Project no.:	**637268**
Project full title:	**Robust Internal Thermal Insulation of Historic Buildings**
Project Acronym:	**RIBuild**
Deliverable no.:	**D1.2**
Title of the deliverable:	**State of the art on historic building insulation materials and retrofit strategies**

Contractual Date of Delivery to the CEC:	**M12**
Actual Date of Delivery to the CEC:	**M15**
Lead contractor for this deliverable:	**RTU**
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Work package contributing to the deliverable:	**WP1**
Nature:	**R**
Version:	**1.0**
Total number of pages:	**87**
Start date of project:	**01.01.2015**
Duration of project:	**31.12.2019**

Abstract:

This report provides an analysis and evaluation of a state-of-the-art of internal insulation materials and methods for application in historic buildings, and review on methods, tools and guidelines used as decision making tools for implementation of internal insulation in historic buildings. Historic buildings in RIBuild represent all types of protected[1] and non-protected buildings built before 1945. The survey is limited to buildings with heavy walls (stone, brick, timber framing), thus excluding wooden buildings.

Keyword list: Internal insulation, historic buildings, hygrothermal process, energy efficiency, material properties.

[1] A protected building represented a potential high architectural degree of relevance and cultural heritage. The definition can be given at the national or local levels.

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Executive Summary

This report provides an analysis and evaluation of a state-of-the-art of internal insulation materials and methods for application in historic buildings, and review on methods, tools and guidelines used as the decision making tools for implementation of internal insulation in historic buildings. Historic buildings in RIBuild represent all types of protected[2] and non-protected buildings built before 1945. The survey is limited to buildings with heavy walls (stone, brick, timber framing), thus excluding wooden buildings.

Methods of analysis include survey of scientific literature, data bases and other sources of literature about insulation materials applicable for internal insulation as well as methods, tools and guidelines used for assessment of internal insulation application in historic buildings.[3]

The literature review on insulation materials and their application for internal insulation show that:

- The research studies carried out can be broadly classified as based on:
    - the insulation material itself,
    - simulating properties of insulation materials,
    - laboratory tests on insulation materials,
    - case studies on the insulation materials suited for selected objects,
    - in-situ measurements on the properties of internal insulation materials.
- The main focus of reviewed papers and studies is on thermal properties of walls after insulation material is applied and on hygrothermal performance of the internally insulated wall. Limited number of papers is available on heat transfer and moisture transport in-situ measurements in historic buildings which have internal wall insulation.
- Research papers available on application of internal insulation in historic buildings with massive walls are limited.
- Wide range of insulation materials is available on the market for application as internal insulation in historic buildings either as single materials or pre-fabricated insulation systems.
- Selection of insulation material is sensitive to the specific case study and there is not a common solution for all possible cases and tailor made solution has to be found based on number of parameters influences the final outcome and durability of the facades and walls.
- Moreover there is still lack of knowledge on the performance of building elements under various conditions after internal insulation is applied. Especially better understanding of hygrothermal behaviour mechanisms is needed, which will allow to better simulate real life behaviour of the interaction between insulation materials, surrounding environment and the composition and condition of the existing external wall.

Results of literature review on methods, tools and guidelines used as decision making tools for implementation of internal insulation in historic buildings show that:

[2] A protected building represented a potential high architectural degree of relevance and cultural heritage. The definition can be given at the national or local levels.

[3] Relevant articles were searched in the scientific databases of Scopus and Web of Sciences where peer reviewed scientific papers are published. In the search procedure the key words used were: historical building, internal insulation, historical building materials, energy efficiency in historical buildings.

- The type and number of alternative energy efficiency measures determines decision problems and the tools to solve these problems.
- Large number of parameters and variables, the non-linear relations between variables, conflicting criteria and second-order effects makes global optimization of a building as a whole a very complex problem. Hence in most cases improvement of building performance is focused on specific actions and groups of actions and not on a global approach.
- When discrete decision approaches are used, the process and decisions taken mainly depends on experience and knowledge of building/energy expert and/or decision maker. It implies that decisions are based on predefined solutions and alternatives and not all feasible alternatives and criteria are taken into account.
- A number of challenges to implement energy modelling tools exist, e.g. unstructured nature of current design process, research on designers' decision making process in a highly changing design practice has to be carried out, better communication between actors has to be fostered as well as trust in modelling results and the role of uncertainties have to be taken into account.
- Despite the use of sophisticated hygrothermal simulation tools their applicability in retrofit decisions is limited by various factors, including uncertainty or simple lack of knowledge about boundary conditions (climate and exposure) and material properties. There are uncertainties coupled to the models for calculating impact indicators. These tools require experienced professional and, moreover the obtained results are sensitive to the assumption made by the program and modeller, therefore the results should be interpreted by the person with the specific background knowledge. A major question is which damage models or performance thresholds should be used to guide the interpretation of the model results.
- Life Cycle Assessment does not have ability to be used as decision making optimization tool as it is mainly used as an instrument to quantify inflows and outflows and environmental impacts. If optimisation of different criteria is used in RIBuild WP6, it should be discussed how Life Cycle Assessment can be adopted for optimisation tool.
- Uncertainties regarding results from the Life Cycle Assessment method require more development on environmental impact from buildings, particularly concerning adaptation to the various regional conditions.

As the result findings from this report will be used for project's activities within WP2, WP4, WP5 and WP6. Based on literature review list of recommendations have been prepared for RIBuild WP2, WP5 and WP6.

1 Introduction

Historic buildings are a tribute to Europe’s rich cultural heritage. Historic building energy efficiency potential is dependent on a delicate balance between energy efficiency measures and the necessity to preserve the cultural heritage inherited in the building throughout different centuries that the building has lived through.

Throughout Europe there are a large number of masonry buildings with poor energy performance in need of upgrading and in certain cases also retrofitting. One retrofit option when considering energy performance upgrading is to use internal insulation as part of an interior retrofit. This will increase the wall insulation and could also improve the air tightness levels. This is often considered for historic buildings where the aesthetic of the external façade is of great value and sometimes external modifications are prohibited. Apart from energy savings, such measures usually improve the thermal comfort for the users; raising the surface temperatures of the internal walls and reduces draughts. However, there are several possible issues relating to durability of the existing walls and materials and also questions regarding indoor air quality that need to be addressed. External insulation retrofits, however, are more favourable from a hygrothermal point-of-view, raising the temperature of the existing wall structure and increasing the drying potential under certain conditions. Unfortunately external retrofit measures will have impact on the aesthetical appearance of the buildings and is sometimes not a viable option, in particular for historic buildings.

The general objective of RIBuild is to develop effective, comprehensive decision guidelines to improve the energy performance of historic buildings by investigating internal insulation measures. The conservation of historic buildings’ cultural values and the improvement of their energy performance can be first seen as rather contradictory. Indeed, a thermal insulation cannot always be applied on the external walls e.g., due to the preservation of the façade. In that case, internal insulation measures should be investigated and currently represent the most difficult retrofit measure in historic buildings.

The main objective of Task 1.3. of WP1 is to provide a state-of-the-art on insulation materials and insulation methods for historic building retrofit projects with emphasis on internal insulation materials. The study is based on extensive review of available literature sources and recently published scientific papers and has to serve as basis for other WPs of RIBuild.

Task 1.4 of WP1 aims at review of existing guidelines and decision making tools related to internal insulation of historic buildings.

At the beginning of the project, it was defined that “historic buildings” in RIBuild represent all types of protected[4] and non-protected buildings built in Europe before 1945. In this report, the “historic building” term will thus refer to this definition.

Literature review has been carried out based on a literature study.[5]

[4] A protected building represented a potential high architectural degree of relevance and cultural heritage. The definition can be given at the national or local levels.

The report consists of two main section covering literature review on insulation materials and systems for internal insulation of historic buildings (Section 2) and existing main strategies and methodologies used for retrofit of buildings, with focus on internal insulation of historic building walls (Section 3).

Section 2 starts with an overview of the main aspects of application of internal insulation in historic buildings (Section 2.1). These include the hygrothermal behaviour (Section 2.1.1), material properties (Section 2.1.2), construction elements' properties (Section 2.1.3), outdoor climate (Section 2.1.4), indoor climate (Section 2.1.5), thermal bridges (Section 2.1.6), other aspects (Section 2.1.7) and damage risks (Section 2.1.8). An overview of insulation systems available for internal insulation and details about different insulation materials that can be applied internally are given in Section 2.2 and 2.3. The findings from the literature survey on insulation materials and insulation system are concluded in Section 2.4, followed a list of references (Section 2.6).

Section 3 starts with an overview of decision making tools and methods applied in energy efficiency retrofit projects in buildings (Section 3.1). Section 3.2 illustrates how these tools have been used for assessment of internal insulation applications in historic buildings. Section 3 ends with conclusions and recommendations (Section 3.3) and a reference list (Section 3.4).

[5] Relevant articles were searched in the scientific databases of Scopus and Web of Sciences where peer reviewed scientific papers are published. In the search procedure the key words used were: historical building, internal insulation, historical building materials, energy efficiency in historical buildings.

2 Insulation materials and systems available for internal insulation of historic buildings

The building planning process spans a multitude of functionalities and properties of the construction. An application of internal insulation affects the existing structure and functionality of the building. Nevertheless these impacts are studied rarely.

An analysis of all relevant insulation layer properties is therefore essential and characteristic values should be identified to enable a comparison of different insulation materials. Internal insulation will likely influence the following functionalities of the building:

- Hygrothermal performance
- Energy performance and thermal comfort
- Sound protection
- Fire protection
- Robustness of the construction (susceptibility)
- Economic efficiency

When investigating the potential for existing buildings to be retrofitted using internal insulation it is important to consider several parameters that could influence functionalities of the building. These include hygrothermal behaviour (Section 2.1.1), material properties (Section 2.1.2), construction elements' properties (Section 2.1.3), outdoor climate (Section 2.1.4), indoor climate (Section 2.1.5), thermal bridges (Section 2.1.6), other aspects (Section 2.1.7) and damage risks (Section 2.1.8).

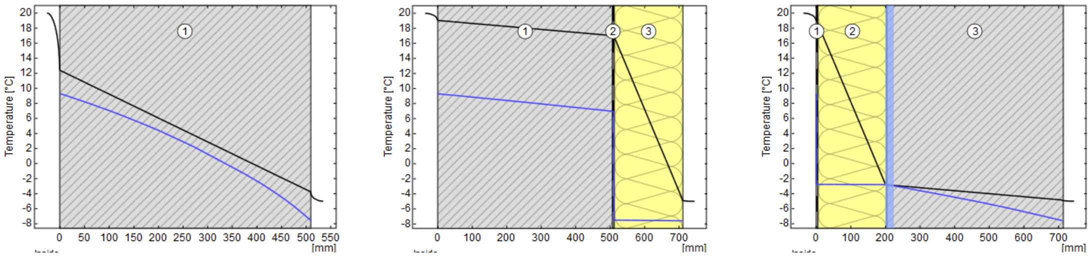
2.1 Main aspects of internal insulation

2.1.1 Impact on hygrothermal performance of walls

A changed hygrothermal performance traces back to the reduced temperature level in the existing construction. Resulting consequences can be high surface relative humidity or condensation, interstitial condensation or high material moisture contents with several linked risks, e.g. frost damage (Hens, 1998).

In a building physics context, external insulation of external walls is preferred to internal insulation, as external insulation prevents the walls to be subjected to temperature levels below freezing point and outdoor exposure in general. Further it reduces the negative influences caused by thermal bridges. By choosing internal insulation the existing external wall becomes colder and as a result it gets subjected to a number of potential hazards which may initiate the deterioration of valuable construction elements. These effects makes it relevant to consider assessing suitable methods for treatment of external walls to hinder potential damage caused by outdoor exposure, i.e. wind driven rain.

One of the potential causes for damage is interstitial condensation which occurs due to the fact that moisture interferes with applied material of internal insulation and cold surfaces and therefore condensates inside the structure of wall (see Figure 2.1). The diffusion of the vapour or moist air is slowed down or blocked by the applied internal insulation material thus creating the boundary of temperature difference where vapour condensates (Hens, 1998). In special cases summer condensation can also take place. This phenomenon occurs after heavy rain; the façade is drying due to solar irradiation and the vapour flow inwards and condensates on the surface of insulation material (Wilson, 1965 in Carmeliet et al., 2003). The presence of condensate increases the risk of mould growth, reduces service life of thermal insulation material and can give damage to the structural components of the building, such as wooden beam ends or wooden studs (Vereecken, 2013).



a) b) c)

Figure 2.1. Temperature profile in brick wall a) without insulation, b) with external insulation and c) internal insulation. Indoor climate is adjacent to left side, outdoor climate to the right side, black curves illustrate the dew point temperature profile (equivalent to saturation pressure), blue curves illustrate the temperature profile (equivalent to partial pressure), blue area indicates condensation risk (diagrams generated with https://www.u-wert.net/)

Another potential risk factor is the reduced drying potential of the building elements, in detail given in the studies by Kunzel (1998), Buxbaum and Pankratz (2008), Vereecken, (2013), Murgul and Pukhkal (2015). The drying potential can be reduced for the moisture coming from the outside environment and/or for the moisture trapped inside the building's elements. The study by Haupl et al. (2005) on renovated historical building showed that the increased moisture in the wall was caused mainly by the driving rain but not condensation. Another aspect – trapped moisture – was studied by Borsch-Laaks and Walther (2009), where authors found that the reduced drying potential was found after the application of internal insulation.

Built-in moisture during installation and high internal moisture loads in cold climate have shown to be a source for high relative humidity level and it can cause interstitial condensation when adding internal insulation of polyurethane (PUR) board (0.05 m), polisocyanurate (PIR) board (0.03 m), aerated concrete (0.06 m) and calcium silicate (0.05 m). Therefore the retrofitting period should be careful chosen to avoid the risks of moisture capture in the structure of building. The behaviour of four materials used as internal insulation in-situ for historic building in Estonia was studied by Klošeiko et al. (2015). The original external wall is made of bricks (0.73-0.75 m) composed of three brick layers, two air cavities and one layer with peat insulation. Temperature sensors and relative humidity sensors were placed between insulation material and brick masonry. Heat flow sensors were located on the surface of wall. Internal and external surface temperatures were measured. Internal temperature was kept at +21°C and high internal load (the moisture excess of +2.3 to +4.4 g/m^3). The fastest drying out time was obtained for calcium silicate material, followed by aerated concrete, however the same materials showed rapid increase of the moisture level behind the insulation materials in case the moisture content in the room was increased. In the case of PIR the moisture content between the insulation and the wall did not increase as fast, nevertheless relative humidity exceeded the critical limit for mould growth. For all tested material relative humidity between the insulation and brick wall was suitable for mould growth, in the case of aerated concrete even condensation occurred. Obtained results show that the built-in moisture during installation is a source for high relative humidity level and it can cause interstitial condensation.

After the system of internal insulation is installed, this system should be as much airtight as possible (without open joint), otherwise the risk of interstitial condensation will be even higher (Hens, 1998). Methods and models are described in detail in Section 3.

2.1.2 Properties of materials

Historic brick and stone facades and masonry walls have been exposed to moisture loads from both external and internal sources for many years and are, depending on maintenance, in varying shape and condition. It is always important to investigate the actual state of the facades and material properties before considering any modification to the walls and in particular when applying internal insulation. Bricks, stones, mortar and render are the materials that create the whole unit and are commonly used in heavy walls.

Material properties such as density, thermal conductivity, and pore structure can vary more or less because of the spread of use geographically. Each porous building material has its own response to water vapour. As porous materials are non-homogeneous and anisotropic, saturation vapour pressure and temperature have to be determined by means of sorption isotherm. Scientists have studied and grouped many materials by means of representative sorption isotherms. Porous materials are described by size and shapes of pores that are forming the structure of building material. Porosity characterises the total volume of open pores while the pore size distribution illustrates material in more details by dividing pore volume into fractions of pores. The latter determines the equilibrium moisture content of a material as well as how the pores are interlinked. The tortuosity – geometrical complexity of the pore structure – influences the moisture transport properties. Moisture is well exchanged and stored in pores if they are open and connected to each other. Water storage functions are based on different mechanisms and are illustrated by moisture content curve. This curve is divided into three regions: the hygroscopic region, the super-hygroscopic region and supersaturated region (see Figure 2.2). In the hygroscopic region the moisture content curve is identical to the sorption isotherm. In the super-hygroscopic region the water content is determined by capillary suction of liquid water. In the supersaturated region can be brought into pores that are still empty by external pressure. When all pores are filled with water, vacuum saturation is reached. Moisture is transported in porous materials either by diffusion, capillary flow, hydraulic flow and surface diffusion. Diffusion takes place in the hygroscopic region by means of a vapour pressure difference and is influenced by water content of the material. Capillary flow takes place in the super-hygroscopic region and the main driving force is internal pressure gradient in the capillary pores. In the supersaturated region moisture transport is driven by external pressure and can be described by Darcy's law.

