-open insulation materials coupled with a vapour barrier***	
Expanded polystyrene (EPS) Extruded polystyrene (XPS) Cellular glass (CG) Polyurethane (PUR) …	Mineral wool (MW) + PE-foil Cellulose (CEL) + PE-foil …	Calcium silicate (CaSi) Wood fibreboard (WFB) Cellular concrete Autoclaved aerated concrete (AAC) …

*: In some countries, e.g. Switzerland, vapour-open insulation materials are also used in combination with a smart vapour retarder.

To select the proper insulation solution, it is important to know the hygrothermal properties of the materials in the existing wall and the insulation systems. Among them, the *thermal conductivity* λ [W/(m K)], the *capillary activity* and the *water vapour diffusion resistance factor* μ [-] are the most important (RIBuild Deliverable D1.2, 2016).

The *thermal conductivity* λ [W/(m K)] expresses the rate at which heat is transferred by conduction through a unit cross-section area of the material when a temperature difference exists. All λ-values of the materials composing the insulated wall should be known to calculate the targeted air-to-air *U-value* (thermal transmittance, [W/(m^2 K)]) of the wall, usually specified in building regulations. It is calculated as follows:

$$U = \frac{1}{R_{si} + \sum_{i=1}^{N} \frac{s_i}{\lambda_i} + R_{se}} \tag{5.1}$$

where R_{si} and R_{se} are respectively the internal and external surface thermal resistances [m^{2}K/W], while s_i and λ_i are the thickness (m) and the thermal conductivity [W/(m K)] respectively, of the i-th layer of the retrofitted wall.

The c*apillary activity* is the ability of some materials to absorb liquid water due to capillary suction and to redistribute it through the material. The pore size in capillary active materials permit liquid water to be absorbed and redistributed towards the room in both vapour and liquid phase, following the inwards capillary pressure gradient (Vereecken & S. Roels, 2016). Generally, capillary active materials, such as calcium silicate (CaSi) and wood fiberboards (WFB), are expensive compared with traditional insulation materials and often characterized by a higher thermal conductivity (typically 50 % higher).

The *water vapour diffusion resistance factor* μ (-) expresses the relative reluctance of a material to let water vapour pass through. It is calculated as the water vapour permeability of air divided by that of the material concerned. This property is generally used to classify insulation materials in *vapour-open* insulation systems (with low μ values) and *vapour-tight* insulation systems (with high μ values). Typical vapour-open insulation materials are mineral wool, cellulose, calcium silicate and wood fiberboard. Typical vapour-tight insulation materials are extruded polystyrene, polyurethane, expanded polystyrene and cellular glass.

Vapour-tight insulation systems are obtained by applying a vapour-tight insulation material or, alternatively, by coupling a vapour-open insulation material with a vapour barrier. In Figure 5–1, a typical Glaser diagram for a *vapour-tight* internal insulation system based on the use of vapour-tight insulation material is reported. If the μ or the Z-value (water vapour diffusion resistance in absolute values [(m^2 s Pa)/kg] of the insulation material is sufficiently high, interstitial condensation can be avoided, in Figure 5–1 seen by the p_v curve staying below the $p_{v,sat}$ curve.

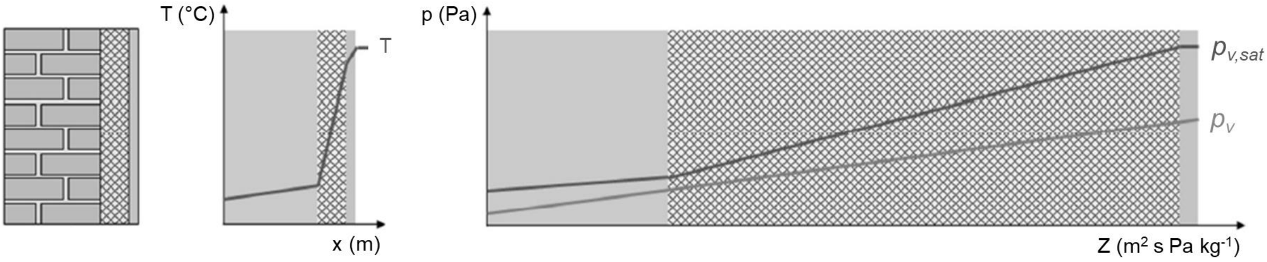


Figure 5–1: Typical Glaser diagram for an internal insulation system adopting a vapour-tight insulation material. T: temperature; x: coordinate; p: pressure; Z: vapour diffusion resistance; $p_{v,sat}$: saturation vapour pressure; p_v: vapour pressure (adapted from* (Vereecken, Hygrothermal Analysis of Interior Insulation for Renovation Projects, 2013)*).

In Figure 5–2, a typical Glaser diagram for *vapour-tight* insulation systems obtained by adopting a vapour-open insulation material coupled with a vapour barrier is shown. If the vapour barrier is characterized by a sufficiently high μ, interstitial condensation can be avoided in the heating season (a). However, during the cooling season, a sufficiently low μ is needed to avoid summer condensation (b).

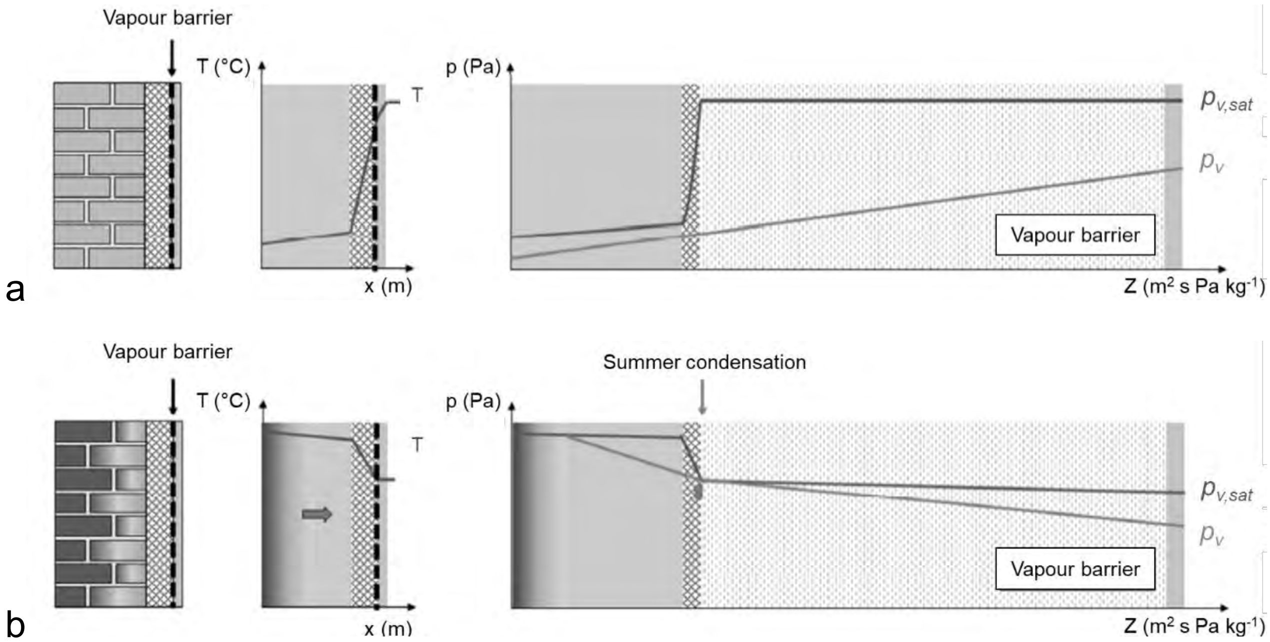


Figure 5–2: Typical Glaser diagram for a vapour-tight internal insulation system with a vapour open insulation material coupled with a vapour barrier: a) interstitial condensation; b) summer condensation. T: temperature; x: coordinate; p: pressure; Z: vapour diffusion resistance; $p_{v,sat}$: saturation vapour pressure; p_v: vapour pressure (adapted from **(Vereecken, Hygrothermal Analysis of Interior Insulation for Renovation Projects, 2013)***).*

In *vapour-open* insulation systems, a vapour-open capillary active insulation material is adopted, generally coupled with specific glue and finishing mortar. In Figure 5–3, the working principle of such an internal insulation system is shown. During the heating season, the temperature and vapour gradients generate an outward vapour transfer. If the temperature between the glue mortar and the insulation is lower than the dew point, interstitial condensation can occur. Good contact between the existing wall and the insulation system is fundamental for the proper functionality of the system. In fact, in case of a discontinuity between the masonry wall and the capillary active material, interstitial condensation can occur at the warm side of the wall (Figure 5–4).