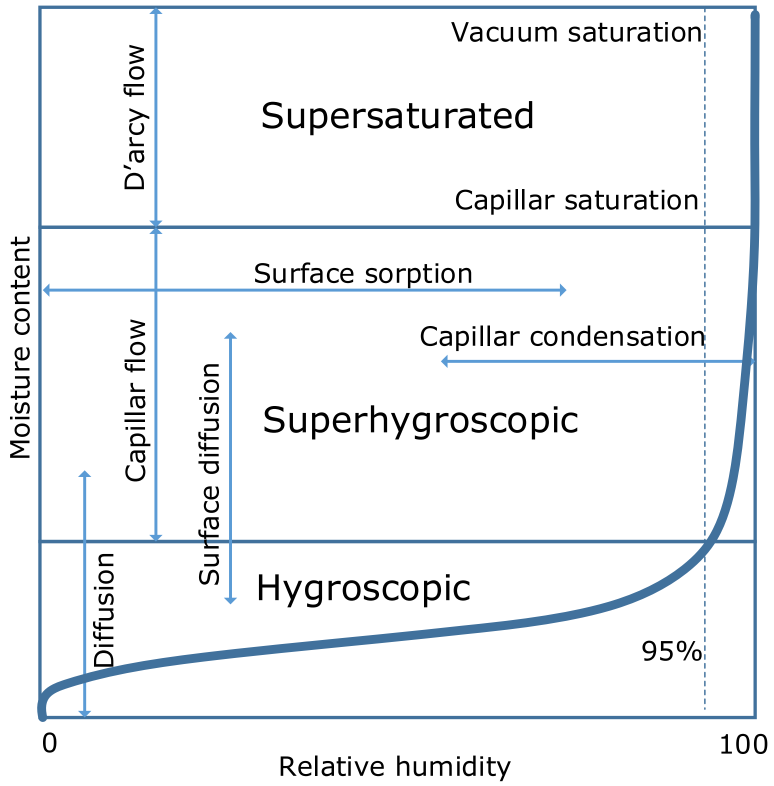


Figure 2.2. Water content curve for porous materials

Installation of internal insulation is expected to improve the energy performance. The improved energy performance/reduced heat loss is mainly influenced by the thermal resistance of the insulation layer and thus characterized by the thermal conductivity and thickness of the product. Nevertheless the differences between measured and expected heat loss reduction might occur due to increased moisture content of the insulation material (Haupl et al., 2005), leakages in the insulation resp. sealing layer (Hens, 1998), disregarded thermal bridges (Smout, 2012) etc. In general, internal insulation will decrease the thermal inertia of the room, since the external walls after the application of internal insulation will no longer function as heat storage (Hens, 1998; Al-Sanea and Zedan, 2001). Depending on the location (e.g. hot regions with required high thermal storage capacity) and the usage (e.g. temporary used rooms with required short heating-up periods and thus desired low thermal storage) this effect can be wanted or unwanted. Nevertheless, these factors are strongly depending on the building's characteristics and could therefore hardly be described with material properties solely. The study by Hens (1998), showed that in the case of poor installation unwanted air circulation between the insulation material and building's structure can result in the actual U-values (for one-dimensional wall) even 2.5 times higher than the projected. These all mentioned risks together can hardly be characterized by specific values.

Some building material properties have a direct mutual impact. For example variation of porosity in the brick generates different insulating capabilities; a more porous brick is more insulating. This is due to the air having a low value of thermal conductivity, hence increasing the insulating capabilities but it also requires the air to remain stationary. The content of moisture in bricks can through micro-cracks become higher after an intense day of driven rain, thus decreasing the insulating capabilities since water has a higher value of thermal conductivity than stationary air (Kunzel, 1998). Bricks can in a worst case scenario suffer from frost weathering, which is caused by stresses in the brick when water freezes to ice and expands in volume during intense freeze-thaw periods (Maurenbrecher et al., 1998). To counteract this problem hydrophobic treatment can be applied on the outer surface to prevent rain from transporting inwards. This treatment also requires that no cracks are present in the masonry wall; since it can give the unwanted effect where high moisture loads accumulate locally and will take long time to dry out (Buxbaum and Pankratz, 2008 in Vereecken, 2013), (Møller, 2004).

The physical parameters (density, porosity, size pore distribution, turtuosity) and moisture parameters (moisture content) as well as moisture transportation properties of bricks are important, e.g. Larsen (1995) carried out drying experiments of three types of historic bricks and has found that moisture physical characteristics (pore structure, water vapour resistance, sorption) of historic bricks are different hence modern industrially produced bricks cannot be used to simulate historic brickwork. Similar interdependencies exist for other building materials used in historic buildings such as sand stone, clinker bricks, dolomites etc.

Besides the development of models, even more research is carried out on laboratory measurement of various internal insulation materials. Pavlik and Cemy (2008) showed that using the same internal insulation materials for two different wall types, the obtained results can differ. Hydrophilic mineral wool and vapour retarder on brick wall and on argillite stone wall was used in laboratory conditions. Applied vapour retarder performed well on the brick wall, but failed on the argillite wall because over-hygroscopic moisture was present on the argillite wall during the study (expressed by relative humidity and volume water content).

In-situ research was carried out by Walker and Pavía (2015). The authors analysed thermal performance of seven insulation materials on a historic brick wall (0.77 m) and compared them to traditional lime plaster finish (0.007m). These materials are thermal paint (0.012 m), aerogel (0.0195m), cork lime (0.04m), hemp lime (0.04 m), calcium silicate board (0.06 m), timber fibre board (0.04 m) and PIR board (0.0375 m). Indoor temperature was kept at +18°C. In-situ measurements show that U-value of insulated walls was reduced after insulation was applied in all cases, except the case of thermal paint, which did not have any effect on the thermal performance of the wall. On average the performance of insulation materials is overestimated by producers by 13 to 25%, except the case of cork-lime insulation. Authors conclude that aerogel and PIR showed the best thermal performance in this case study.

2.1.3 Properties of construction elements

Structural strength in masonry walls depends on many factors: brick formats, porosity in bricks, thickness of gap where mortar is applied, structural strength of the mortar and the ratio between the height and thickness of the wall. Except homogenous masonry walls there are cavity walls were an external façade made of bricks is being attached with anchors to the carcass. These anchors have a minor effect on the total structural strength of the masonry wall. Reinforcing bars are also used in masonry walls for different purposes. Both anchors and reinforcing bars made their debut in the 1940's and unfortunately it was commonly not made of stainless steel. It usually ended with extensive corrosion, where the anchors and bars expanded and therefore initiated cracks in the mortar and bricks (Zagorskas et al., 2014; Ionescu et al., 2015). or even resulted in walls that tilted (Hansen and Egholm, 2005).

Solid masonry walls, for instance, could have a satisfactory performance considering both external and internal moisture sources but any alteration of the wall could change this (Borsh-Laaks and Walther, 2008). Vereecken and Roels (2014) in hot box – cold box laboratory measurements tested 11 different configurations of internal insulation materials for single leaf massive masonry walls (0.29 m): mineral wool, cellular concrete, cellular glass, calcium silicate, wood fibre, cellulose combined with smart vapour retarder and glue mortar. X-ray projection method was used to investigate the moisture distribution. Temperature and relative humidity sensors were placed between material layers. Experiments were performed for severe and rather unrealistic boundary conditions (relative humidity in hot box 85% and cold box 45%; temperature in cold box 2 °C and in hot box 35 °C). The results showed that the glue mortar accumulated large amount of the moisture, thus leading to overall worse performance of capillary active insulation. A numerical simulation on the hygrothermal performance of tested systems at less severe steady-state winter condition and it showed similar behaviour. Based on the results vapour tight systems should be preferred, but it should be kept in mind, that this research only studied insulation materials under steady-state conditions. Therefore more research is needed to generalize findings.

Mortar and render used in historic heavy walls consists of a binder, sand and water. Different types of binders and a variation of particle size in sand can be used to give both the mortar and render its unique properties. Depending on the ratio between the binder and sand in the mixture various values in structural strength and tightness are achieved. That is, if sand with bigger particle sizes are added the overall structural strength will increase and if the content of binder increases the tightness of the mixture will improve. Portland cement is well known for its high structural strength and fast set time. This in turn means it is a brittle material and prone to initiate a formation of cracks. Lime is another common binder and gives unlike the Portland cement a low structural strength when mixed into a mortar. A positive factor about lime mortar is its permeability which allows moisture to dry out more effectively. Another positive factor is that it is less brittle and enables the brickwork to “react” on climatic conditions with introducing crack at once (Zagorskas et al., 2014; Ionescu et al., 2015). Driving rain can be absorbed by the external cladding and in addition flaws in the façade and the connections and fixings around for instance windows can lead to transportation and accumulation of moisture in the walls (Haupl et al., 2005). Depending on the performed maintenance over the years, this can be of small or significant importance. Also, the drying potential of the walls may previously have been high due to a low level of insulation and large heat flows throughout the walls. Similar interdependencies can be found in other systems used for external walls in historic buildings (clinker brick, lime sand stone etc.) (for more information see RIBuild deliverable D1.1).

2.1.4 Climate conditions

Depending on location and climate, orientation and even micro-climate, the facades are exposed to varying hygrothermal loads including large temperature differences, solar radiation, wind and driving rain.

Aspects of weather that causes degradation of building components:

- wind effects on buildings: interior-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.

2.1.5 Indoor climate

There are several factors to consider when investigating the sources of internal heat and moisture in existing buildings. Apart from heat and moisture generated by the current use of the buildings, there can also be substantial built-in moisture in the walls that need to be addressed before applying any modification to the existing constructions (Borsch-Laaks and Walther, 2008 in Vereecken, (2013)).

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 can vary. Usually more moisture is generated in the mornings and late afternoons due to cooking, cleaning, showering etc. In office and commercial buildings heat loads are concentrated during office hours and also often coincide with solar gains. Similarly, for commercial buildings, moisture production is high during daytime but often the ventilation rate compensates for this and the excess moisture is removed.

However, in naturally ventilated buildings, often the case for historic buildings, the ventilation rates are governed by season and outdoor conditions and hence the ventilation can be low during parts of the year and moisture loads can be higher. A high internal moisture load will lead to diffusion throughout the walls if vapour open materials are used.

Besides the internal heat and moisture factors, the thermal capacity of buildings elements itself are reduced after the internal insulation is applied (Hens, 1998). This occurs due to the fact that external walls no more 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. overheating risks in summer (Al-Sanea and Zedan, 2001).

2.1.6 Thermal bridges

In all possible methods for the thermal retrofit of exterior facades – external insulation, cavity insulation, internal insulation – thermal bridging is a focal issue. In either of these approaches the continuity of the introduced insulation may be compromised, at protrusions from the surface to be insulated, or at connections with other building components (Hens, 1998; Theodosiou and Papadopoulos, 2008; Ge et al., 2013; Sallée et al., 2014). For an internally insulated massive facade, common walls, partition walls or internal floors exemplify the first category (Figure 2.3a) while connections between walls and windows, roofs or foundations typify the last category (Figure 2.3b).

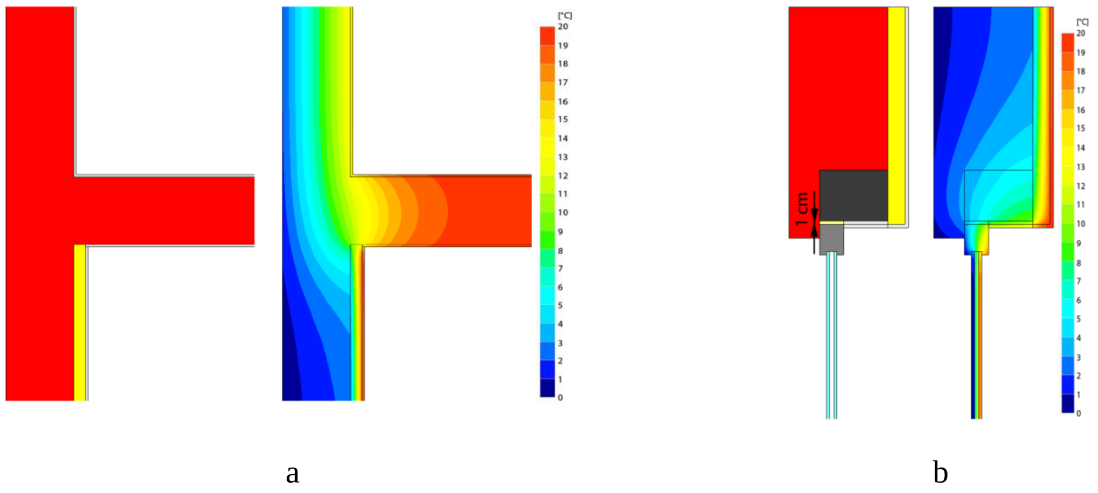


Figure 2.3. Geometric configuration and simulated isotherms for massive facade connected with a) common wall b) window lintel, without thermal bridge insulation (Smout, 2012). The massive facade is 29 cm wide.

Thermal bridges typically result in amplified heat transfers and reduced surface temperatures (Ge et al., 2013; Finch et al., 2014; Sallée et al., 2014) (Figure 2.3). The latter may give excessive relative humidity at the surface promoting mould growth and condensation; the former may undermine the intended upgrade of the insulating quality of the facade. Special care should be taken in the case of wooden beam ends, since they might be exposed to combined hydrothermal risk (Vereecken, 2013).

Both impacts are typically undesirable, and correct solutions for thermal bridges are required (Figure 2.4). These solutions generically intend to uphold the continuity of the introduced insulation (Figure 2.4.b) or to extend the conduction path resistance through the thermal bridge (Figure 2.4.a).

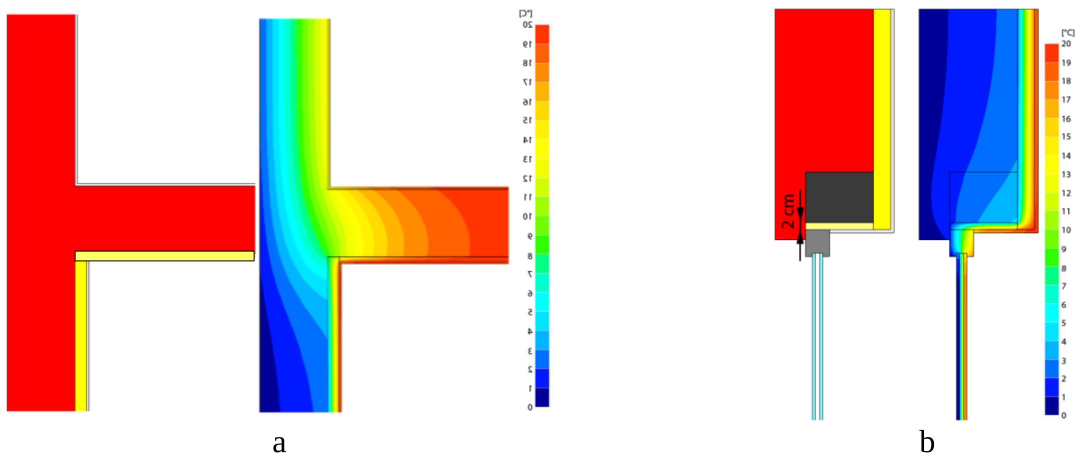


Figure 2.4. Geometric configuration and simulated isotherms for massive facade connected with a) common wall b) window lintel, with 2 cm thermal bridge insulation (Smout, 2012). The massive facade is 29 cm wide.

Thermal bridges typically result in amplified heat transfers and reduced surface temperatures. In the literature, the first aspect receives much attention, while less is available for the second.