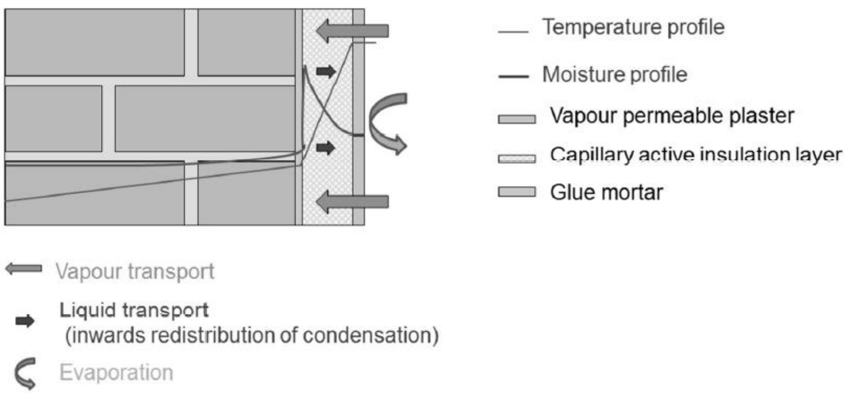


Figure 5–3: The working mechanism of a capillary active internal insulation system (adapted from **(Vereecken, Hygrothermal Analysis of Interior Insulation for Renovation Projects, 2013)***).*

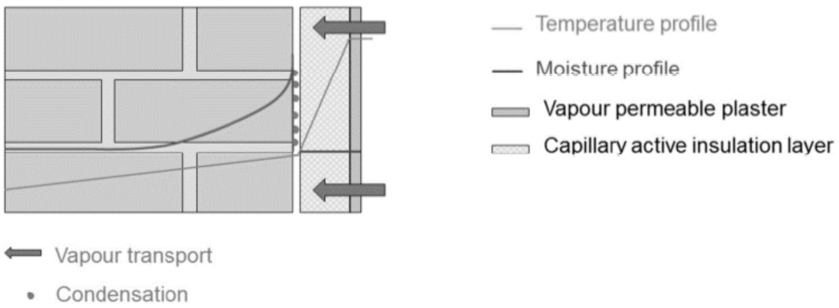


Figure 5–4: Capillary active internal insulation system failure caused by an air gap between the existing masonry wall and the insulation system (adapted from **(Vereecken, Hygrothermal Analysis of Interior Insulation for Renovation Projects, 2013)***).*

Internal insulation can significantly modify the hygrothermal performance of the existing wall, inducing frost damage, interstitial condensation, mould growth and other damage patterns. When internal insulation is applied to historic buildings, it is then important to assess its hygrothermal performance, to evaluate the possible impact on an existing structure. In Figure 5–5a and b typical ranges of dry λ and μ values for commonly used insulation materials are reported.

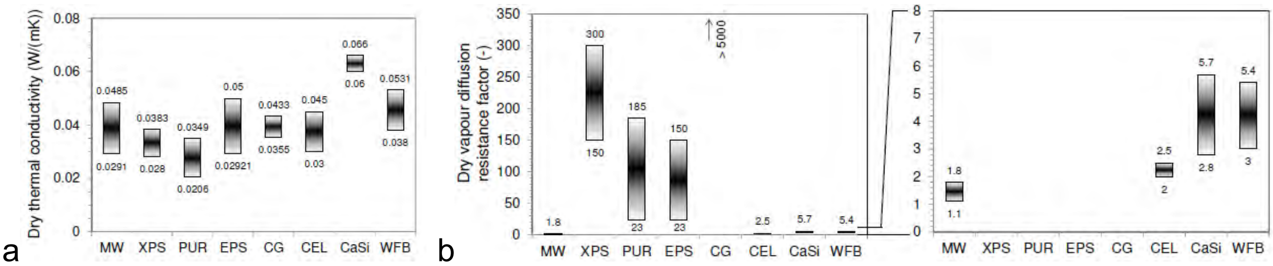


Figure 5–5: Dry thermal conductivity (a) and dry vapour diffusion resistance factor (b) of the main insulation materials. In the case of wet materials, the thermal conductivity and the vapour diffusion resistance can be higher and lower, respectively. The insulation systems compared are Mineral wool (MW), Extruded polystyrene (XPS), Polyurethane (PUR), Expanded polystyrene (EPS), Cellular glass (CG), Cellulose (CEL), Calcium silicate (CaSi) and Wood fiberboard (WFB)(adapted from **(Vereecken, Hygrothermal Analysis of Interior Insulation for Renovation Projects, 2013)***).*

In the case of *vapour-tight* insulation systems with vapour-tight insulation material, μ of the insulation material must be sufficiently high to prevent interstitial condensation. Conversely, if a vapour-open insulation material is coupled with a vapour barrier, the vapour resistance of the vapour barrier should be sufficiently high to avoid interstitial condensation during the heating season and, at the same time, sufficiently low to allow the drying out of the masonry wall during the cooling season.

In the case of the *vapour-open* capillary-active insulation system, it is important that the hygrothermal properties of the capillary active insulation material and those of the glue mortar are correctly selected to ensure the proper functioning of the system. The glue mortar should have a higher vapour resistance and a lower liquid conductivity than that of the insulation material (Scheffler & Grunewald, 2003). In this way, in fact, the over-hygroscopic moisture is generated between the glue mortar and the insulation material, allowing the insulation material to transport the moisture by capillarity towards the indoor environment.

Finally, it should be noted that the thermal conductivity of capillary-active insulation materials is higher than for traditional mineral wool. The moisture dependency shown in Figure 5–6 and Figure 5–7 is based on DELPHIN using values for a material in dry condition and the thermal conductivity of water. This is why the slope of the two curves in Figure 5–6 are the same. Although the assumption of having the same moisture dependency in both cases can be questioned, notice, only at very high RH values the thermal conductivity increases considerably compared to the values at normal indoor climate conditions. Further, as the capillary-active insulation material (ID 571) absorb more moisture from the air at RH between 80 % and 97 % (Figure 5–7 and Figure 5–8) the difference in thermal conductivity between calcium silicate and mineral wool is higher at a high RH.

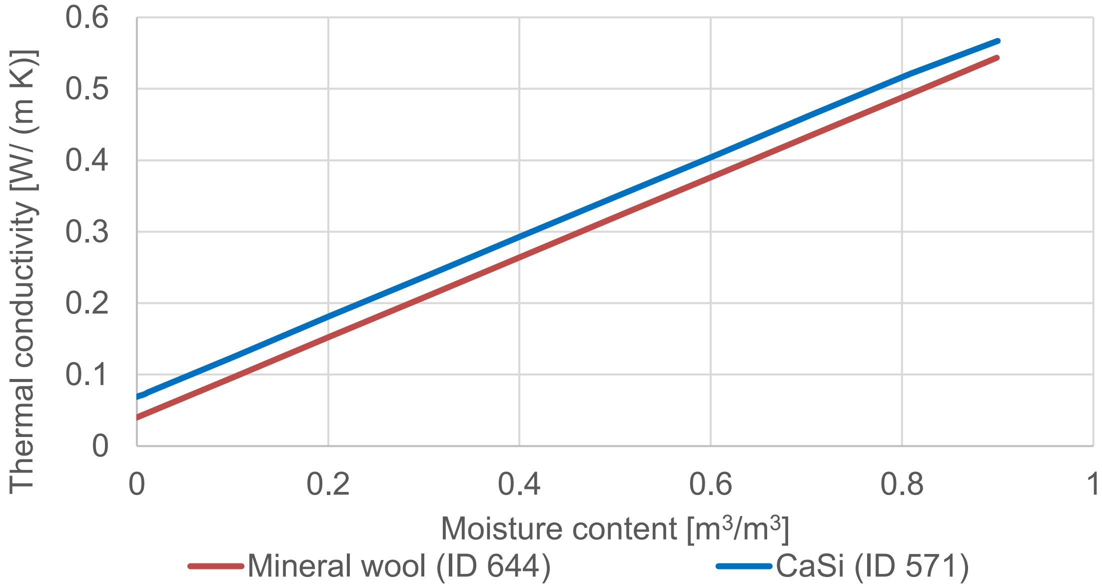


Figure 5–6: Moisture dependent thermal conductivity of calcium silicate (CaSi) (DELPHIN ID 571) and mineral wool (DELPHIN ID 644), based on data for themal conductivity in dry condition and the thermal conductivity of water. Thermal conductivity as a function of moisture content (kg/m^3)

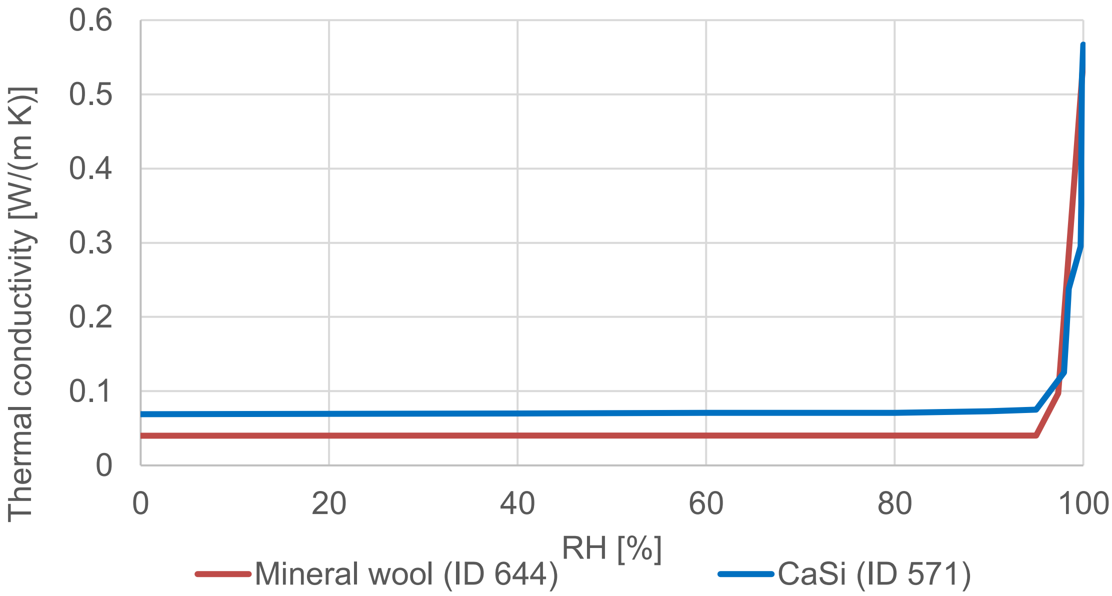


Figure 5–7. Moisture dependent thermal conductivity of calcium silicate (CaSi) (DELPHIN ID 571) and mineral wool (DELPHIN ID 644), based on data for thermal conductivity in dry condition and the thermal conductivity of water. Thermal conductivity as a function of RH (%).

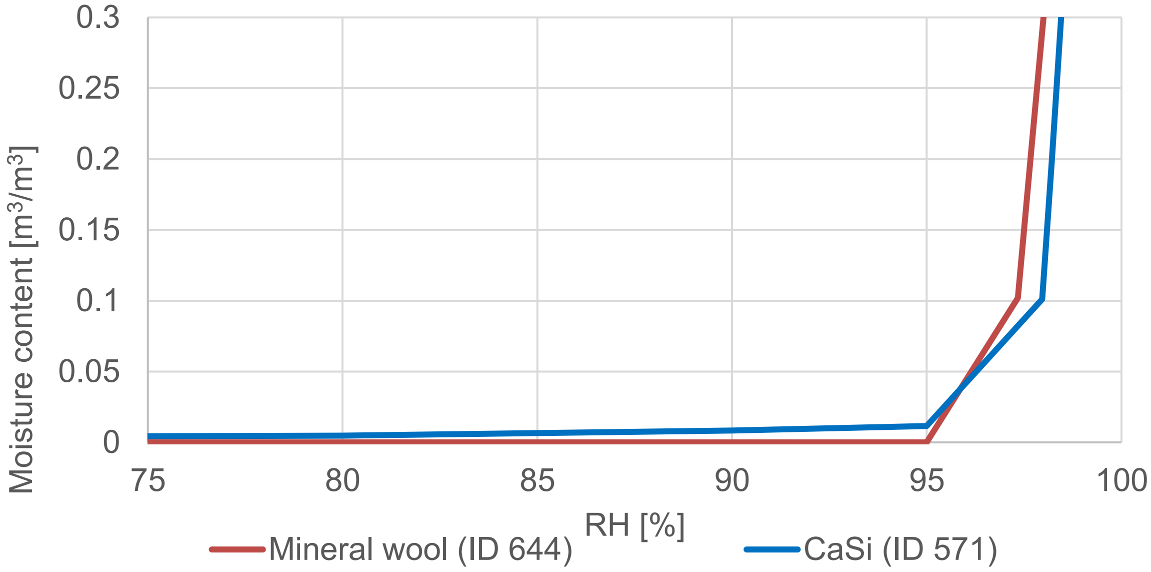


Figure 5–8. Sorption isotherm for calcium silicate (CaSi) (DELPHIN ID 571) and mineral wool (DELPHIN ID 644) zooming in on the interval from 75 % and upwards.

Recently, also insulation boards consisting of multiple materials have been developed, such as wood fiberboard with embedded mineral functional layer, PUR in combination with calcium silicate, calcium silicate in combination with PUR, pyrogenic silicas, etc. In Figure 5–9 the working principle of a wood fibre insulation board with an embedded functional layer is shown. During the heating season, water vapour is transported inside the insulation system. The functional layer restricts the vapour transport and a condensation plane arises at the functional layer. Thanks to the capillary active forces of the wood fiberboard, the redistribution of the potential interstitial condensation towards the room side is thus allowed.

A similar working mechanism occurs even in the case of a two-layered capillary active internal insulation system consisting of a retarder layer at the side of the masonry wall and an insulation layer at the room side. The aim of the two-layered system is to force the occurrence of the interstitial condensation between the retarder layer and the insulation layer instead of at the masonry wall, ensuring in this way the functionality of the capillary internal insulation system even in case of an air gap between the original wall and the insulation system. In this case, to locate the interstitial condensation plane between the retarder and the insulation layer, appropriate thermal, vapour and capillary conductivity for both layers of the system should be selected. In particular, the insulation material should have a low thermal conductivity, a high liquid conductivity and a low vapour diffusion resistance. The retarder layer, instead, should have higher thermal conductivity, a lower capillary conductivity and a higher vapour diffusion resistance (Künzel, 1999).