2.1.6.1 Amplified heat transfer

Many studies have presented many results for different cases (Janssens et al., 2007; Theodosiou and Papadopoulous, 2008; Cappelletti et al., 2010; Gronau, 2010; Evola et al., 2011; Smout, 2012; Capozzoli et al., 2013; Berggren and Wall, 2011; Ge et al., 2013; Finch et al., 2014). It is however not possible to join these disperse outcomes into generic results for the relative impact of thermal bridges on the overall heating or cooling demands of dwellings. Everything depends on the geometrical convention – internal or external dimensions (Berggren and Wall, 2011) –, the dwelling typology – more or less compact buildings (Janssens et al., 2007) –, the insulation thickness and position, the quality of the thermal bridge solutions, etc. They all however infer that:

- unresolved thermal bridges may very strongly contribute to the heating demand of insulated buildings, while slightly smaller impacts are observed for the cooling demand;
- resolved thermal bridges moderate these impacts significantly, but even then thermal bridges may still add notably to the heating demand of insulated buildings. The impact on the cooling demand, on the other hand, is in this case fairly small;

These findings are confirmed in a survey study performed within the ASIEPI project – Assessment and Improvement of the EPBD Impact for new buildings and building renovation -, where the results of numerous other case studies are collected and compared (Erhorn-Kluttig and Erhorn, 2009). It should lastly be noted however that an economical cost-benefit analysis may not always decide in favour of resolving thermal bridges, particularly for more ’mild’ climates (Evola et al., 2011).

Some fragmented literature information allows discussing the required size of thermal bridge insulation. Sallée et al. (2014) investigation results show that the efficiency of the thermal bridge insulation wanes quickly once over 60 cm long. Besides that a decrease in width can be compensated by an increase in thickness, but also that length should be prioritised over thickness (at least up to lengths of 50 cm). Finally, with each doubling of the thermal bridge insulation thickness, the linear thermal transmittance coefficient drops some 15 %. Studies by Smout (2012) and Hermes and Künzel (2015) on the thermal bridge insulation in wall-window connections yield a larger relative drop: doubling – from 2 cm to 4 cm – the thermal bridge insulation thickness in wall-window connections reduces the linear thermal transmittance coefficient with roughly 30 %.

The general tendency is that more effective is internal insulation (thicker material or lower thermal conductivity of the material), the more dominant becomes the heat losses from the thermal bridges in overall heat loss balance (Vereecken, 2013).

2.1.6.2 Reduced surface temperatures

Much less information is available with regard to the reduced surface temperatures provoked by thermal bridges (Mumovic et al., 2006; Gronau, 2010; Ge et al., 2013; Finch et al., 2014; Sallée et al., 2014). These results can neither be synthesised into generic values. They all do though confirm that:

- unresolved thermal bridges may lead to excessively low local surface temperatures, thus invoking a risk on mould growth or surface condensation;
- resolved thermal bridges moderate this impact significantly, and generally sufficiently high surface temperatures are obtained;

The required size of thermal bridge insulation with respect to surface temperature is not analysed in literature.

Implementing thermal bridge insulation is thus necessary to remediate the potential negative influence. From all analysed examples, it can be deduced though that limited quantities of the thermal bridge insulation suffice to that aim.

To prevent the mould formation, the various design rules and simulation tools can be used. Some of them are: temperature ratio, biohygrothermal models, isopleth systems, mould prediction models etc. (Anon, 1991; Hens 1998, Vereecken, 2013). However each of these tools have some assumption and simplifications integrated within the model, therefore during the assessment of mould formation risk, the influence of these simplification on the real system should be kept in mind and not overestimated. More detailed review on the advantages and drawback of various prediction models can be found in study by Vereecken and Roels, (2012).

2.1.7 Other aspects

Normally, internal insulation will not worsen the sound protection of the building in the audible frequency range. The only risk can be seen in a displacement of resonance frequency into the audible range. This is also not a material property but strongly depending on the constructive system (fixation, distances, existing construction properties etc.) and can’t be characterized by a material property.

Fire protection level of the building could be affected if flammable materials are used. A common classification of building material’s fire protection levels is suggested by EN 13501. Construction materials range from quickly flammable materials (Class F) to inflammable materials (Class A1). There is furthermore a difference in the classification of installed and isolated materials.

There are different risks attributed to the installation of insulation layers. One could be an under/overestimation of the underground (priming coat, non-supporting or sanding base materials etc.) or the existing construction itself (wind driven rain protective coating or properties, moisture content, material compositions, remaining installations in the wall etc.). Other error sources could be an incorrect installation (insufficient drying periods, leaky connections etc.) or damage during the usage (e.g. wall fixations permeating the sealing or/and the insulation layer and causing thermal bridges or convection inlets).

Installation of internal insulation reduces energy consumption of the building. The amount of saved energy depends on thermal properties of selected insulation material or system and the thickness of material. Selection of both thermal properties and thickness of material depends on predicted hygrothermal behaviour. An investment in internal insulation is generally lower compared to external insulation as less material and labour is required.

2.1.8 Damage risks

In the case of seasonal variations in outside air temperature, damage to the external wall can occur. The combination of the exposure of the building to the weather, especially wind driven rain, the condition of the external wall and the outdoor temperature can cause freeze-thaw damage. The damage could be amplified when internal insulation material is used, as the temperature in the wall is reduced, especially at the inner part, closest to the internal insulation, as the insulation reduces the heat loss through the wall, thereby increasing the interstitial condensation potential and reducing the drying potential (Scheffler, 2008). Currently there is a lack of reliable risk assessment methodology for the identification of potential damages caused by the cycle of freeze-thaw in buildings (Vereecken, 2013). Also salt efflorescence (salt deposits after the moisture is evaporated) can occur due to evaporation of the moisture from the building façade, cause damage to the building (Lstiburek, 2007) and increase the damage risk in the case of freeze-thaw cycles (Ueno et al., 2013).

Impact of wind driven rain loads (WDR) on walls in moderately cold and humid climate is much larger near the edges of the walls than at the centre, according to whole building hygrothermal modelling (Abuku et al., 2009). The results also show that WDR can have serious impact on mould growth especially at the edges of the walls and cause a significant increase of indoor relative humidity and energy consumption for heating.

Probability of structural damages for historical buildings with internal insulation was studied by Pasek and Kesl (2015). They have modelled 5 storey building with two thicknesses of external brick walls (0.45m and 0.6 m) insulated internally with foam polystyrene (0.14 m). Internal temperature was assumed to be +20°C and the measured internal and external surface temperatures are used for simulation. They found that for central Europe's climate conditions, the risk of structural damage is especially high for internal insulation of bricks and stone masonry with low strength mortar. Moreover two methodologies were presented to assess the damage risks due to temperature changes after installation of internal insulation.

Kolaitis et al. (2013) compared application strategies for internal and external insulation in buildings built before 1980 in Greece. The original external walls are composed of plaster/brick/air cavity/brick/plaster with total thickness with U-value 1.262 W/(m^2K). Internal insulation of EPS (0.08m) is added. Indoor temperature was fluctuating between 20 and 26°C. The performed simulations showed that in the warm Mediterranean climate negligible condensation potential is obtained in the case of internal insulation strategy.

2.2 Insulation systems available for internal insulation

Products used for internal insulation can be divided into two main categories:

- Insulation system – pre-fabricated product containing layers of materials, e.g. insulation material, vapour barrier, finishing material etc. to be used for insulation of building envelope (Section 2.2)
- Insulation materials – stand-alone materials used for insulation of building envelope (Section 2.3).

Two decisive material properties of internal insulation layers are thermal resistance and vapour diffusion resistance. Neglecting the thickness of a particular chosen insulation layer, thermal conductivity (λ) and vapour diffusion resistance factor (μ) can be identified as very basic hygrothermal properties of insulation materials. A multitude of other material properties and functions is relevant for hygrothermal simulations and partially simulation model depending. Their explanation and identification requires an increased expenditure and will therefore be topic of WP 2.

The overview of applicability of internal insulation materials or systems is presented in Table 2.1.

Table 2.1. Assessment tool for the applicability of internal insulation (Steskens et al. 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)
Moisture load and frost damage	Typology of the existing facade and exposure to rain		
	Solid masonry facade having a width of two stones or thicker, or (≤ 1½ stone) exposed to a relatively small (wind-driven) rain load Solid concrete wall Non-insulated cavity wall Insulated cavity wall Internal wall	1½ stone (exposed to a moderate/high rain load)	≤ 1 stone (exposed to a moderate/high rain load)
	Floor construction		
	Concrete floor or wooden floor, which is not connected to the facade	Undamaged wooden construction which is connected to the facade	Wooden construction, connected to the facade, containing moisture damages
	Technical installations		
	Water pipes or ducts, which are susceptible to frost or frost damage are not present • Technical installations which do not require the penetration of the internal insulation are not present		Water pipes or ducts, which are susceptible to frost are frost damage are present
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 which has not 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)
Indoor climate	Indoor climate		
	Indoor Climate Class 3 according to ISO EN 13788	Indoor Climate Class 4 according to ISO EN 13788	Indoor Climate Class 5 according to ISO EN 13788
	HVAC system		
	Well-controlled and efficient ventilation, climate control and heating system		Insufficient ventilation

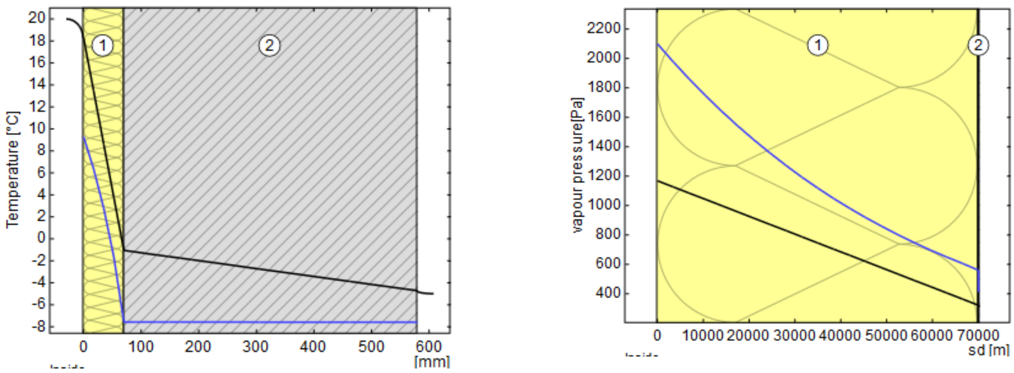
In accordance to the basic properties and following WTA 6-4 and DIN 4108-3, existing product range can be distinguished into three systems:

1. Condensate-preventing insulation systems
2. Condensate-limiting insulation systems
3. Condensate-tolerating insulation systems

Detailed information about insulation materials and material systems products and producers is available in Appendix 1 of this report.

2.2.1 Condensate-preventing insulation systems

Condensate preventing systems disable vapour transfer from the room side into the construction by a vapour barrier. According to WTA 6-4 and DIN 4108-3, vapour barriers are sealing layers with a vapour diffusion equivalent air layer thickness s_d (product of μ and layer thickness) of min. 1500 m. The barrier can be a separate layer at the room side of the construction or alternatively be part of the insulation layer itself. Depending on the system only a minor or none interaction between the construction (maybe inner cladding) and the room climate can be expected. Typical application fields are buildings with high inner moisture loads, i.e. water vapour pressures like indoor swimming pool. Temperature, dew point, vapour saturation pressure and vapour pressure profiles for this system is seen in Figure 2.5.



a) *b)*

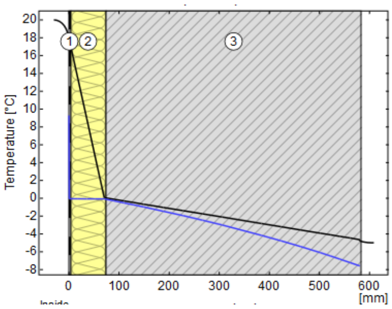
Figure 2.5. a) Temperature profile (black line) and dew point profile (blue line), b) vapour pressure profile (black line) with vapour saturation pressure (blue), for a massive wall (2) with condensate preventing internal insulation system including vapour tight insulation material (1) (diagrams generated with https://www.u-wert.net/)

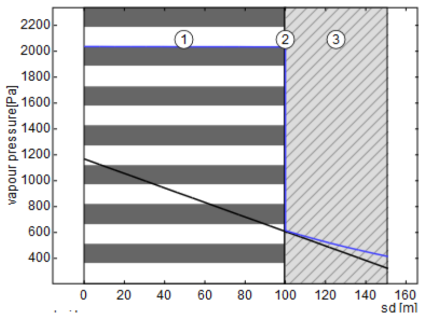
Condensate-preventing system's performance is normally independent on the room climate and prevents moisture accumulation in the construction due to vapour transfer from inside to outside. It is very sensitive to high moisture loads from outside, e.g. wind-driven rain, and other additional loads, e.g. convective moisture input through leakages, because there is no drying potential towards room side. An intact coating for the reduction of the wind-driven rain input and a precise workmanship (esp. sealing around openings and junctions) are therefore essential for the functioning of these constructions (Haupl et al., 2004). Furthermore, standard surface requirements ensuring hygienic minimum standards (no mould growth, no surface condensation) and comfort requirements (no strong radiant asymmetry resp. limited differences between construction surface and indoor operative temperature) are to be ensured.

Examples for condensate-preventing systems are vapour tight insulation materials (e.g. foam glass, extruded polystyrene, polyurethane), and systems including metal sealing foils (e.g. aluminium foils). Vacuum insulation panels (VIP) can be regarded as a special case of vapour tight insulation materials. The work by Baetens et al. (2010) give a review of VIP.

2.2.2 Condensate-limiting insulation systems

Condensate- limiting insulation systems include, according to DIN 4108-3, a vapour brake with an s_d- value of min. 0.5 m and max. 1500 m. Vapour control layer should reduce the vapour input from the room side into the construction and has to be combined with a sufficient wind-driven rain protection. The wide range of vapour resistances implies a great diversity of constructive solutions and potential problems. In any case constructions with potential condensate must fulfil three criteria beside standard surface requirements. These are no long-time accumulation of condensate within the construction, sufficient drying-out of interstitial condensate during the drying period (summer) and uncritical moisture loads of the particular material (e.g. wood). Temperature, dew point, vapour saturation pressure and vapour pressure profiles for this system see Figure 2.6.





a) *b)*

Figure 2.6. a) Temperature profile (black line) and dew point profile (blue line), b) vapour pressure profile (black line) with vapour saturation pressure (blue), for a massive wall (3) with condensate limiting insulation system including vapour open insulation material (2) in combination with a vapour barrier (1) (diagrams generated with https://www.u-wert.net/)

To fulfil the requirements for condensate-limiting insulation system, the physical characteristics of vapour brake and insulation material should be such, that during the heating season vapour resistance should be sufficiently high to avoid interstitial condensation, while during the off-heating season vapour resistance should be sufficiently low to allow drying out of the building structures. Therefore Kunzel (1999) proposed a vapour barrier with variable vapour resistance values depending on the humidity, a so-called smart vapour retarder. A smart vapour barrier having variable values of vapour resistance depending on the humidity, was proposed (Kunzel 1999), (Christensen & Bunch-Nielsen, 2005).

Damage due to planning of these insulation systems might occur if boundary conditions, e.g. influence of precipitation, are underestimated or material properties, e.g. performance moisture-adaptive vapour brakes, are misjudged. The complex and non-linear interaction of materials due to their properties (heat and moisture transfer and storage processes as well as boundary conditions) requires a sound evaluation of these constructions. Use of HAMT simulation tools is recommended.

Moreover the precise installation and exploitation of these systems is crucial, since the research by Slanina and Silorova (2009) performed wet-cup tests of vapour retarders and the results showed that the performance is significantly reduced in the case the vapour barrier has some small, artificially made damages.

Harrestrup et al. (2015), Morelli et al. (2010) and Morelli et al. (2012) report on a historic building built in 1896 and located in Copenhagen, Denmark, where internal insulation solutions was part of in-situ retrofitting measures, including also replacement of windows and ventilation system. One façade of this building was insulated from outside using mineral wool (with thermal conductivity of 0.039 W/(m K)) and remaining facades from inside using an aerogel/mineral wool mix (with thermal conductivity 0.019 W/(mK)) and thermoset modified resin insulation ((with thermal conductivity of 0.02 W/(mK)). The achieved energy saving was 47 % and specific energy consumption reached 82 kWh/(m^2 year). From this energy saving around 40 % was achieved by insulation, around 40 % by replacement of windows and remaining by mechanical ventilation with heat recovery. At some spots the buildings had potential problems because of a high humidity level, especially the façade not receiving sunlight. A solution was presented where the insulation is stopped 200 mm above the floor, showing no risk of moisture problems, but the specific energy consumption increased by 3 kWh/(m^2year).