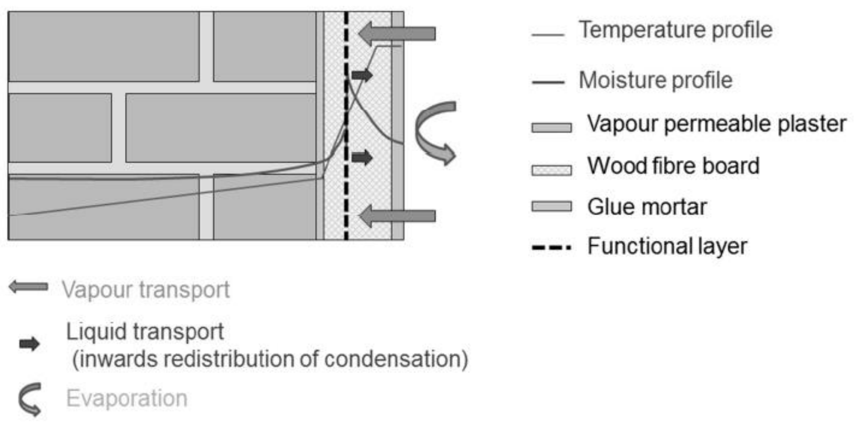


Figure 5–9: Working principle of a wood fiberboard with an embedded mineral functional layer (as explained by the manufacturer) (adapted from* (Vereecken, Hygrothermal Analysis of Interior Insulation for Renovation Projects, 2013)*).

More information about insulation materials and systems is available in (RIBuild Deliverable D1.2, 2016).

(RIBuild Deliverable D3.2, 2019) gives an overview of the hygrothermal performance in practice for a number of internally insulated case study buildings, either RIBuild-cases (14) or published (31) monitoring projects. They cover a wide range of weather conditions (locations), constructions (wall materials, wall thickness, type of constructive details) and typologies (office, residential and others). Different aspects have been analysed, e.g. performance risk factors addressing the construction (Section 3.1 and 3.3) or weather conditions (Section 3.4).

Among 31 case studies published since 2003 and 14 RIBuild case studies, only two damage cases occurred. However, critical moisture contents were measured in several projects for the first monitoring years; in 14 published case studies and five RIBuild case studies. In nine of these cases, critical moisture content could be attributed to a high built-in moisture of the system and the corresponding drying phase in the first year after installation of internal insulation. The length of the drying phase depends on the amount of built-in moisture, drying potential due to the vapour diffusion resistance and capillary activity of the system.

Most of the projects with critical moisture contents showed a strong initial drying process with an acceptable moisture level in the wall after the first or the second year. Further reasons for high moisture levels in the construction were poor thermal resistance of the existing wall, a missing sealing of joist ends towards indoor air, a poor drying potential due to a high vapour resistance of the insulation system in combination with an insufficient wind driven rain protection or an inactive heating system. Other factors like the driving rain load or the air tightness of the construction are not documented in a comprehensive way for all cases.

5.2 Calculation methods

An important step for choosing an internal insulation system is calculation of impact of heat and moisture processes. A calculation method or simulation tool must be chosen. The simplest of combined heat and mass transfer calculation methods is the Glaser model; it is a 1-D model with stationary climate on both sides of the building component only considering thermal conductivity for heat transport and diffusion for moisture transport. Material properties are simplified to be independent of hygrothermal conditions and therefore constant. The method is not considered to be a simulation mainly because the climate is constant. More advanced methods like DELPHIN, WUFI and MATCH operate with transient conditions and hygrothermal dependent material properties and are therefore considered to be simulation tools.

The main purpose of modelling combined heat and mass transfer in building components is to evaluate how the building component will perform in reality without doing physical experiments. The aim of each model is therefore to mimic what happens in reality.

A perfect model would predict the hygrothermal condition in a building component if all boundary conditions and material parameters were known. Unfortunately, there will always be unknown factors as reality is too complex to be described in a model; models are simplifications of reality, e.g. 3-D modelling has only recently become possible, and materials are not perfect. Therefore, in reality material properties will vary within the material. Uncertainties in measurements will make boundary conditions uncertain; time steps in measurements are often different from time steps in calculations, etc. Perfect agreement between calculated and measured values are unrealistic. To increase the reliability of simulation models, (RIBuild Deliverable D3.1, 2018) provides insights in closed technology loop of laboratory experiments and simulation models in the field of internal insulation testing.

Glaser method

This method was developed by German scientist Helmut Glaser. It is also called moisture profile method, or dew point method. The Glaser method was developed to determine interstitial condensation risk and condensation speed in building components. The method can also be used as a fast but not very precise method to assess corrosion and mould growth risks. Glaser restricted condensation to interfaces of layers since interlayer condensation caused difficulties with the mass conservation law. The Glaser method only handles stationary conditions. Further, it does not include capillary suction, which takes place in both brick masonry and capillary-active insulation materials.

Further description of Glaser method is provided in (RIBuild Deliverable D2.1, 2018), Section 2.3.1.

COND

The COND software was developed at The Institute for Building Climatology at Dresden University of Technology, Germany. The calculations are based on an algorithm developed by Prof. Dr.-Ing. habil P. Häupl in the 1980s. COND was developed to improve the Glaser method especially in relation to certain constructions. In the analysis, many simplifications and idealisations have been introduced that further narrow the scope of the method.

COND is a software for hygrothermal evaluation of one-dimensional building envelope systems, as it calculates the stationary heat and moisture transport. Based on the Glaser scheme standard method according to the German standard DIN 4108-3 (2014) and described in Section 5.2.1 Glaser that only takes vapour fluxes due to differences in vapour pressure into account, COND additionally includes liquid fluxes, i.e. the redistribution of occurring internal condensate. Thus, the results are more realistic and it is therefore especially useful for multilayer constructions with capillary active internal insulation materials that are used for a thermal upgrade and refurbishment of older buildings.

COND is a simple and fast practice tool for the evaluation of possible moisture damage of the building envelope taking simplified climatic conditions into account. It needs limited input data and climatic conditions and material properties can be used-defined. The outcome is a short report stating whether or not the requirements of the chosen standard are fulfilled can be customized. The report includes a sketch of the construction, material and climate data, temperature, moisture and vapour pressure profiles and individual remarks. This report can be used for documentation purposes. Since COND provides the needed verification according to the German DIN 4108-3 (2014), it is mainly used in Germany, but may also be useful elsewhere if the German standard is regarded as acceptable.

Further description of COND is provided in (RIBuild Deliverable D2.1, 2018), Section 2.3.2.

Eco-Sai tool based on Glaser method

Eco-Sai is a stand-alone tool developed by the University of Applied Sciences of Western Switzerland that combines the calculations of U-value, thermal inertia and life cycle assessment of a construction (homogeneous and inhomogeneous) (www.eco-sai.ch). At present it is the single integrated tool for these three calculations. Eco-Sai can evaluate the characteristics of a construction during the preliminary stage or the project phase, for new buildings or renovation projects. Planners using the CAO Autodesk® Revit® software can also conduct these calculations within Revit®.

Further description of Eco-Sai is provided in (RIBuild Deliverable D2.1, 2018), Section 2.3.3.

DELPHIN

The hygrothermal transport model DELPHIN was developed at Dresden Technical University by John Grunewald. It was extended by air flow, pollutant transport, and salt transport. It has used it as platform for material and transport model development (moisture transport) and for non-linear thermal storage and transport. Simulation program for calculation of coupled heat, moisture, air, pollutant, and salt transport. The program is commercially available in 1- and 2-D. A new 3-D version is being tested. Balance equations are used to carry out numerical analysis of the following transport processes:

- Heat transport in building components and construction details, incl. wall constructions, thermal bridges
- Moisture transport of both liquid and vapour transport, and moisture storage in constructions
- Air transport.

DELPHIN is used as simulation tool in the RIBuild project.

Further description of DELPHIN is provided in (RIBuild Deliverable D2.1, 2018), Section 2.2.1.

In RIBuild, DELPHIN hygrothermal simulation program has been significantly extended, concerning both effectiveness and efficiency. The main focus was on efficiency improvements of both the deterministic simulator and the probabilistic methodology since prior to the initiation of the RIBuild project, both a deterministic simulator and a probabilistic methodology were already available but their joint application to internal insulation solutions required further developments. More detailed description can be found in (RIBuild Deliverable D4.1, 2017) and (RIBuild Deliverable D4.2, 2019).

WUFI

WUFI is designed to calculate simultaneous heat and moisture transport in one- or two-dimensional multi-layered building components in the building envelope based on laboratory and outdoor tests. WUFI is the acronym for "Wärme- und Feuchtetransport instationär" ("Transient Heat and Moisture Transport"). The original basis for the program is given in a thesis by H. M. Künzel and has been developed into the WUFI-family (WUFI-Plus, WUFI-2D, WUFI-Pro and WUFI-ORNL/IBP) which are commercial programmes developed in Germany by the IBP-Fraunhofer Institute for Building Physics. WUFI simulations can be done according to several regulations; EN 13788 (Glaser method), ASHRAE Standard 160 and EN 15026. WUFI-Bio is a post-processor to simulate the risk of mould growth. The results are given as the Mould Growth Index according to the Viitanen model and in mm mould growth per year according to Sedlbauer's biohygrothermal model. Many possibilities exist to adjust material properties, outside and inside boundary conditions.

Further description of WUFI is provided in (RIBuild Deliverable D2.1, 2018), Section 2.2.2.

MATCH

MATCH (Moisture and Temperature Calculations for Constructions of Hygroscopic Materials) is a commercial computer simulation program for the calculation of combined transient moisture and heat transport through composite building materials. The one-dimensional model was developed within a research project at the Thermal Insulation Laboratory of the Technical University of Denmark around 1990. It was developed as an alternative to the steady state numerical Glaser scheme that is not feasible - i.e. accurate enough - for hygroscopic materials. It was originally developed for roofs, but useful to most kinds of building constructions. The MATCH model (limited to the vapour region) has been partly incorporated in another simulation program, BSim for whole building simulation, since the early 2000's.

Further description of MATCH is provided in (RIBuild Deliverable D2.1, 2018), Section 2.2.3.

Guideline for evaluating energy saving potential, environmental impact and life cycle cost

6 Guideline for evaluating energy saving potential, environmental impact and life cycle cost

The main goal of this guideline is to provide support to the building owner or the building owner's consultant to assess the energy saving potential, the environmental impact and the life cycle cost of internal insulation solutions.

This guideline presents a set of practical procedures on how to select an optimal internal insulation solution in a renovation scenario based on a number of decision criteria. First, the guideline shortly introduces three different methods for estimating the energy saving potential based on heat loss calculations (Section 6.1). Second, it illustrates how to quantify the environmental impact caused by the application of internal insulation using Life Cycle Assessment (LCA) (Section 6.2). Finally, it details the calculation of Life Cycle Cost (LCC) of internal insulation solutions (Section 6.3).

Figure 6.1 presents the link between a probabilistic hygrothermal assessment and a subsequent calculation of heat loss, environmental impact and life cycle cost, all being part of tools prepared within RIBuild. The calculations of heat loss, environmental impact and life cycle cost has been implemented in the WP5 software tool (RIBuild Deliverable D5.1, 2017). Calculations of heat loss has been implemented in a simplified way in the WP6 web tool for hygrothermal assessment – and environmental impact might be as well[3] (RIBuild Deliverable D6.1, Web tool including feasibility study of possible input and output data, 2020). Both tools are accessible through the RIBuild project webpage, www.ribuild.eu. These tools enable the probabilistic assessment for both hygrothermal performance and environmental impact/life cycle cost of an internal insulation solution, to support risk management and decision-making.

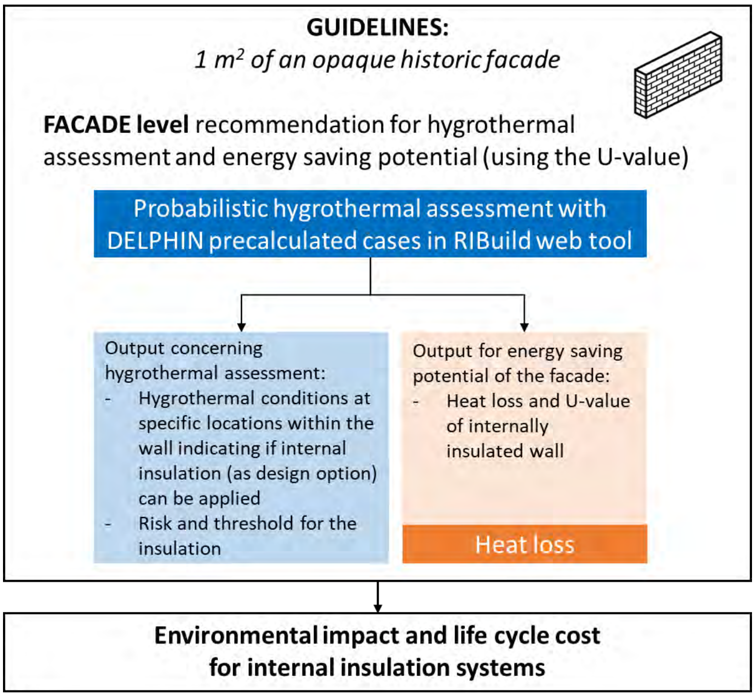


Figure 6–1: Link between hygrothermal assessment and energy saving potential, environmental impact and life cycle cost in RIBuild guidelines.

[3] Not clarified when finalising this deliverable

6.1 Energy saving potential

The energy saving potential is found by comparing the heat loss through the existing external wall before and after applying an internal insulation system. Heat transmission loss exists as soon as there is a temperature difference between indoor (e.g. set at 20°C) and outdoor. Calculating the heat loss requires values for the U-value of the wall, monthly outdoor temperature at the location, average indoor temperature and the number of heating hours. The U-value represents the ability of the external wall to resist to the heat transfer through the wall. Energy saving potentials are expressed for instance as kWh/m^2 per year.

The RIBuild web tool provides heat loss (W/m^2/year) for different internal insulation systems, external wall types and locations, including a non-insulated wall. The heat loss reduction or the energy saving potential of different systems are only comparable if there is a common basis for the comparison (e.g. the same U-value for each alternative). In the case of comparing insulation systems with the same thickness, it is important to keep in mind that systems with a better thermal performance will be favoured, as they require less thickness to provide the same savings. The more the wall is insulated, the higher the savings will be. However, the thickness is in general limited from a hygrothermal point of view, as the risk of moisture related damage described in Section 4.1 and 4.2 otherwise might be too high.

It is important to recall that heat losses through the opaque or non-transparent part of the facade do not cover the entire heat demand of a building. More aspects have to be included such as solar gains, ventilation losses, thermal bridges etc. Those aspects are not investigated in the RIBuild web tool and guidelines.

Different calculation methods can be used to perform the annual calculations of heat loss through the facade during the heating season. Three different approaches (or ”options”) can be considered:

1. coupled heat and mass (HAM) transfer numerical model based on hourly climate data;
2. monthly calculation between the internal temperature and the average monthly temperature;
3. annual calculation based on annual Heating Degree Days (HDD).

Option 1 allows having an accurate and consistent assessment on hygrothermal aspects prior to the LCA. However, option 1 is highly demanding in terms of accurate climatic data and indoor conditions, material properties of the historic facade and of the chosen internal insulation systems. The details of the heat loss calculations using a coupled heat and moisture transfer simulation are not presented in this guideline. Nevertheless, the software tool for probabilistic LCA of internal insulations developed as WP5 software tool (RIBuild Deliverable D5.1, 2017) allows using HAM tools results (even provided as PDFs) for the LCA assessment.