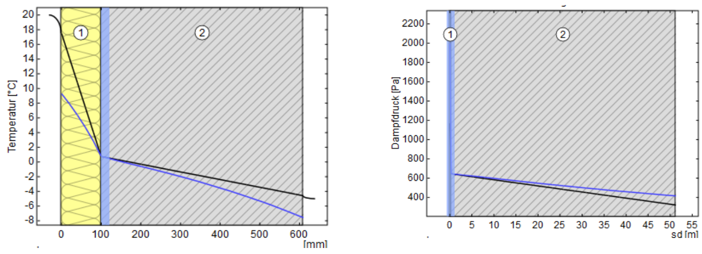
Examples for condensate-limiting insulation systems range from vapour open insulation material with vapour barrier mineral wool based systems (mineral wool with PE-foil or SVR), EPS or PUR based systems, wood or textile fibre based systems, or glass foam granulated systems to insulation systems made of composite boards with vapour controlling sealing.

2.2.3 Condensate-tolerating insulation systems

Condensate-tolerating insulation systems consist of capillary active insulation material and glue mortar. The only vapour resistance in these insulation systems is given by the material itself, therefore they show very small vapour transfer resistances (s_d value < 0.5 m, according to DIN 4108-3).

The main advantage of the application of condensate-tolerating systems is that they are not dependent on the precise workmanship and additional climate or human behaviour factors, e.g. wind-driven rain or temporary raised usage loads. This is because drying-out of these systems is not hindered, neither inwards nor outwards.

Since the diffusion of moisture occurs freely in these systems, the material is porous and acts as a sponge, which means that the insulation material is not moisture-sensitive and is able to absorb and distribute water in its pores. As the material is diffusion open, water vapour penetrates into the wall and condensates in the wall near the surface of original historic wall, e.g. brick or stone. At some point inwards diffusion stops and equilibrium situation due to capillary forces is established. In order for the moisture to diffuse evenly an air gap must be avoided as this will hinder diffusion processes and condensation can occur. As drying periods for these systems are necessary to avoid moisture accumulation and associated risks (e.g. frost damage), they cannot be applied for buildings with permanently high usage or high loads of outdoor moisture, see Figure 2.7.



a) b)

Figure 2.7. a) Temperature profile (black line) and dew point profile (blue line), b) vapour pressure profile (black line) with vapour saturation pressure (blue), for a massive wall (2) with a condensate tolerating insulation system (1) (diagrams generated with https://www.u-wert.net/)

Examples of these systems are absorptive insulation boards with an additional cladding at the indoor side (e.g. vapour-open internal plaster) and absorptive insulation plastering. As capillary active materials in these insulation system wood fibre board, calcium silicate or aerated concrete are often used. Recent products also contain multiple materials in one insulation board. For example, wood fibre with mineral functional layer, PUR with calcium silicate or calcium silicate with PUR, pyrogenic silica or VIP.

An internal insulation system with calcium silicate was first presented in 1995. Further research of such systems focused on obtaining the same hydrothermal properties of glue mortar and insulation material, and at the same time providing the glue mortar with higher thermal conductivity than the insulation material (Scheffler and Grunewald, 2003). Haupl and Fechner (2003) proposed a methodology to describe moisture storage and moisture transport in the insulation material. As case study calcium silicate (capillary active insulation material) was modelled. Calcium silicate was selected as it is used often as internal insulation in historic buildings. Insulation systems containing calcium silicate are not cheap, therefore research on hydrophilic mineral wool is on-going (Pavlik et al., 2005; Pavlik and Cerny, 2008; Pavlik and Cerny, 2010).

Complex retrofitting strategy was analysed by Ascione et al. (2015) for heritage building located in Italy. The authors found that most economically viable energy efficiency measures included replacement of windows, application of internal insulation and insulation roof slab. As the internal insulation material thermal insulating plaster (with thermal conductivity of 0.058 W/(mK) and thickness of 0.05 m) was selected. For the roof insulation expanded polystyrene panels of 100 mm thickness was chosen.

Toman et al. (2009) studied thermal performance of an internally insulated historical brick building located in Prague, Czech Republic which has been used for 4 year after the renovation. The applied strategy for internal insulation was to use two types of hydrophilic mineral wool insulation boards. Each of these boards has different bulk density and was tightly put together. The “hard” board of 0.03 mm was used. This layer was used for moisture transport. The “soft” board of 0.005 m was fixed to the brick wall. The water vapour retarder on lime-cement basis was put on the brick wall. Surface finishing was done using plaster. The water condensation was not observed during the 4 years period.

Standard surface requirements ensuring hygienic minimum standards and comfort requirements have to be provided as for the other systems, too. For absorptive systems, greater differences between estimated and real thermal resistance might be a consequence of higher moisture contents, since the thermal conductivity linearly reduces when the moisture content in the insulation material increases (Haupl et al., 1995). Despite this, absorptive materials show an increased tolerance against critical surface conditions because temporary surface condensate can be distributed and the usually high pH-value (board systems) limits the risk of mould growth strongly.

2.3 Insulation materials

2.3.1 Research fields on insulation materials

Insulation materials that can be used for internal insulation in historic buildings can be classified according to various principles, for example, as coming from natural occurring materials or man-made materials, or as traditional, state-of-art and future thermal insulation materials.

Research on insulation materials is widely covered by material science field. As given in the review by Jelle (2011) most of the research fields today are related to nanotechnology insulation materials and dynamic insulation materials, where cold outdoor air flows through insulation material fibres and collects heat. However, some research directions are dedicated directly to insulation materials for historic buildings, e.g. a new thermal insulating plaster used on a historic building in Turin, Italy (Bianco et al., 2015). Preliminary results show that thermal conductivity of the plaster is 2.5 to 3 times lower than conventional plaster, but more research is needed on the long-term performance of this material. While Sallee et al. (2014) have designed, manufactured and tested two types of new slim thermal breakers made with vacuum insulating panels for internal applications in historic buildings. Both types of thermal breakers give 60 % heat loss reduction

Therefore in the field of the insulation materials, both directions are studied – improvements of current technologies and development of novel technologies.

Regardless of the classification chosen, the key parameter for all types of insulation materials is their thermal conductivity. The aim is to achieve as low thermal conductivity as possible. A low thermal conductivity, expressed as W/(m K), means that relatively thin layer of this material will have high thermal resistance, expressed as m^2K/W, and low thermal transmittance or U-value, expressed as $W/(m^2K)$.

This report reviews natural (organic) as well as inorganic insulation materials such as:

- Cellulose
- Cork
- Mineral wool
- Polyurethane (PUR)
- Polyisocyanurate (PIR)
- Expanded polystyrene (EPS)
- Extruded polystyrene (XPS)
- Aerogel

- Vacuum insulation panels (VIP)
- Thermal insulating plaster (TIP)
- Calcium silicate.

2.3.2 Insulation made of natural materials

2.3.2.1 Cellulose

Cellulose (polysaccharide $(C_6H_{10}O_5)_n$) fibre is the basic raw material for both wood fibre and wood wool insulation. The cellulose fibre comes from paper (fresh or recycled) or wood (Rahul, 2012).

During the production process, the raw materials are shredded to create fibres, see Figure 2.8 for the composition of cellulose under magnification. Binding products and additives[6] are used to form final product. In final product 82 - 85 % by weight is cellulose, the remaining being chemical fire retardant in form of dry powder (Jelle, 2011; Rahul, 2012).

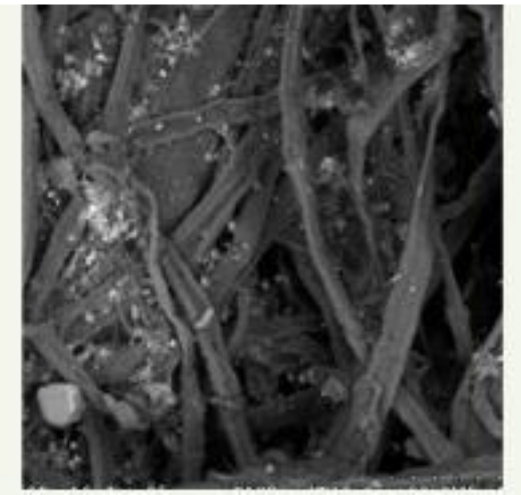


Figure 2.8. Structure of cellulose insulation under magnification x400 (ERC, 2015)

Two final products can be obtained based on the thickness of the fibres – wood fibre or wood wool. For wood fibre the typical ratio between the length and thickness is 20:1, for wood wool even smaller. Typical wood wool products are distributed in as filling materials and mats. The wood wool can be used to fill in cavities and also used in the same manner as mineral wool when coming in mats. Wood fibre insulation is usually coming in boards (Jelle, 2011).

Thermal properties of cellulose insulation are dependent on temperature, moisture content and mass density of the material itself. Typical values for thermal conductivity of cellulose insulation is 0.04 – 0.066 W/(mK). Thermal conductivity of cellulose insulation depends on temperature, moisture content and mass density and increases by 40 % (from 0.04 W/(m K) to 0.066 W/(m K)) in the case the moisture content in the insulation material increases from 0 vol% to 5 vol% (Jelle,

[6] usually boric acid and borax and ammonium sulphate for mould, insect and rodent resistance

2011). For wood wool EN 13168:2012 gives values of 0.09 – 0.15 W/(mK) and for wood fibres EN 13171:2012 gives values of 0.037 – 0.042 W/(m K), in both cases for dry material at 10°C.

2.3.2.2 Cork

Cork insulation is made from the protective layer of the cork oak tree (quercus suber L.) which may be periodically removed from its trunk and branches to provide the raw material for cork products.

During the production process, product is made from ground granulated cork expanded and bonded exclusively with its own natural binder exuded from cork cell walls by heating under pressure (Jelle, 2011); see Figure 2.9 for the structure of cork under magnification.

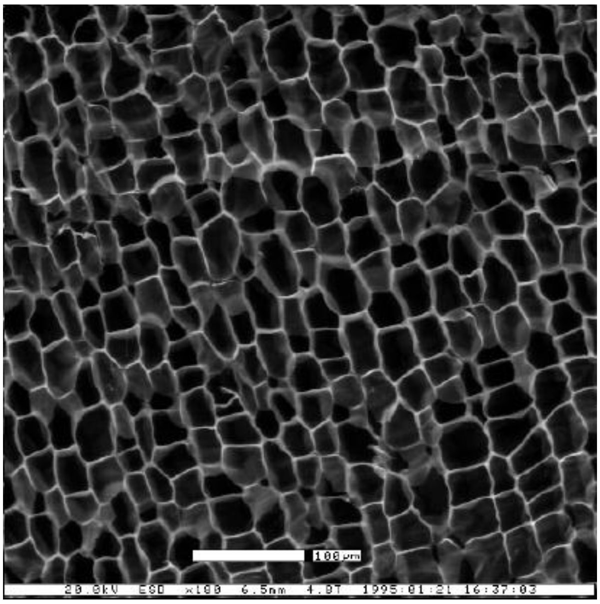


Figure 2.9. Structure of cork insulation under magnification x100 (UCMP, 2015)

Typical final products are distributed in cork boards and granulated cork. The perforation and cutting can be done at the construction site without losing the thermal properties of the material (Jelle, 2011).

The review by Jelle (2011) defines typical values for the thermal conductivity of cork insulation as 0.04 – 0.05 W/(m K), while the reference standard EN 13170:2012 gives values of 0.039 – 0.041 W/(m K) for dry material at 10 °C.

Cork can also be used together with the hydraulic lime or cement mortar, in that case the measured thermal conductivity is in the range of 0.04 – 0.08 W/(m K) (Walker and Pavia, 2015).

2.3.3 Insulation made of man-made materials

2.3.3.1 Mineral wool

The basic raw material for mineral wool is sand and basalt rocks. These resources are abundant and usually locally found. In the case only sand is used, the final product will be glass wool (fibre glass), in the case only slag and basalt are used, final product will be stone wool (rock wool). For glass wool the recycled glass and fluxing agents are usually added (Rahul, 2012). Glass wool and stone wool together are covered under the name mineral wool.

During the production process, the raw materials are melted in a furnace where the temperature reaches 1300-1500 °C. The obtained liquid materials are going to fiberizing process. This process takes place in a device where disks with small holes and centrifugal force or rotating nozzles are used to create fibres, see Figure 2.10 for the composition of mineral wool under magnification. Binding products and additives (usually dust abatement oil and phenolic resin) are used to form the final product (Jelle, 2011; Rahul, 2012).

Figure 2.10. Structure of mineral wool under magnification x200 (TAMU, 2015)

Typical final products are distributed as mats and boards or sometimes as filling material. The mineral wool can be used to fill in frames, cavities, floors and roofs. The perforation and cutting can be done at the construction site without losing the thermal properties of the material (Jelle, 2011).

Thermal properties of mineral wool are dependent on temperature, moisture content and mass density of the material itself. Typical values for the thermal conductivity of mineral wool is 0.03 – 0.04 W/(mK) (Jelle, 2011), while the reference standard EN 13162:2012 gives values of 0.034 – 0.045 W/(m K) for dry material at 10 °C. The thermal conductivity increases 30 % (from 0.037 W/(m K) to 0.055 W/(m K)) in the case the moisture content in the insulation material increases from 0 vol% to 10 vol% (Jelle, 2011).

2.3.3.2 Polyurethane (PUR)

Polyurethane (PUR) insulation materials are made during chemical reaction of isocyanate7 and polyols8. During reaction of these chemical compounds, a material with closed pores is obtained; see

[7] product of ammonia based product treatment with poisonous gas – phosgene

Figure 2.11 for the composition of PUR under magnification. The pores are then filled with various gasses: Hydrofluorocarbons (HFC), carbon dioxide (CO2) or cyclohexane (C6H12) (Jelle, 2011).

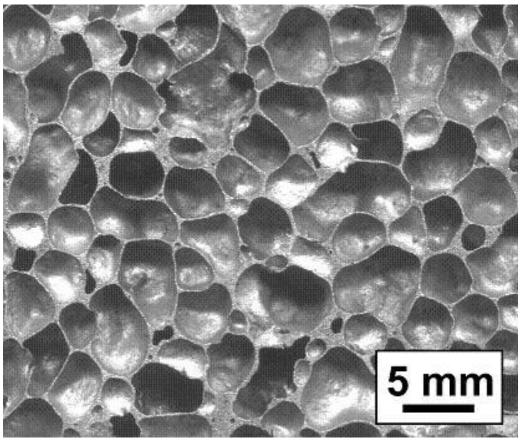


Figure 2.11. Structure of polyurethane (PUR) under magnification (SIP, 2015)

Typical final product is PUR boards or loose-fill to fill in small cavities. Perforation and cutting of PUR boards can be done at the construction site without losing the thermal properties of the material (Jelle, 2011).

Thermal properties are dependent on temperature, moisture and mass density of the material. Typical values for thermal conductivity is 0.02 – 0.03 W/(mK) (Jelle, 2011), while the reference standard EN 13165:2012 is 0.023 – 0.03 W/(mK) for dry material at 10 °C. Thermal conductivity of PUR increases 45 % (from 0.025 W/(mK) to 0.046 W/(mK)) in the case the moisture content in the insulation material increases from 0 vol% to 10 vol% (Jelle, 2011).

Additional point of consideration is the hazardous properties of PUR materials in the case of fire. PUR is certified as safe for its intended use, but the chemically very poisonous initial materials that the product is made of are being released during a fire and badly affect the respiration system (Jelle, 2011).

2.3.3.3 Polyisocyanurate (PIR)

Polyisocyanurate (PIR) is a polymeric insulation material with the same thermal properties as PUR. Nevertheless PIR is chemically differently based on polyisocyanurate groups; see Figure 2.12 for the composition of PUR-PIR insulation under magnification.

The main aim of developing PIR was to reduce hazardous risk of PUR material during fire. PIR insulation boards also emit hazardous flames during the fire, but in smaller quantities than PUR and PIR itself is not on flame but smouldering. The study by Modesti et al. (2002) shows also the development of PUR-PIR insulation material to reduce the hazardous flames during the fire hazards.

[8] chemically synthesized polymer

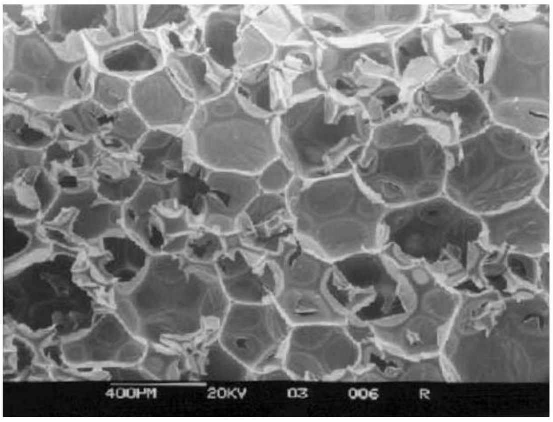


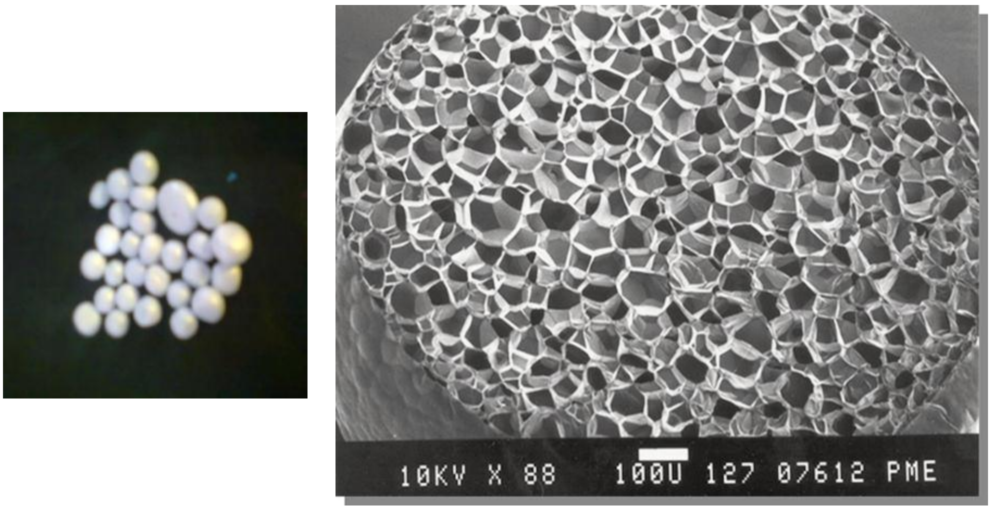
Figure 2.12. Structure of polyurethane (PUR) - polyisocyanurate (PIR) under magnification (Modesti et al., 2002)

Besides the concerns connected with behaviour during fire, the concerns on PIR or PUR-PIR usage in buildings are refers to vapour impermeability of the material and the potential of moisture accumulation in building structures (Walker and Pavia, 2015). This is highly relevant during the exploitation of this material in historical buildings.

2.3.3.4 Expanded polystyrene (EPS)

Expanded polystyrene (EPS) is from the family of polystyrene products, made from cellular plastic (Rahul, 2012), see Figure 2.13a for polystyrene insulation Thermocol before expansion.

The raw material for polystyrene is crude oil. During manufacturing polystyrene balls are expanded, as the expansion agent pentane (C_6H_{12}) is used and water vapour and heat is applied. The obtained spheres are then merged together to form the boards, therefore EPS has partly open structure of pores (Jelle, 2011); see Figure 2.13b for the structure of EPS under magnification.



a) b)

Figure 2.13. a) Structure of polystyrene (PS) before expansion under magnification (Rahul, 2012), b) Structure of expanded polystyrene (EPS) under magnification (CC, 2015)

Typical final product is EPS boards. Since the pores of insulation material are filled with air, this insulation material is used in non-load bearing applications. The perforation and cutting can be done at the construction site without losing the thermal properties of the material (Jelle, 2011).

Usually EPS boards are white, but the more innovative have grey colour because of graphite additives; these additives are applied to improve the insulation performance (Rahul, 2012).

Thermal properties are dependent on temperature, moisture and mass density of the material. Typical values for thermal conductivity is 0.030 – 0.040 W/(mK) (Jelle, 2011), while reference standard EN 13163:2012 is 0.034 – 0.037 W/(m K) for dry material at 10 °C. Thermal conductivity of EPS increases 33 % (from 0.036 W/(m K) to 0.054 W/(m K)) in the case the moisture content in the insulation material increases from 0 vol% to 10 vol% (Jelle, 2011).

2.3.3.5 Extruded polystyrene (XPS)

Extruded polystyrene (XPS) is made from the same material as expanded polystyrene (EPS), therefore the general properties are similar. The difference is in the production process, as XPS is made in a continued production process. The polystyrene balls are melted in the presence of an expansion gas (usually CO_2), then the mass is extruded through a nozzle where the drop of the pressure causes the expansion of material. XPS is cooled down and cut. Opposed to EPS, XPS has a closed pore structure (Jelle, 2011; Rahul, 2012); see Figure 2.14 for the comparison of the XPS and EPS structure under magnification.

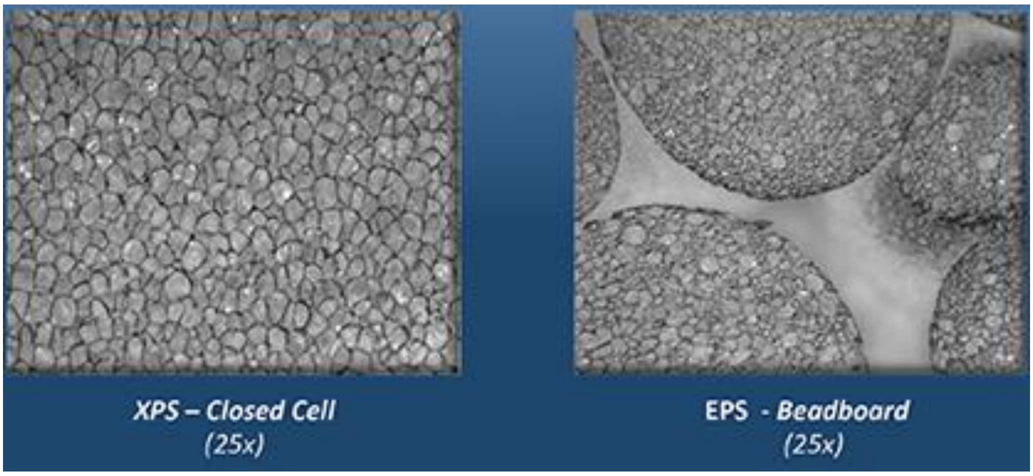


Figure 2.14. Comparison of structure of extruded polystyrene (XPS) and expanded polystyrene (EPS) under magnification x25(CS, 2015)

Typical final product is XPS boards. The perforation and cutting can be done at the construction site without losing the thermal properties of the material (Jelle, 2011).

Usually the XPS boards are in white colour, but the more innovative have grey colour because of the graphite additives; these additives are applied to improve insulation performance (Rahul, 2012).

Thermal properties are dependent on the temperature, moisture and mass density of the material. Typical values for thermal conductivity is 0.03 – 0.04 W/(m K) (Jelle, 2011), while the reference standard EN 13164:2012 is 0.033 – 0.035 W/(m K) for dry material at 10 °C. Thermal conductivity of EPS increases 23 % (from 0.034 W/(m K) to 0.044 W/(m K)) in the case the moisture content in the insulation material increases from 0 vol% to 10 vol% (Jelle, 2011).

2.3.3.6 Aerogels

Aerogels are current state-of-art insulation materials made from silica based gel, where the gas replaces liquid components. Aerogels are formed by crosslinking polymerization reaction and a careful drying phase. The polymerization process forms a solid network surrounded by a liquid (sol–gel). The drying procedure removes the liquid and leaves behind a delicate structure with nanoscale-sized pores (Walker and Pavia, 2015). See Figure 2.15 for the structure of aerogel under magnification.

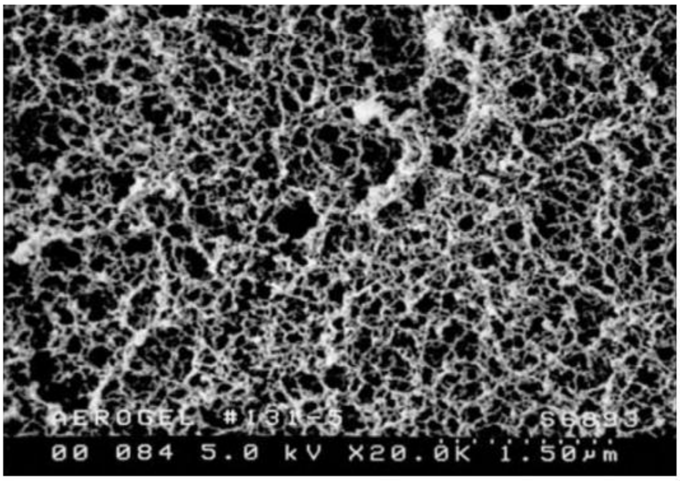


Figure 2.15. Structure of aerogels under magnification x20 (Jones, 2006)

Aerogels are typically used for insulation material by bonding it with plasterboards. Nevertheless data of aerogels on real on-site performance are rare in the literature (Walker and Pavia, 2015).

The review by Jelle (2011) gives values for thermal conductivity as low as 0.004 W/(m K) at pressure of 50 mbar, nevertheless commercially available specimens show typical values for thermal conductivity in the range of 0.013 – 0.014 W/(m K) at atmospheric pressure (Baetens et al., 2011).

Aerogel is very expensive compared to other insulation materials. Moreover the material has high compression strength and is very fragile. On-going research is to incorporate carbon fibre matrix into the aerogel in order to make the material more susceptible to deformations (Ren and Cheng, 2013).

Aerogel render (0.06 m) with thermal conductivity of 0.025 ± 0.002 W/(mK) at 23 °C and 50% relative humidity was used as internal insulation in laboratory set up to simulate hydrothermal behaviour of massive wall (0.26 m) during wetting (Guizzardi et al., 2015). The wall was set up to simulate the Swiss residential houses built in 1850-1920. The obtained results showed that the water diffusion in the wall has not linear nature and that on average it takes 21-30 days for water front to cross exterior brick. A detailed model of the moisture transport in the massive wall was obtained, to be used for further simulation.

2.3.3.7 Vacuum insulating panels (VIP)

Vacuum insulating panels (VIP) are also considered current state-of-art insulation materials VIP is a nearly gas-tight enclosure surrounding a rigid core, from which the air has been evacuated. Fumed silica is used as the core material and several metallized polymer laminate layers are used as the envelope (Jelle, 2011); see Figure 2.16 for the structure of VIP.

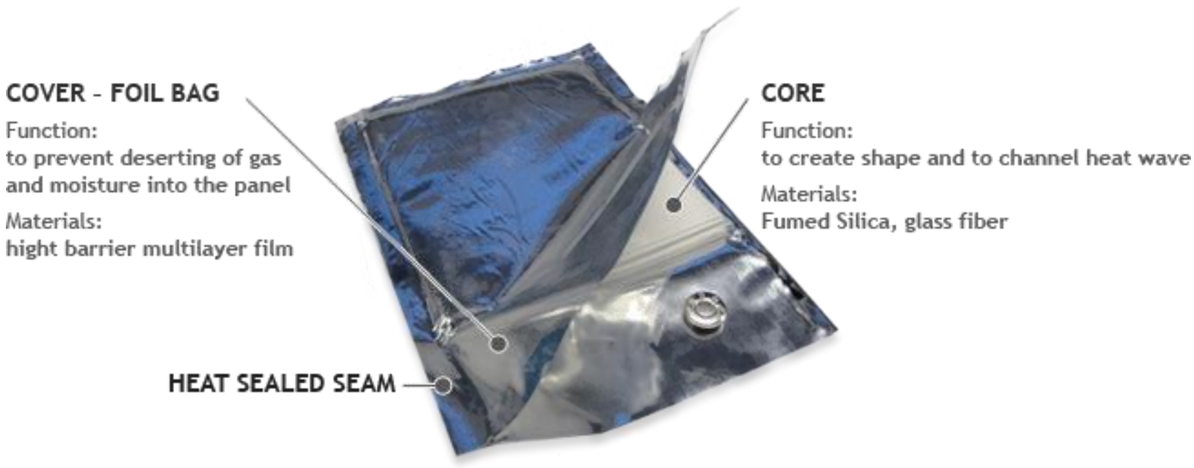


Figure 2.16. Structure of VIP (TURVAC, 2015)

VIP is produced as panels and they cannot be adjusted at the construction site as the vacuum between the components in the panel then will be lost.

The review by Jelle (2011) gives values for thermal conductivity as low as 0.003 – 0.004 W/(m K) in just-from-manufactured condition and up to 0.008 W/(m K) after 25 years of exploitation. The reduction of thermal properties with the time is typical for VIP, as moisture and air slowly replaces the vacuum inside the VIP. Based on the type of foil used, thermal conductivity after 100 years can be in the range of 0.006 – 0.016 W/(m K). The decrease in thermal properties is the main disadvantage of all VIP. In the case VIP is damaged by some sharp objects the thermal conductivity can reach up to 0.020 W/(m K) (Kalnaes and Jelle, 2014).

The main advantage of VIP is 5 - 10 times lower thermal conductivity compared with traditional insulation materials, with means that the same energy efficiency class can be achieved using much thinner layer of insulation material. This has great advantages in the case of internal insulation in historic buildings where loss of living area is reduced. Therefore even taking into account the relatively high cost of VIP, in the case of high value real estate, application of VIP is economic profitable (Jelle, 2011).

Johansson et al. (2014) found that adding VIP to internal surface of historic brick walls lead to higher relative humidity in wooden beam ends and drying capacity on the side of VIP is substantially reduced. Relative humidity in the wall increases substantially when exposed to wind driven rain. Laboratory experiments show that brick and mortar were more capillary active compared to modelling results.

2.3.3.8 Thermal insulating plaster (TIP)

Thermal insulating plaster is a plaster with incorporated particles of heat insulation. TIP has 10 times lower thermal conductivity (around 0.07 W/(m K)) compared with traditionally used plaster. Therefore TIP can serve not only as finishing layer or protection layer, but also as heat insulation material. Two types of TIP can be distinguished: plaster with natural binders (lime) and plasters with cement of artificial binders. TIP is made by incorporating light weight aggregates: clay, cork, expanded polystyrene, expanded glass, etc. It can improve both thermal and acoustic properties of the building. TIP is pre-mixed and ready to use on-site, see Figure 2.17 (Bianco et al., 2015).

Figure 2.17. Application of TIP (Bianco et al., 2015)

Thermal insulating plasters have specific compositions and additives that provide insulating properties. In accordance with EN 998-1, there are two categories of thermal insulating mortars, T1 (≤ 0.1 W/(m K)) and T2 (≤ 0.2 W/(m K)), related to their thermal conductivity.

Through the thermal plaster it is possible to follow the irregularities of the internal walls, and keep typical bends between walls and ceiling, while other internal insulation systems, with their effect of "regular inner box”, are not authorized in listed buildings by the authorities on cultural heritage.

Moreover TIP has a high water vapour diffusion coefficient therefore can be used for walls that are affected by capillary rising damp (Bianco et al., 2015).

2.3.3.9 Calcium silicate

Calcium silicate is an insulation material comprised of hydrated calcium silicate, normally reinforced by incorporating fibres; see Figure 2.18 for the structure of calcium silicate.

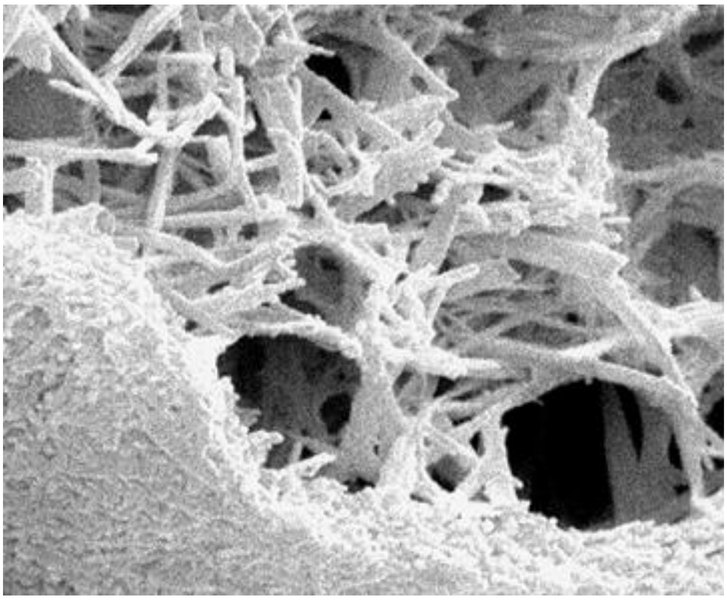


Figure 2.18. Structure of calcium silicate (PRTC, 2015)

Typical final product is calcium silicate boards. The perforation and cutting can be done at the construction site without losing the thermal properties of the material.

Calcium silicate is widely used insulation material for historic buildings, since it has capillary active structure, therefore wicks away the possibility of moisture accumulation in building's structures (Walker and Pavia, 2015).

As other advantages high pressure resistance, non-combustibility and frost-resistance can be mentioned. Moreover the high bulk density of the material leads to sound-absorbing properties (Xella, 2015).