The other two calculation procedures can be used when a HAM simulation is either not feasible or not possible (i.e. calculation cost or time issue, missing material properties leading to irrelevant HAM simulations etc.). The procedures can be used, as stand-alone calculation methods, to estimate the heat losses through the facade using simplified but standardised approaches, as described in Section 6.2 and 6.3. *Option 3* has been implemented into the WP5 software tool (RIBuild Deliverable D5.1, 2017) to easily obtain transmission losses through the wall in a probabilistic or deterministic way.

6.2 Environmental impact using Life Cycle Assessment

The environmental impact associated to the implementation of internal insulation should be quantified by a consolidated, comprehensive and systematic method. Life Cycle Assessment (LCA) is a standardized and internationally recognized method to quantify resource consumption, environmental impact, and emissions linked to a product or service through its whole life cycle. The probabilistic LCA methodology developed in RIBuild, as implemented in the WP5 tool and – if possible[4] – in the WP6 web tool, can calculate possible ranges of the environmental impact of several internal insulation solutions, thus to investigate and compare different design options upon their optimized hygrothermal performance.

To do so, both *induced* and *avoided* impacts of the insulation systems should be quantified (Figure 6.2). The former is related to the added internal insulation system, and the latter is due to the heat losses reduction (i.e., the energy saving potential) for a specific heat source in the building (heat pump, oil-fired boiler, natural gas, wood pellet boiler, district heating, etc.).

For the internal insulation of 1 m^2 opaque facade, the environmental impact is mainly dominated by the operational energy use, rather than the *induced* impact from the applied internal insulation systems. Here, the most influencing factor is whether the heat production system has been replaced during the renovation as the environmental impact is mainly driven by the operational energy use.

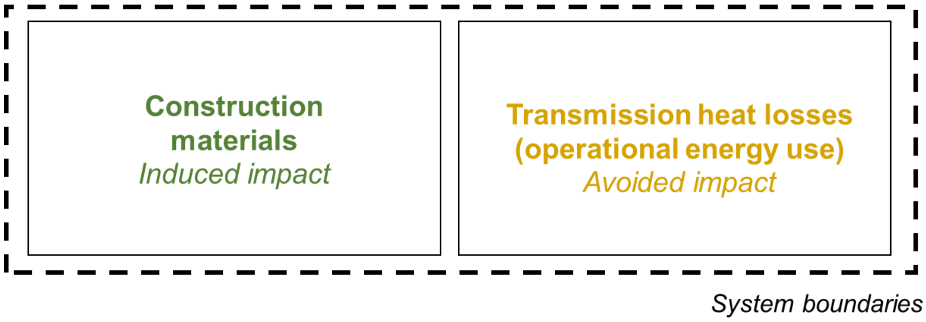


Figure 6–2: Induced and avoided impacts due to the installation of an internal insulation system for a historic building facade.

LCA can calculate a number of indicators to evaluate the environmental performance among different insulation solutions. RIBuild focuses on the indicator of Global Warming Potential (GWP) by quantifying the greenhouse gas emissions (GHG) caused by the construction materials (induced impact) and the transmission heat loss (avoided impact). The defined system boundaries of the insulation systems in RIBuild are in accordance with (EN 15804, 2012), as shown in Figure 6.3. The analysis covers the production stage (modules A1-A3), the use stage (module B2 (maintenance), B4 (replacement) and B6 (operational energy use)), and the end-of-life stage (EoL) (modules C1-C4), making this a 'cradle-to-grave' simplified LCA. Modules A1-A3, B2, B4 and C1-C4 are the induced impact, whereas module B6 is the avoided impact from saved energy consumption via space heating. Due to the assumed low influence of impact from construction materials in the scope of RIBuild (where most of the impacts are linked to the operational energy use), module A4 (the transportation to building site), module A5 (construction process), module B1 (use), B3 (repair) and B5 (refurbishment) are excluded in the RIBuild LCA modelling. More information is available in

[4] Not clarified when finalising this deliverable

(RIBuild Deliverable D5.1, 2017). Practitioners should be aware that the defined system boundary in RIBuild WP6 web tool (if environmental impact is included[5]) can be different from the WP5 tool.

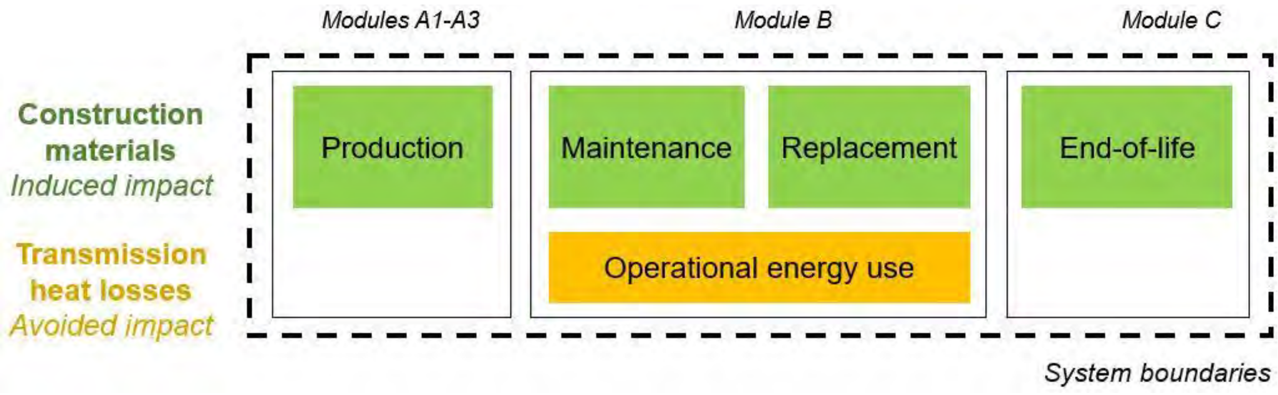


Figure 6.3: Life cycle stages included in the calculation of environmental impact in RIBuild.

The LCA calculation requires input data on transmission heat loss before and after the renovation (i.e. data from the energy saving potential calculation, see section 6.1) to determine the operational energy use and the environment impact savings caused by the added insulation thickness. To do that, heat loss savings are converted into environmental impact savings using LCA data, expressed as 1 kWh (or MJ) of heat provided by the building's heating system (e.g., heat pump, oil boiler, naturel gas, wood pellet boiler, district heating etc.).

Figure 6.4 presents an example of a typical probabilistic LCA result, where uncertainty ranges of environmental impact are calculated for five insulation solutions and different heat producer replacement scenarios. The calculation takes account of parameter uncertainties in the heat loss and LCA input. As shown in Figure 6.4 (left), there are no significant differences in terms of the GHG emissions among the internal insulation systems. While in comparison, a clear ranking with a relatively high confidence (robust choice) is shown for the GHG emissions in the scenario of heat producer replacement, see Figure 6.4 (right). This result suggests that, the LCA results are highly influenced by the choice of a new heating system, rather than the material of insulation systems.

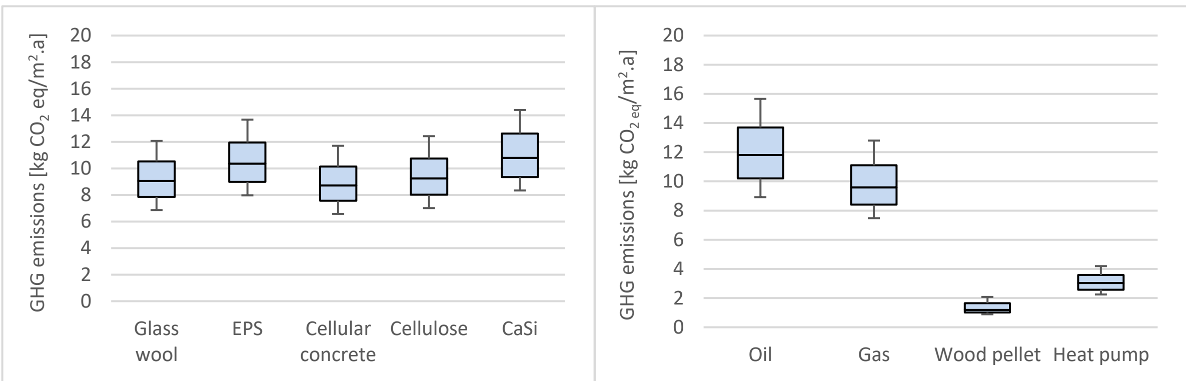


Figure 6.4: (left) Illustration of a typical LCA result of insulation systems for the greenhouse gas emissions (GHG); (right) illustration of a typical LCA result for the scenario of heat producer replacement.