Thermal conductivity of calcium silicate is about twice as high as conventional insulation materials. The Reference standard EN 14306:2009 gives typical values for calcium silicate thermal conductivity as 0.063 W/(m K) at 10 °C.

2.3.4 Comparison of insulation materials

Common advantages and disadvantages of the insulation materials presented in Section 2.3.3 are given in Table 2.2. The table contains general information and in some specific cases the advantages and disadvantages can be spread differently than shown in the table.

Table 2.2. Advantages and disadvantages of insulation materials used for internal insulation

	Parameter	Mineral wool (MW)	Insulation made from natural fibres	Polyurethane (PUR)	Polyisocyanurate (PIR)	Expanded polystyrene (EPS)	Extruded polystyrene (XPS)	Aerogel blanket/mat	Vacuum insulation panels (VIP)	Thermal insulating plaster	Calcium silicate
Advantages	Cheap compared to other materials in Table 2.1	x				x	x				
	Easy to customize on the construction site	x		x	x	x	x				
	Low thermal conductivity compared to other materials in Table 2.1			x	x			x	x		
	Low density compared to other materials in Table 2.1			x	x	x	x				
	Wide range of insulation thicknesses is available	x	x	x	x	x	x				
	Fire resistant	x						x	x	x	x
	Improved sound blocking	x	x	x	x	x	x	x	x		
	Can be applied on uneven surfaces of historic walls									x	
	Suitable for places where the insulation thickness is limited							x	x		
Disadvantages	Expensive compared to other materials in Table 2.1							x	x		
	Requires flat surface to apply material	x	x	x	x	x	x	x	x		x
	Cannot be customized at construction work site								x		
	High thermal conductivity compared to other materials in Table 2.1	x	x							x	x
	High density compared to other materials in Table 2.1									x	x
	Small range of insulation thicknesses is available							x	x		
	Contains fibres that can be potentially harmful when inhaled	x	x					x			
	Protective gear must be worn when installing the insulation							x			
	Suffers from loss of heat conductivity during the lifespan			x	x				x		
	Can change the dimensions due to shrinkage over time			x	x	x	x				

Next the data for important thermal and physical parameters are presented based on specifications provided by the European Standards and other sources provided in Sections 2.3.2 and 2.3.3. The comparison of insulation materials based on their thermal conductivity is given in Figure 2.19. In the terms of historical buildings, lower thermal conductivity value means, thinner layer of material will be needed to ensure same energy efficiency level.

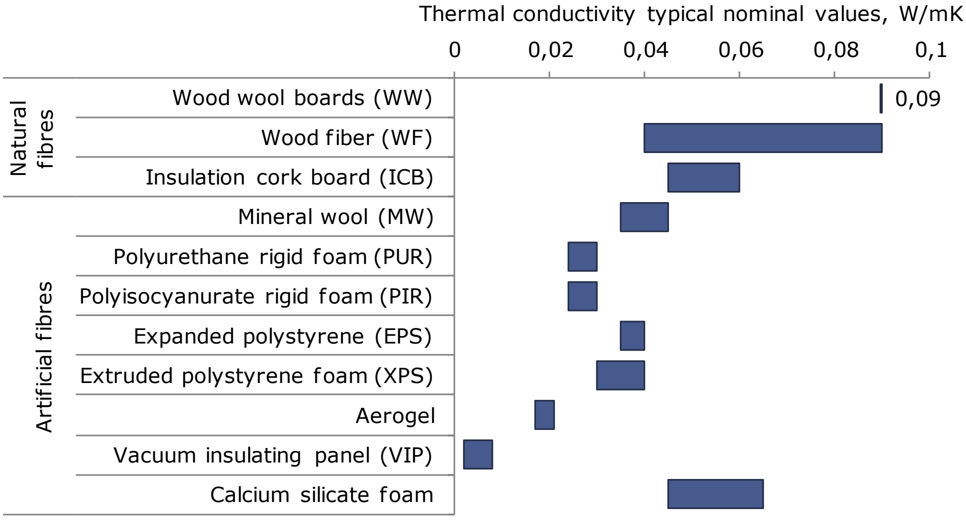


Figure 2.19. Comparison of insulation materials based on their thermal conductivity

Based on the vapour diffusion value various types of insulation system can be selected, such as condensate limiting, condensate tolerating or condensate preventing systems. The comparison of insulation materials based on their vapour diffusion resistance is given in Figure 2.20.

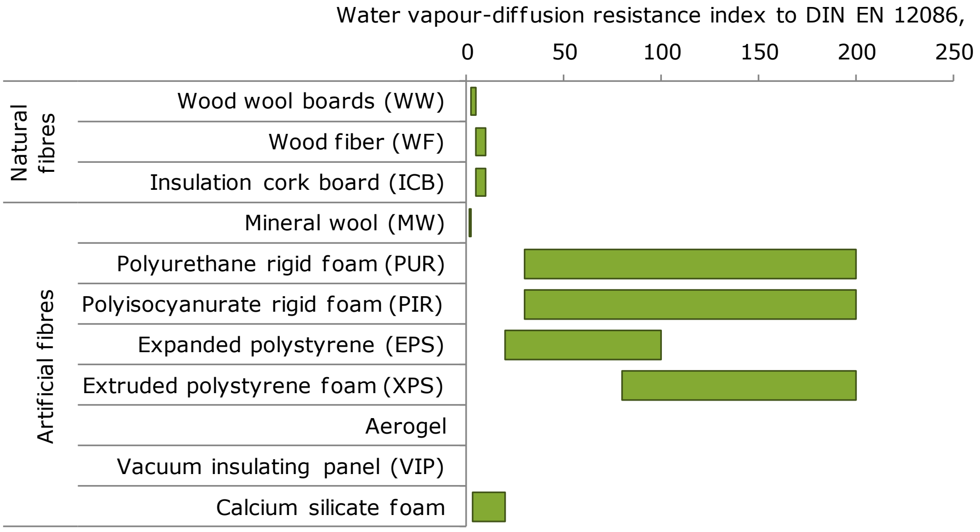


Figure 2.20. Comparison of insulation materials based on their vapour diffusion resistance

Based on the specific heat capacity the thermal storage volume of the building can be defined. The comparison of insulation materials based on their specific heat capacity is given in Figure 2.21.

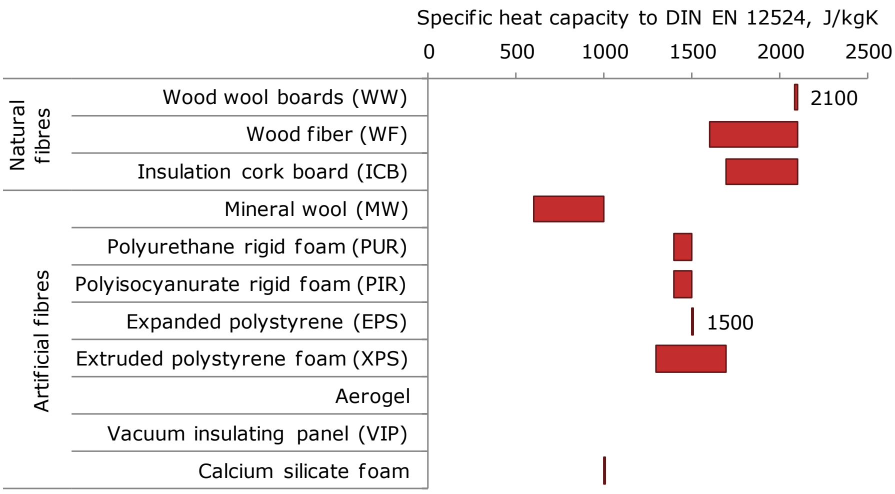


Figure 2.21. Comparison of insulation materials based on their specific heat capacity

The comparison of insulation materials based on their bulk density is given in Figure 2.22. Higher bulk density values insure sound absorbing properties, but at the same time increases the weight of construction.

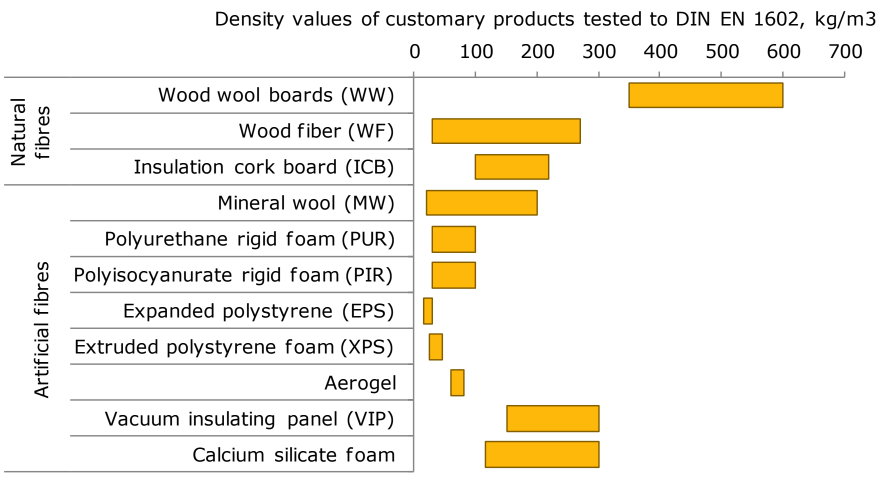


Figure 2.22. Comparison of insulation materials based on their bulk density

A class of fire protection means nearly non-combustible materials, where F class describes the flammable materials with hazardous gas flumes during the combustion. The comparison of insulation materials based on their fire protection class is given in Figure 2.23.

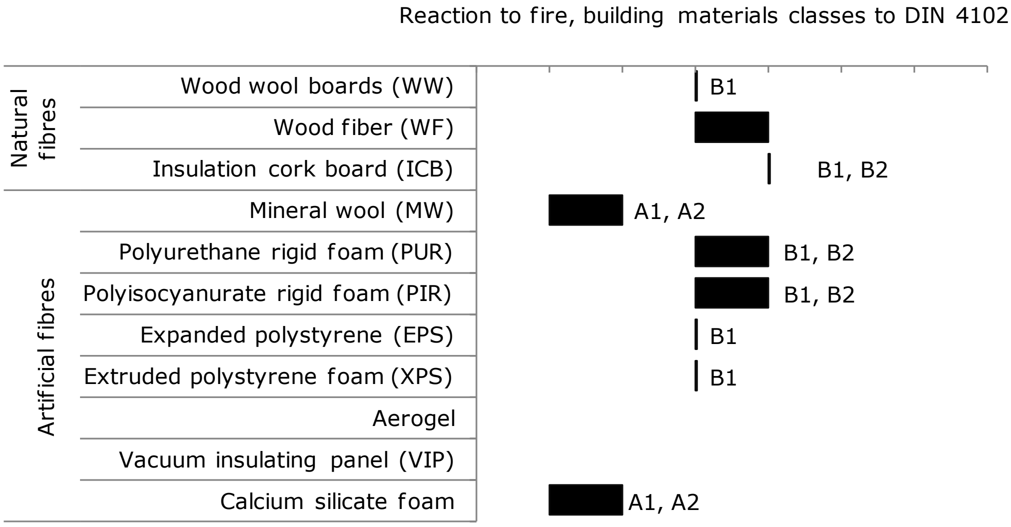


Figure 2.23. The comparison of insulation materials based on their fire protection class

2.4 Conclusions and recommendations

General conclusions from literature review are:

- Literature review revealed that the research studies carried out can be broadly classified as focusing on:
    - the insulation material itself,
    - simulating properties of insulation materials,
    - laboratory tests on insulation materials,
    - case studies on the insulation materials suited for selected objects,
    - in-situ measurements on the properties of internal insulation materials and the "response" of building's structure to retrofitting measures.
- The main focus of analysed papers and studies is the thermal properties of the walls after insulation material is applied and on the hygrothermal performance of the internally insulated wall. Limited number of papers is available on heat transfer and moisture transport in-situ measurements in historic buildings which have internal wall insulation.
- Nevertheless all presented case studies showed that the reduction of energy demand in historic buildings incorporates internal insulation strategies. Therefore the solution for this situation is twofold: better materials and better installation. The various research showed that the selection of the material are sensitive to the specific case study and that sometimes it is better to sacrifice bit of energy efficiency, but to avoid problems with moisture build up.
- As can be concluded from the literature review the main point of research it better understanding of hydrothermal behaviour mechanisms, which will allows to better simulate the real life behaviour of the interaction between internal insulation materials, surrounding environment and structure of historical building.

The main goal of WP2 is to provide data for material properties and threshold values for historic building materials and existing insulation materials as a background for material characterisation models and guidelines for safe renovation measures. The main objective of WP4 is to develop an efficient strategy for the probabilistic hygrothermal assessment of internal solutions. Both WPs can use

- methodologies that are developed by testing internal insulation and are found in literature review and they are:
  - Different methodologies to assess insulation material or system have been proposed by researchers
  - there are some fields where is lack of reliable risk assessment methodology, e.g. identification of potential damages caused by the freeze-thaw cycles in buildings.
- critical areas in the construction and failure modes, i.e. what can go wrong when installing internal insulation described in scientific literature are:
  - for central Europe's climate conditions, the risk of structural damage is especially high for bricks and stone masonry with low strength mortar.
  - some spots in the building have potential problems with the extensive humidity level, especially the façade not receiving sunlight.
  - the glue mortar accumulated large amount of moisture, thus leading to overall worse performance of capillary active insulation. Based on the results vapour tight systems should be preferred.
  - using the same internal insulation materials for two different wall types, the obtained results in laboratory tests differ.
  - adding vacuum insulating panels to internal surface of historic brick wall leads to higher relative humidity in the wooden beams and drying capacity on the side of VIP is substantially reduced. Relative humidity in the wall increases substantially when exposed to wind driven rain.
  - laboratory experiments show that brick and mortar are more capillary active compared to modelling results.
  - aerogel render wetting tests showed that the water diffusion in the wall does not have linear nature.
  - the preformed simulations showed that in the warm Mediterranean climate negligible condensation potential is obtained in the case on internal insulation strategy
  - for the humid climate the strategy how to avoid moisture built up is proposed.
  - in-situ measurements show that on average the performance of insulation materials is overestimated by producers by 13 to 25 %, except the case of cork-lime insulation.
  - in-situ measurements showed that the initial preparation of the surface and constant monitoring of the humidity level was found important for appropriate functioning of internal insulation materials.
  - the physical and moisture parameters of historic bricks are very different hence modern industrially produced bricks cannot be used to simulate historic brickwork .

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EN 13165:2012 "Thermal insulation products for buildings - Factory made rigid polyurethane foam (PU) products – Specification"

EN 13168:2012 "Thermal insulation products for buildings - Factory made wood wool (WW) products – Specification"

EN 13170:2012 "Thermal insulation products for buildings. Factory made products of expanded cork (ICB). Specification"

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3 Existing main strategies and methodologies used for retrofit of buildings

Building retrofit is a very complex process as it involves many variables that can be either independent or linked in a dynamic feedback system. These are hygrothermal properties of 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 building, building regulations, productivity etc. Decision about retrofit measures is taken based either on one criterion or on a set of different criteria that are important to the building owner. Vast number of decision support methods and tools have been developed and used by designers, architects, energy auditors and engineers to support building owners during implementation process of building retrofit.

Section starts with an overview on general classification of decision support tools for overall building retrofit process (Section 3.1). The second part of section is devoted to application of decision support tools and methods by researchers for internal insulation projects in historic buildings (Section 3.2). Section ends with conclusions (Section 3.3) and list of references (Section 3.4).

3.1 Decision making methods and tools for building retrofit

The heterogeneous structure of the building sector, large variety of technical measures and technical conditions of the existing building stock is a great challenge for implementation of energy efficiency retrofit projects (Hakinnen, 2012).

In general building retrofit process can be divided in several phases. A number of authors have investigated how building retrofit process can be split into consecutive steps, e.g. Ma et al. (2012) proposes five key phases in retrofit projects: (1) the project setup and pre-retrofit survey; (2) energy audit and performance assessment; (3) identification of retrofit options; (4) site implementation and commissioning, and (5) validation and verification. Kolokotsa et al. (2009) introduces four steps in the procedure of retrofit project: (1) buildings analysis; (2) walk-through survey; (3) creation of the reference building, and (4) evaluation of energy saving measures.