[5] Not clarified when finalising this deliverable

More information, case studies and interpretation are available in (RIBuild Deliverable D5.1, 2017). Further, in the WP6 web tool, heat loss and – if possible – environmental impact[6] are computed based on user input about a specific building (RIBuild Deliverable D6.1, Web tool including feasibility study of possible input and output data, 2020).

Other tools exist as well to calculate energy saving potential and LCA for a 1 m^2 of an opaque facade insulation as well as for a whole building, including tools developed and used in RIBuild partner countries, such as the Swiss tools Eco-sai (Ecosai) and Lesosai (Lesosai, 2017), the Danish tool Be18 (Aggerholm, 2018), and the Italian software Termo Namirial (Termo Namirial, version 3.3). However, they do not cover a full probabilistic LCA approach as the one developed in RIBuild.

6.3 Life Cycle Cost assessment

Life Cycle Cost assessment (LCC) is a useful decision support method to investigate benefits and risks of the investments in the building renovation sector. LCC can be practically used to select the most profitable design option, providing estimates of total expected costs and savings (due to lower energy consumption), during an established time period and adjusted for the time value of money.

Concerning LCC of internal insulation solutions, it is important to consider the initial investment costs (to install the insulation system) and the future costs over a certain time period, i.e. the costs related to the possible maintenance and replacement needs and the costs related to the building (reduced) heating energy consumptions due to the renovation measure (Figure 6.5).

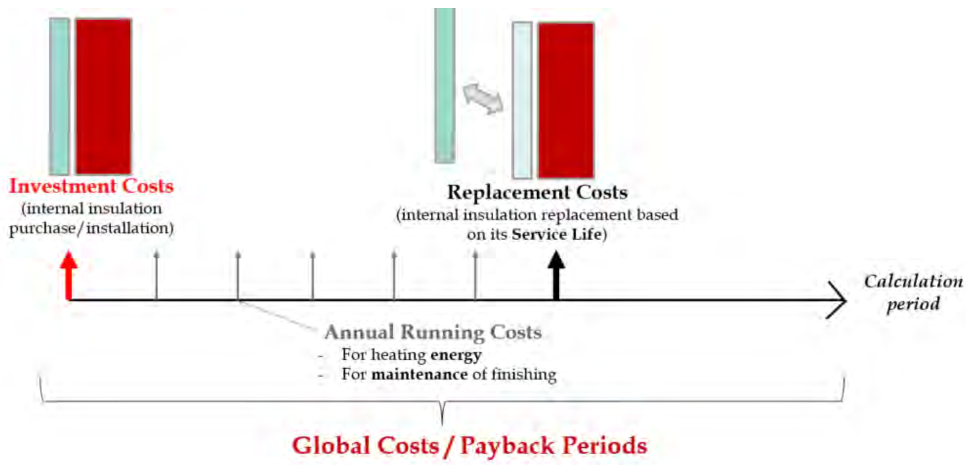


Figure 6–3: Schematic illustration of the cost categories included in the LCC assessment of an internal insulation solution.

In practice, the initial investment cost represents the cost for the purchase and construction/installation of the insulation system. It depends on the cost of each material and on the installation procedure and time. When installing internal insulation there might be additional investment costs depending on the intervention complexity that should be considered (*Figure 6–4*), such as: removing everything fixed to the walls to be insulated, cleaning and preparing the wall surface, eventually reinstalling the previously removed items (see Section 5.1). Furthermore, in certain

[6] Not clarified when finalising this deliverable

Countries and for certain building typologies with high architectural and cultural value, additional costs could be due to the administrative process to get the intervention permissions.

When the internal insulation is applied to a wall, during the building life cycle, possible maintenance or replacement operations could occur for preserving and restoring the desired quality of the building element (e.g. in case of mould growth on the new internal surface).

The energy cost is the cost related to heating/cooling the building. It is obtained by multiplying the energy consumption with the tariff for the energy carrier considered.

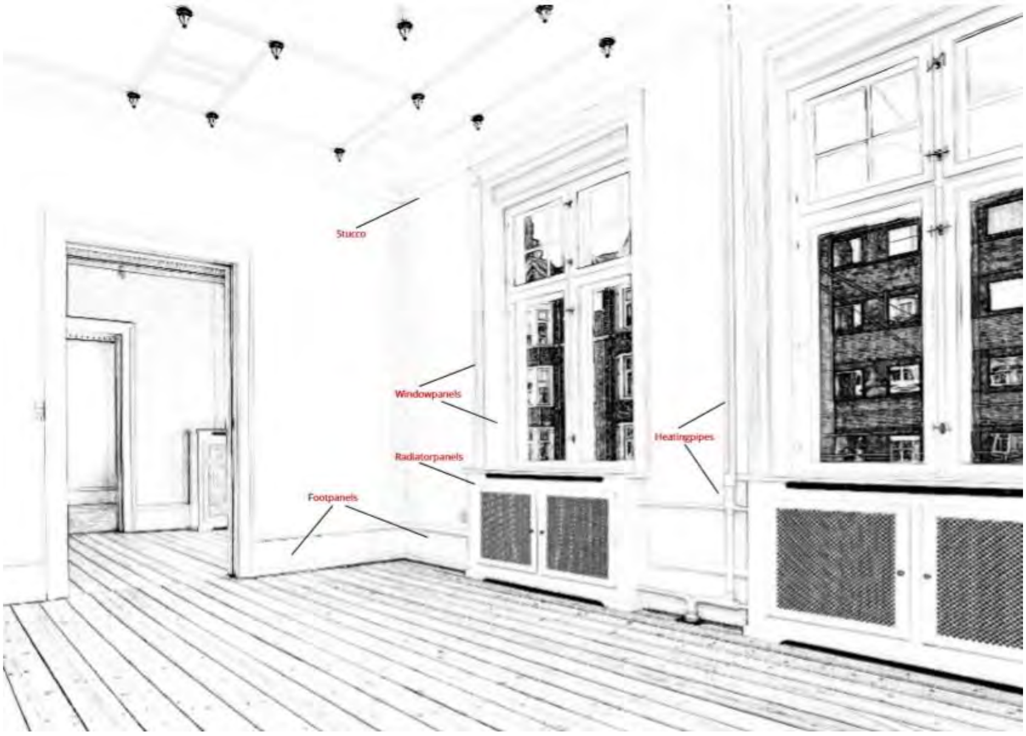


Figure 6–4: Example of a situation where the installation of internal insulation entails a certain complexity.

The importance of using LCC in the building sector has been attested at regulatory level in Europe by Directive 2010/31/EU (European Parliament, 2010), which establishes that Member States shall calculate "cost-optimal levels" of their building energy performance requirements using a comparative methodology framework (EU No244/2012, 2012), (European Parliament, 2012). "Cost-optimal level" means the building energy performance level which leads to the lowest cost during the estimated economic lifecycle, where the lowest cost is determined by taking into account energy-related investment costs, maintenance and operating costs including energy costs and savings.