Strachan et al. (2012) reviewed a number of existing decision support tools for improvement of existing buildings. Each decision support tool was assessed against a set of criteria: carbon emission savings, energy consumption savings, cost, assessment of current building state, assessment of refurbishment interventions, assessment of user acceptability, data quality, and ease of use. The author proposed a generic decision support tool which allows design of the optimum intervention packages through a seven step process: (1) assessment of current building state; (2) assessment of energy demand interventions; (3) assessment building state of post energy demand interventions; (4) assessment of energy supply interventions; (4) assessment of post refurbishment performance; (5) preparations of energy management action plan, and (7) continuous improvement.

3.1.1 Decision making process in building retrofit projects

Decisions taken during building retrofit process determine whether the goal will be reached. Decision making process is an iterative and circular process. Alanne (2004) illustrates it as a loop where definition of the main goal and decision criteria for process assessment, development of actions and decision variables, estimation of performance, evaluation, and solutions and proposals are strongly interlinked (see Figure 3.1).

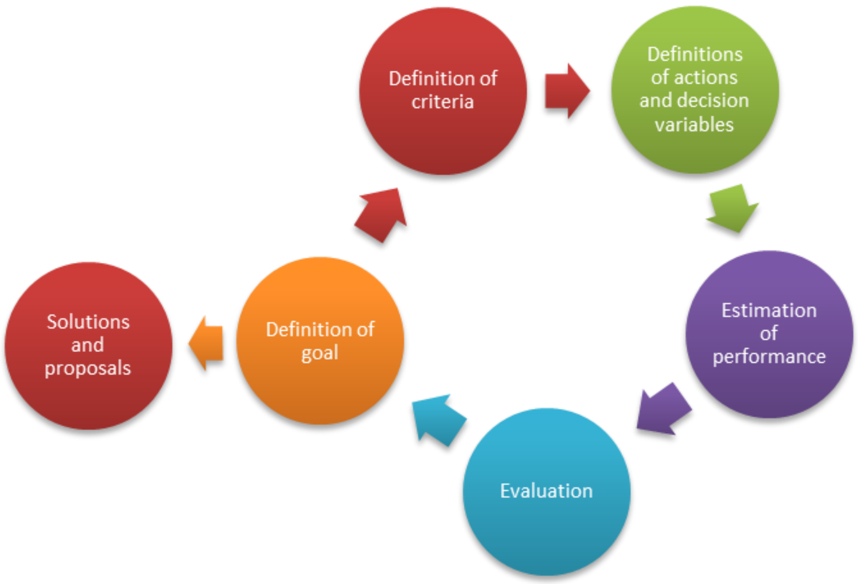

Figure 3.1. Decision making process (adapted from Alanne (2004))

Decision making process starts with goal setting. It can be either one goal like reducing energy consumption or several goals, e.g. reducing energy costs and reducing environmental impact. Each goal can be described with one or more criteria. Ferreira et al. (2013) have analysed and compared 40 different methods of decision support tools for retrofit of buildings, which focus on the goals of retrofit, complementary to what was proposed by Kolokotsa et al. (2009) as presented at the following page.

Ferreira et al. (2013) propose to distinguish five groups of goals and lists number of criteria attributed to these goals:

- *Improve energy and/or CO_2 emission performance* – these objectives are mainly aimed at minimising buildings operational energy consumption. Consequently by lowering buildings energy consumption the related CO_2 emissions also are lowered. Additionally renewable energy sources may be implemented to achieve even further CO_2 emissions reduction.
- *LCA methods* – the set of indicators included in this method are aimed at providing lowest possible environmental impacts considering cradle to grave approach. The different set of indicators included in this approach generally considers embodied energy, climate change impacts and other relevant environmental impacts (ecotoxicity, acidification, etc.), all

along the system life cycle i.e., the construction phase and the operation and maintenance phase and finally the end of life phase.

- *Sustainable assessment methods* – the main principle of this method is to incorporate principles which already are recognized in internationally acknowledged sustainable building design and sustainable assessment methods, i.e., BREEAM, LEED, DGNB and others.
- *Purely economic analysis* – the main considerations of this approach are related to buildings retrofit investment costs and post-retrofit operational costs. Criteria used for this group are related to cost-effectiveness of implemented measures during the service life of construction materials.
- *General methods* – this subcategory of methods may comprise of different assessment criteria which may largely vary from one case to another depending on main objectives defined by the client or specific issues which should be addressed. Methods from this group are considered to be very flexible due to possibility to incorporate different assessment criteria. However the general method implies that assessment criteria should be evaluated according to defined scoring table. Further, each criterion should have its own weight in the final scoring when all the criteria are combined into one total score. Although methods from this group are very flexible and it can be tailored to client's needs and each specific case, there is necessity for large amounts of initial data and because there is a necessity to define different weights for each parameter in final score, the quality of results are largely influenced by the experience of person carrying out the assessment.

Ferreira et al. (2013) concluded that decision tools have developed from tools based on operational aspects to life cycle approach, including both energy operation consumption and embodied energy. They also mention that life cycle cost analysis and analysis of social aspects could support life cycle assessment tools. Besides that a national or regional scale has to be taken into account.

Figure 3.2 illustrates five main categories of criteria used in decision support for energy efficiency projects distinguished by Kolokotsa et al. (2009).

Figure 3.2. Categories of main criteria for energy efficiency in the building sector (adopted from Kolokotsa et al. (2009))

Kolokotsa et al. (2009) have listed different criteria based on literature survey:

- *Energy use criteria* include
    - heating and cooling load for conditioned buildings
    - normalized specific energy consumption for heating
    - specific electricity consumption
    - embodied energy
    - energy and time consumption index

    - energy savings by retrofitting expressed as fraction from baseline consumption.
- *Indoor environment criteria* include
    - thermal comfort, e.g. predicted mean vote, dry resultant temperature for unconditioned buildings, indoor temperature and humidity etc.
    - visual comfort, e.g. daylight availability, lighting and visual comfort etc.
    - indoor air quality, e.g. CO2 concentration index, ventilation rates etc.
    - acoustic comfort, e.g. noise level in dB at workplace, noise rating index etc.
- *Global environmental criteria* are considering direct and indirect impacts (i.e. considering the entire life cycle of the systems) such as for example annual GHG emissions, primary energy consumption reduction potential of global warming emissions, life cycle environmental impact, acidification potential, and water use.
- *Costs criteria* are encompassing direct costs and initial investment costs, economic life span, annual on-going maintenance charges, annual on-going charges, net present value of the energy investment, internal rate of return of the energy investment, cost of conserved energy, life cycle cost, and cost of retrofitting.
- *Other criteria*, e.g. construction duration, uncertainty factors, functionality etc.

Attia et al. (2013) have carried out interviews among users of building energy optimisation tools and they found that optimisation objective functions among respondents was dominated by energy (100% respondents), followed by costs (64% respondents), comfort (36% respondents), carbon (17% respondents), lighting (7% respondents) and finally indoor air quality (4% respondents). Some of respondents consider indoor air quality as constraint.

The majority of criteria listed above are conflicting thus global solution or optimum cannot be reached and different methodological approaches have to be used.

When the goal is set and criteria are selected, actions have to be defined. In most building retrofit cases several actions have to be carried out simultaneously to reach the goal. In that case they can be combined under strategies. The number of actions and strategies are building specific. The goal, strategies and actions scheme is presented in Figure 3.3.

Figure 3.3. The actions and strategies tree (adopted from Kolokotsa et al. (2009))

The type and number of alternatives determines decision problems and tools to solve these problems. When the number of alternatives is very high but finite and alternatives are well known, the goal is to select the most favoured alternative. If the set of alternatives is presented by constraints that are presented as mathematical functions, discrete problems may arise. Continuous problems arise when the set of alternative solutions is generally presented through constraints (Ehrgott, 2005).

Estimation of performance is carried out based on building specific information and selected strategies and actions. Kolokotsa et al. (2009) notes that in most cases improvement of building performance is focused on specific actions and groups of actions and not on global approach since holistic approach is very complex.

The next phase is evaluation and it is based on assessment of goal and selected criteria versus selected strategies and actions. The problems that can arise during this process are related to conflicting criteria.

3ENCULT project (Troy, 2014) proposes in the case of historic building retrofit project to include more radical architectural and technical actions compared to traditionally used actions. To avoid exclusion of any action and strategy proposals have to be prepared without any reference to architectural and conservation value of buildings. Then all proposals are subject to discussions for all stakeholders and reviewed taking into account the architectural and conservation value. Specialists with technical and cultural competences have to be present during decision making meetings and present their arguments for and against each proposal.

3.1.2 Assessment methods and tools for selection of building retrofit measures

Kolokotsa et al. (2009) have reviewed methodological approaches for building retrofit and have proposed classification for building retrofit needs that can be applied during implementation steps of a building retrofit project. The classification of methodological approaches is based on how alternative strategies/actions are considered and is presented in Figure 3.4.

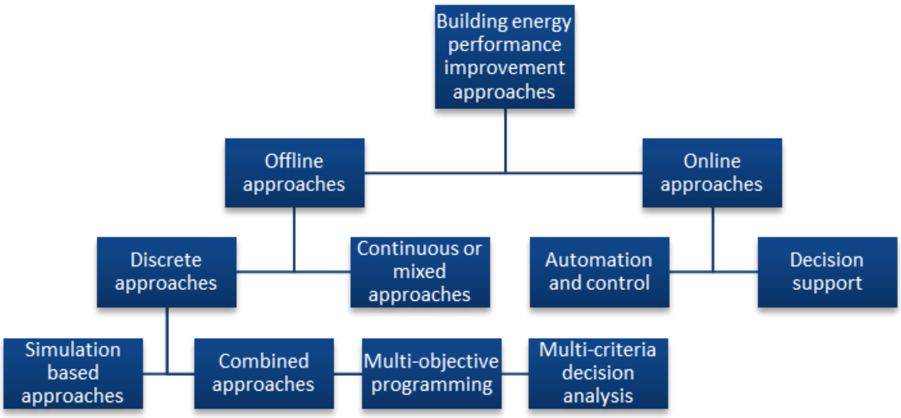

Figure 3.4. Classification of methodological approaches for building retrofit projects (adopted from Kolokotsa et al. (2009))

According to classification systems proposed by Kolokotsa et al. (2009), building energy performance improvement approaches can be divided into two main subcategories – *offline* approaches and *online* approaches.

Online approach aims at improving building performance during its operational phase by identifying parameters which influence building energy performance. These measures are mainly associated with fine-tuning of technical systems, i.e. optimizing indoor temperatures in different areas of building, defining night setback temperatures, lowering air exchange rates when it is acceptable and technically possible, as well as implementing other measures which may be associated with building energy management. The utilization of online approach requires that there should be an operational Building energy management system (BEMS) on site to fully realize and achieve potential energy savings. Two approaches can be used: automation and control, and decision support (Kolokotsa et al. (2009)).

Offline approaches focus on measures that can be implemented during building renovation process and they are aimed at improving overall energy and environmental performance of the building. The energy efficiency measures which fall into this category are mainly associated with thermal improvement of buildings envelope and improvement of building technical systems, such as boiler replacement, refurbishment of heating system, etc.

In this report only offline approaches will be discussed as RIBuild focuses on improvement of energy efficiency by internal thermal insulation. Off-line approaches are divided in continuous or mixed approaches (Section 3.1.2.1) and discrete approaches (Section **Fejl! Henvisningskilde ikke fundet.**), cf. Figure 3.4.

3.1.2.1 Continuous or mixed approaches

Continuous or mixed approaches are applied to overcome the problem of predefined strategies/actions. Not all feasible strategies/actions are taken into account during decision making process since strategies/actions are predefined by decision makers based on their knowledge and biases. Multi-objective programming or genetic algorithms combined with simulation tools are used with all alternatives. Attia et al. (2013) have reviewed papers on simulation-based building performance optimization tools used for net zero energy buildings and classified them as:

- simulation based optimisation (TRNOPT, BeOpt, OptiMaison, OptiPlus, ARDOT, Polysun, GENE_ARCH, Lightsolve, ParaGen, ZEBO),
- optimisation packages (MATLAB optimisation toolbox, Phoenix integration, GAlib, modeFrontier, Homer, DER-CAM) and
- tailor made-programming (C++, Cygwin, Java, R, Visual Studio).

They also found that the most popular optimisation tool used by interviewed users is Matlab optimisation toolbox and GenOpt followed by other tools which are more rarely used.

Kolokotsa et al. (2009) suggest combining both multi-objective modelling and multi-criteria decision analysis, starting with finding the Pareto optimal outcomes by means of multi-objective modelling and followed by multi-criteria analysis to find optimal solution. Alternatively, evaluation process can start with multi-criteria decision analysis providing aggregated score for all alternatives and followed by multi-objective to find optimal solution.

Several challenges to implement energy modelling tools exist, e.g. unstructured nature of current design process, research on designers' decision making process in a highly changing design practice has to be carried out, better communication between actors has to be fostered as well as trust in modelling results, and the role of uncertainties have to be taken into account (Mumovic et al., 2009).

3.1.2.2 Discrete approaches

Discrete approaches are used when large but finite number or alternative strategies/actions are considered. They are divided as:

- *Simulation based approaches* – simulation tools are used to develop models. Different alternative strategies/actions are defined through iterative process of simulation analysis. Kolokotsa et al. (2009) suggest to select simulation tool based on the following criteria: the required accuracy, easiness, availability of required data.;
- *Combined approaches* – different approaches can be combined, e.g. multi criteria decision analysis and analytical simulation tools.
- *Multi-objective programming* – is used when multi objective problems are faced. One optimal solution is rarely possible. The goal is to find Pareto optimal solutions that correspond to Pareto frontier.
- *Multi-criteria decision analysis* – allows comparing different alternatives by assigning weights to criteria and calculating the distance from the ideal solution. The main challenge for this approach is subjectivity of assigning weights.

There are many simulation based approaches and tools developed for different purposes. E.g. 3enCULT project team assumes that more than two dozen hygrothermal simulation methods have been developed worldwide. Hence, most of them are developed in the scope of either research project or PhD thesis and are not further developed and not used (Troy, 2014).

3.1.2.2.1 Hygrothermal assessment methods

Hygrothermal behaviour is a complex function dependent on several internal and external conditions as well as the included materials. The response of each material and the interaction with adjoining materials will directly influence the performance and durability of the structure. A wall retrofit will change the hygrothermal behaviour and could cause an improvement or degradation of its durability. The response of the materials included in the retrofitted wall is of high importance when considering durability issues.

Simplified simulation methods and tools for hygrothermal assessment can assist in the evaluation and risk analysis of the modified wall:

- *Glaser method* (Glaser (1958)) serves as basis for ISO 13788 *Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation*. This method allows an isolated evaluation of steady-state, one-dimensional vapour diffusion processes, assumes constant material properties.
- *WTA-sheet* provides a simplified method to underrun a relative humidity of 95% at the boundary between insulation layer and existing construction by the help of a diagram which displays the relationship between insulation layer thermal resistance, vapour

diffusion resistance and existing construction water uptake coefficient (wind driven rain load) derived from hygrothermal simulation studies (Geburtig, 2009).

Examples of *analytical simulation tools* for hygrothermal assessment are:

- *One-dimensional software tools* which allow an estimation of steady-state vapour diffusion, capillary transfer and moisture storage processes, e.g.:
  - WUFI-Pro by Fraunhofer Institute for Building Physics (IBP),
  - COND by Technical University of Dresden (IBK),
  - IQ-Lator by Remmers (Remmers).

  These tools are useful in most of cases and do not need deep expert knowledge.
- *Two-dimensional hygrothermal simulation tools*, e.g.:
  - Delphin by Technical University of Dresden (IBK, TUD)
  - WUFI2D by Fraunhofer Institute for Building Physics (IBP).

  These are used for inhomogeneous layers and offer the widest range of physical processes, e.g. vapour diffusion processes, capillary transport, moisture storage and several boundary conditions like increased indoor air humidity levels, rising damp, wind driven rain loads. Compared to one-dimensional tools, these tools require more time, more detailed input information, deeper expert knowledge and most often are used for research purposes.
- *Two-dimensional and three-dimensional simulation tools for thermal properties, e.g.* HEAT2, Therm.
- *Computational Fluid Dynamics tools are used for cavities or structures with active fluids,* e.g. Comsol, Fluent.

Despite the use of sophisticated simulation tools their applicability in retrofit decisions is limited by various factors, including uncertainty or simple lack of knowledge about boundary conditions (climate and exposure) and material properties. These tools require experienced professional and moreover, the obtained results are sensitive to the assumption made by the program and modeller. Therefore the results should be interpreted by a person with specific background knowledge. A major question is which damage models or performance thresholds should be used to guide the interpretation of the model results.