The main reference standard in the field is EN 15459-1:2017 "Energy performance of buildings – Economic evaluation procedure for energy systems in buildings. Part 1: Calculation procedures, Module M1-14" (EN 15459-1, 2017). It provides a calculation method for the economic assessment of the building components and equipment named "Global Cost", used for aggregation of the past, present and future costs over a calculation period. Indeed, as costs are accumulated during a time period, the assessor needs to keep in mind that the monetary flows can occur at quite different times, and costs that occur at different times are not directly comparable.

In the long run there is a general increase in the overall prices of goods, which at the same time may affect the purchasing power of currency—known as “inflation”. A solution facilitating the comparison among future and present costs in LCC is “discounting”, which assigns a lower “weight” to costs in the future than present costs. The discount rate allows to figure the performance of the money placed on the market during time. It depends on inflation and interest rates and may be different for different types of costs, due to different price development rates for energy, human operation, components, etc.

The outputs of the LCC method included in the standard EN 15459-1:2017 are: global cost and payback period.

The global cost is determined by summing up the costs of all categories and subtracting the cost of the final (residual) value.

The payback period illustrates the potential of different options compared to a reference situation, by the time when the initial investment is expected to be recovered. For internal insulation, the reference could be the actual state (uninsulated wall). Since an investment with future expenditure is considered, a “discounted” payback period is used to reflect the time value of money.

The Global Cost (GC_{cp}) of an internal insulation solution at the end of the calculation period (cp) referred to the starting year can be calculated based on Eq (6.1):

$$GC_{cp} = CI_j + \sum_{t=1}^{CP} \left[\left(CM_{j,t} * R_t^{disc} * R_t^L \right) + \left(CE_{j,t} * R_t^{disc} * R_t^E \right) \right] + CR_{j,t_j} - Val_{j,cp} \qquad (6.1)$$

where:
t is the number of the year;
j is the insulation system;
cp is the calculation period;
CI_j is the initial investment cost of the insulation system j;
$CM_{j,t}$ is the annual maintenance cost of the insulation system j;
$CE_{j,t}$ is the annual energy cost due to the insulation system j ;
R_t^{disc} is the discount rate;
R_t^L is the price development rate for human operation (labour cost);
R_t^E is the price development rate for energy;
CR_{j,t_j} is the replacement cost at year t;
$Val_{j,cp}$ is the residual value of the insulation system at the end of the calculation period.

The frequency of the replacement cost CR_{j,t_j} depends on the service life of the insulation system concerned. The residual value of the insulation system $Val_{j,cp}$ corresponds to the value of the system at the end of the calculation period. It is calculated based on a straight-line depreciation of the initial investment or replacement cost of the component until the end of the calculation, discounted at the beginning of the evaluation period.

The discount rate R_t^{disc} is used to convert a cash flow occurring at a given point in time (year t) to its equivalent value at the starting point (EN 15459-1, 2017). It depends on the real interest rate, d_t, according to Eq (6.2):

$$R_T^{disc} = \prod_{t=1}^{T} \frac{1}{1+d_t} = \frac{1}{1+d_1} \frac{1}{1+d_2} \cdots \frac{1}{1+d_T} \qquad (6.2)$$

The real interest rate, d_t, is a function of the inflation rate, π_t, and the nominal interest rate, i_t^N, according to Eq (6.3)

$$d_t = \frac{i_t^N - \pi_t}{1+\pi_t} \qquad (6.3)$$

Furthermore, the GC calculation includes the possibility to consider the development over time of prices for energy and labour that can be different from the inflation rate. Accordingly, R_T^L and R_T^E are the price development rates that can be applied to all cost components of the LCC equation (i.e. energy costs, periodic or replacement costs, maintenance costs).

The payback period can then be calculated as the number of years (S) required to the cumulative energy savings (Eq (6.4)) to equalize the initial investment costs and the operating costs (maintenance and replacement costs) (Eq (6.5)). The present value of operating-related savings and all other costs are considered, according to the following equations:

$$Savings = \sum_{t=1}^{S} \{ [(Qh^{pre} - Qh^{post})] EnT \} R_t^{disc} \, R_t^E \qquad (6.4)$$

$$Costs = CI_j + \sum_{t=1}^{S} \left[\left(CM_{j,t} + CR_{j,t_j} \right) R_t^{disc} \, R_t^L \right] \qquad (6.5)$$

where:

Qh^{pre} is the pre-renovation energy need; Qh^{post} is the post-renovation energy need; EnT is the energy tariff. Cost categories and economic parameters are calculated in the same way as in the Global Costs calculation.

A considerable amount of research refers to standardized LCC methods (EN 15459-1, 2017) to assess the economic impacts of energy efficiency measures for building design and renovation. In compliance with European and national legislations across Europe, LCC of building design options is usually performed based to these methods, with notable simplifications related to the cost items selection and quantification and to the forecast of macro-economic variables.

Unfortunately, LCC procedures applied to energy renovation measures on historic buildings most often suffer from several intrinsic uncertainties especially related to the long-term perspective of the building intervention. Taking into account uncertainty and variability in LCC is an important challenge to improve the reliability of LCC based decision making. RIBuild Work-Package 5 addressed this issue and proposed a “probabilistic” approach and a software tool for LCC of internal insulation. Further information can be found in (RIBuild Deliverable D5.2, 2018) and (Baldoni, Coderoni, D’Orazio, Giuseppe, & Esposti, 2019).

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Appendix I: Data on building stock for Germany and Sweden

In WP1, data characterising the building stock in the RIBuild countries were collected and reported in (RIBuild Deliverable D1.1, 2015). However, only a few data if any, for the German and Swedish building stock were identified at that stage. Afterwards such data were collected, listed in this appendix and to some extent referred in Section 2.

Data from Germany

1) Total building stock
   - number of residential buildings: 18.7 Mio (Bigalke et al., 2016)
   - living area of: 3.67 Bill m^2
   - number of living units: 41.4 Mio
   - number of non-residential buildings: 2.7 Mio
   - area non-residential buildings (heated): 1.35 Bill m^2

2) Historic building stock (number and area, built prior 1948) (Bigalke et al., 2016)
   - residential buildings 4.84 Mio, 344.7 Mio m^2
   - non-residential buildings 502.6 Mio m^2

3) Total final energy consumption in total building stock (BMWi., 2014)
   - residential buildings (170 kWh/m^{2}a for 3.65 Bill m^2) → 620 TWh
   - non-residential buildings: 356 TWh

4) Total final energy consumption of historic building stock (buildings prior 1979)
   - residential buildings (70% of final energy consumption of all residential buildings: 0.7 x 620 TWh) → 434 TWh
   - non-residential buildings: no data found (estimation: 1.35 Bill m^2 x 0.25 x 150 kWh/m^2) → 51 TWh

Data from Sweden

1) Number of buildings and heated area:
   - All buildings: Around 2.2 ·106 buildings. Heated area: 673 ·106 m2 (Swedish Energy Agency, 2017:6).
   - Residential: Around 2.2 ·106 residential buildings (1 984 000 single and two-family buildings (ES 2017:6), 165 000 multi-family buildings (Boverket, 2010) (total 498 ·106 m2 heated area)
   - Non-residential: 47 000 (Boverket 2010) (heated area 176 ·106 m2) (Swedish Energy Agency, 2017:6)

2) Historic (built before 1945)
   - Approximately 600 000 buildings; estimated to around 27% of total building stock (Eriksson P. , 2015).

3) Total final energy consumption in total building stock: for heating and hot water 80.5 TWh (Swedish Energy Agency, 2017:6).
    - Residential: for heating and hot water 58.8 TWh (Swedish Energy Agency, 2017:6)
    - Non-residential sectors: for heating and hot water 21.7 TWh (Swedish Energy Agency, 2017:6)

4) Total final energy consumption in historic building stock: not available
    - Residential: for heating and hot water approximately 13.5 TWh (approximated based on numbers from (Swedish Energy Agency, 2017:6) and (Eriksson R. , 2017)
    - Non-residential: not available