3.1.2.2.2 Building energy calculation approaches

Many different tools are available for building energy simulations that can be divided in following categories:

- *Calculation tools based on ISO 13790*. The given standard includes both a quasi steady-state monthly or annual method and an extended version for hourly calculations as well as a procedure for dynamic building simulation. This method is widely used by energy auditors, engineers and architects, e.g. the Passive House Planning Package.
- *Dynamic simulation tools* provide energy demand data in every simulation time step as well as give insights in temporary effects such as heat accumulation. Dynamic models provide multi zone modelling option. These models are used mainly by researchers and designers of buildings with special use, e.g. library with hybrid ventilation systems. The main disadvantage of dynamic models is the level of details of input data. Attia et al. (2013) have interviewed professional modellers and found that the most popular dynamic building simulation tools among interviewed professionals are: EnergyPlus, IDA ICE , TRNSYS , Esp-r, DIE-2 and others (e.g. Simulink, Ansys CFX, CFD (Fluent) etc.).

- *Building energy performance calculation models,* e.g. degree-days method.

3.1.2.2.3 Life cycle assessment

Life cycle assessment (LCA) is a methodology used to address the environmental impacts of products and services considering its entire life cycle, i.e. extraction of the primary material until end of life. It models life cycle of both products and services based on energy and material flows entering or leaving the system; then model the environmental emissions and material extraction and finally assessing the associated environmental impacts with environmental impact assessment methods. LCA methodology considers direct and indirect impacts. When LCA is carried out several impact categories can be addressed depending of the initial project goal and scope definition. Inventory flows-based indicators (e.g., use of primary energy or use of net fresh water) can be used as proxy to describe environmental impacts. More often life cycle impact assessment (LCIA) indicators such as global warming, resource depletion or acidification can be calculated.

Thus it is crucial in LCA to clearly identify, according to the scope of the study, what are the required environmental assessment needs. Finally, in LCA, the most important phase is the interpretation phase where design options or retrofit solutions are compared according to a given environmental indicators. As many LCAs are usually not robust enough and not always conclusive, sensitivity analyses are performed in order to in order to identify the most influencing impact contributors and to ensure that the best design or retrofit solution remain the best solution are integrating the uncertainties. This topic is indeed growing in the LCA community and several ways of handling uncertainties and sensitivity analyses have been proposed.

LCA has been defined as a generally applicable method in ISO 14040 and ISO 14044. Extensive documentation on LCA is given in the ILCD Handbook (ILCD 2011a, 2011b, 2010c). More specific definitions on how to use LCA in the construction industry are given in ISO 15804 and ISO 15978 and operational guidance have been recently proposed at the European level (Lasvaux et al, 2014).

LCA has been applied to new and existing buildings. Recent projects have started using it for building renovation to compare different renovation strategies for historic and non-historic buildings. For instance, the IEA EBC Annex 56 proposed a LCA methodology for energy-related building renovation (Lasvaux et al, 2015). This methodology is also embedded in a more comprehensive methodology combining LCA and the LCC. The IEA LCA methodology was recently implemented into existing LCA tools used by the building practitioners, e.g. Eco-Saï LCA software developed in Switzerland (Favre & Citherlet, 2009). Similarly, sustainable labelling schemes such as BREEAM, DGNB, LEED, HQE and Minergie-ECO have started using LCA and decision-making tools are also integrating LCA and related indicators.

3.1.2.2.4 Life Cycle Cost (LCC) analysis

Many projects and previous publications have proposed or analysed LCC methodologies for handling the comparison of building renovation scenarios. The scope is not always limited to historic buildings but can cover new or existing non historic buildings. Nevertheless some basic principles can be recalled here. A recent outcome form the IEA EBC Annex 56 project concerned the development of a cost-effective methodology for energy-related building renovation to find a good compromise between the primary energy and greenhouse gases emissions reductions and the minimization of cost over the life cycle.

The methodology developed is based on a life cycle cost approach and comprised the following key aspects:

- initial investment cost (planning and construction costs, professional fees, taxes, etc.),
- replacement cost during the (remaining) lifetime of the building (periodic investments for replacement of building elements at the end of their lifetime)
- running costs:
  - Energy costs (including existing energy and CO_2 taxes),
  - maintenance costs (repair, cleaning, inspection, etc.),
  - operational costs (taxes insurance, regulatory costs, etc.).

The LCC methodology of the Annex 56 was also implemented in decision making tools e.g., in the INSPIRE tool or in the ASCOT tool. SUSREF project concluded that the most problematic part of Life Cycle Costs in case of extensive renovations is management of risks (Hakinnen, 2012).

3.2 Application of decision making methods and tools for internal insulation of historic buildings

Section 3.2 presents the result of a literature review been carried out to find decision making methods and tools used specifically for application of internal insulation in historic buildings. Methods and tools are evaluated and compared to suggest preferable tools for historic building retrofit measure evaluation. Relevant articles were searched in the scientific databases of Scopus and Web of Sciences. Key words used in the search procedure: historical building, internal insulation, historical building materials, and energy efficiency in historical buildings. The overview of 29 sources found is presented in Appendix 2.

3.2.1 Classification of methods and tools

Classification of decision making methods and tools for internal insulation of historic buildings presented in section 3.1 is adopted based on combination of both classifications proposed by Kolokotsa et al. (2009) and Ferreira et al. (2013).

Based on Ferreira et al. (2013) literature review on decision making tools for sustainable retrofit, the following categories are adopted for decision making methods of energy retrofitting for historic buildings based on the goals of retrofit: general methods, energy consumption and CO_2 reduction methods, and purely economic analysis. Authors of this RIBuild report propose three additional categories: energy and heritage value appraisal methods, hygrothermal assessment approaches and holistic methods (see Figure 3.5). These methods are added to bear in mind that work on heritage buildings might be challenging in regards to both applicability and unacceptable hygrothermal risks as a consequence of internal insulation.

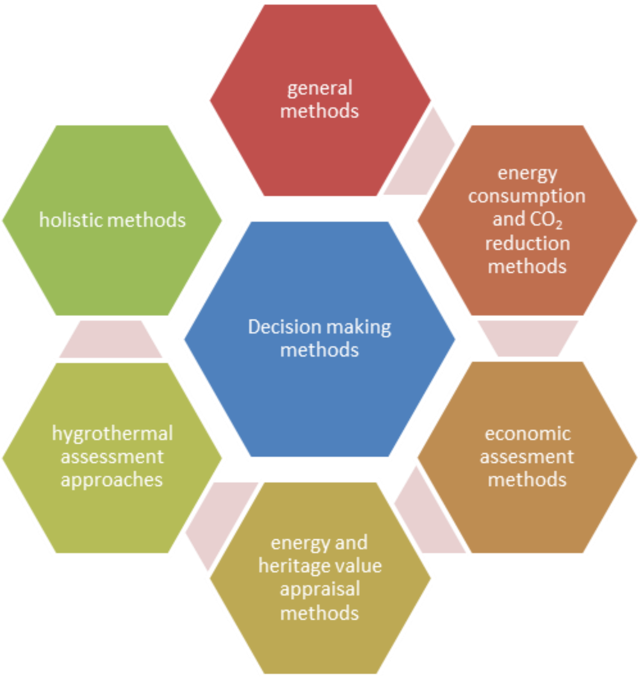

Figure 3.5. Classification of applied methods for internal insulation in historic buildings

The categorizations are as follows:

- *General methods* – goals to be reached with these methods can differ. Criteria vary from situation to situation, with different weights according to the case being under consideration.
- *Energy consumption and CO_2 reduction methods* – the main goal that has to be reached by applying these methods is either energy consumption reduction or CO_2 emissions reduction or both. Criteria are different indicators of energy consumption, U-values of walls, CO_2 emissions.
- *Economic assessment methods* – the main objective when these methods are used is minimisation of all costs, in particular energy and retrofit costs and life cycle costs. It may also consider costs associated with errors in decision making of appropriate retrofit measures and other costs relevant to specific case. Criteria are direct costs, indirect costs of environment and space and thermal comfort of the occupants, energy consumption.
- *Energy and heritage value appraisal methods* – both energy consumption reduction and heritage value are important criteria for decision making process. The main goal to be reached when these methods are applied is reduction of energy consumption while having no effect on heritage value. The main criteria for these methods are indicators of energy consumption, U values, material changes on the construction, visual change on the building appearance, costs, durability, economic feasibility, transformation level of masonry.
- *Hygrothermal assessment approaches* – the main goal for use of these methods is to help to decide whether internal insulation is applicable based on different hygrothermal properties of walls. The criteria used for these methods are relative humidity, temperature on the surface and within the construction, insulation thickness, insulation conductivity, air exchange rate, wall orientation, driving rain, vapour barrier, assembly water content,

drying rate, mould growth, condensation risk, ASHRAE-160 criterion, heat losses, total heat loss, number of moist frost cycles per year, moisture level in construction (between masonry and insulation), moisture level in construction (wooden beam ends), moisture diffusivity, water vapour diffusion resistance factor, hygroscopic moisture content, condensate annual balance of the structure, and heat and moisture transport and storage properties.

- *Holistic methods* – this is a multi-objective complex approach where multiple factors are used as decision making criteria. Often these factors are in opposition, for example, minimise energy consumption and mould growth potential while maximise occupant comfort. Hall et al. (2013) propose to use this approach as basis for an intelligent risk management strategy.

The following sections give an insight into the above listed methods and provide a short description on the methodologies application towards historic building energy efficient retrofit at the same time respecting historic building credentials. The summary of methods described by categories, subtype of categories, goal to be reached by applying method, criteria, methodological approach, simulation tools, description of methods/tools and author(s) is available in Appendix 2.

3.2.2 General methods

When general decision making methods are used, goals that are set can differ. Criteria vary from situation to situation, with different weights according to the case being under consideration.

Multi-criteria decision analysis methods are used when decision makers have to solve complex problems that contain multiple conflicting and subjective criteria that have to be taken into account simultaneously. These methods are applied to evaluate alternative building refurbishment strategies and solutions. Zagorskas et al. (2014) proposes to compare different internal insulation materials used for historic buildings. Five different criteria were used in this case to distinguish most appropriate internal thermal insulation materials for historic building retrofit. For the evaluation they selected five main factors: material costs, heat transfer coefficient, loss of space, moisture properties of the materials. They conclude that ***multi-criteria decision analysis*** can be widely used in the decision making process of optimum energy retrofit measure selection for internal insulation of historic buildings.

Konstantinou et al (2011) propose a toolbox which is a database of energy efficiency measures for different building envelope elements that can be implemented in refurbishment projects. The software used for the thermal simulation is Capsol by Physibel. It calculates the thermal dynamical behaviour using the ***heat balance equation***. The toolbox does not provide an optimised solution, but assists in making effective choices, thus seeking to combine the designer's, client's or user's intentions. The main parameters that are used to compare different alternatives are:

The toolbox presented in this review is presented as a set of energy efficiency measures, which are grouped and systemized thus providing a broad list of possible energy efficiency models. Via energy simulation software, these different energy efficiency measures are applied to reference building, evaluating each of the listed energy efficiency measures impact on the buildings energy consumption. Additionally to energy efficiency measure evaluation, also economic impacts were analysed. The proposed toolbox could be tailored to each specific project needs to meet costumers and designers demands.

3.2.3 Energy consumption and CO2 reduction methods

Methods from this category of decision making tools are used when the main goal of internal insulation application in historic building is either energy consumption reduction or CO_2 emissions reduction or both.

Alev et al. (2014) compare building energy efficiency regulations and their impact on historic building external walls in three countries: Finland, Sweden and Estonia. They conclude that national regulations may force to change appearance of building as in case of Sweden where target values can be achieved only by major renovation of building from outside while in Estonia only minor changes have to be done and in Finland external appearance of the building can stay unattached. They concluded that the high energy efficiency potential may be realized by improving historic buildings energy systems and power source, however these measures are insufficient to meet the energy efficiency targets determined in EE regulations in respective countries. Therefore additional EE measures have to be implemented to the building envelope to comply with regulations. Therefore in the study Alev et al. (2014) compared ***three different wall insulation strategies*** of historic buildings to further develop regulatory framework suited for historic building retrofit.

Hočova et al. (2015) have studied commercially most used internal insulation materials and the internal insulation made from natural fibres and materials based on energy and environmental appraisal using the ***OI3KON indicator***. This indicator is calculated for 1 m² of a structure and it is comprised from environmental indicator of non-renewable primary energy input, environmental indicator of global warming potential and environmental indicator of acidification potential in proportions of one third each, giving a proportional weighting to all of the indicators. Construction U-value of 0.21 $W/(m^2K)$ is chosen as a reference value for different insulation material comparison. Insulation materials with different heat transfer coefficients required different amounts of insulation materials, hence different structure overall environmental impact is calculated for respective material.

The heating energy savings, carbon emission reduction and the return on investment period were used as the main indicators for analysis performed by Ostojič et al. (2015) in Croatia. Software programme Toplinska zaštita Novolit 2009, version 1.06 was used for building energy efficiency status calculation. The ***required amount of thermal energy for heating*** was calculated according to the HRN ***ISO 13790 standard***. In this research different energy efficiency measures were analysed including internal insulation. For different energy efficiency measures space heating, achieved energy efficiency class, CO_2 emission reduction as well as return on investment was calculated. In the specific case energy efficiency measures comprising of thermal insulation of external walls form the inside, insulation of roof as well as replacement of old doors and old windows was chosen as the most suitable retrofit package.

Hola et al. (2015) have proposed three different insulation methods for external timber-framed walls filled with solid materials. Variant 1 and variant 2 comprises of methods dealing with external wall insulation from the outside and restoring the external appearance via rendering layer. Variant 3 suggests external wall insulation from the inside with climate panels made of silica aerogel with a thickness of 40 mm and finishing the surface with a rendering layer. Further, achieved ***U-values*** of different proposed strategies ***were calculated***. Hola et al. (2015) conclude, that currently available insulation materials could largely improve the energy efficiency of historic buildings if either side of the external walls are treated with insulation materials and rendering layers. They also conclude that each historic building is a specific case, therefore further analysis for each case is necessary to hinder possible damages which may occur due to inappropriate insulation strategy selection.

Dukanovič et al. (2015) undertook analysis of the potentials and limitations for energy refurbishment of the historic buildings based on ***software KnaufTERM 2 PRO***. They concluded that if internal and external insulation alternatives are compared, specific energy consumption of building is lower if internal insulation is applied due to decreased internal floor area and may result in one energy class difference for internal and external insulation alternatives. On one hand higher energy class might increase real estate value while on the other hand it might reduce it due to decreased floor area. Analysis also found that investments energy efficiency measures are slightly higher in the case of external insulation.

Moran et al. (2014) consider both energy consumption and CO_2 reduction as important criteria for energy efficiency projects in historic buildings. ***Three appraisal methods*** have been used: ***Integrated Environmental Solutions software***, ***Standard Assessment Procedure*** and ***Passive House Planning Package*** (PHPP). The aim of selecting wide range of energy consumption calculation tools is to asses PHPP adaptability for historic building cases. In total three different retrofit packages were chosen to assess possibilities of historic building energy consumption and CO_2 reduction. First package proposed to implement low-cost energy efficiency measures, second package focused on the evaluation of internal insulation material installation and the third package focused on two energy system potential evaluation – Photovoltaic Panels and Solar hot water system implementation. In the second package internal insulation of sheep wool and hemp batt insulation have been modelled as they have good vapour permeability and hygroscopic performance, which may hinder possible negative effect of moisture build-up in the external walls. In the results it was concluded that all three energy evaluation models overestimate energy consumption of actual building measures energy consumption date due to uncertainties dealing with irregular building occupancy patterns and set-point temperatures. It was also concluded that there is great potential for energy consumption reduction when considering the upgrade of building envelope thermal resistance, however it was noted that this option is not possible nor it is desirable in every specific case.

Morelli et al. (2010) made thermal investigation of beam end thermal interaction with masonry external wall with internal insulation layer by means of ***heat transfer programs HEAT2 and HEAT3***. Secondly they made a coupled heat and moisture transport investigation with ***simulation program DELPHIN***. It was concluded that it is highly recommended to carry out three-dimensional modelling when it is necessary to assess heat transport through external walls near the beam ends to provide reliable set of results. The calculations showed that although there is a high potential for a heat transfer reduction from the external walls with internal insulation, there is also a significant risk of moisture problems that may lead to sever wooden part deterioration, if the matter is not addressed properly. The authors suggest that retrofitting external wall with internal insulation of 200 mm from floor to ceiling might cause moisture problems at the beam ends, which could be solved by leaving a 300 mm non-insulated wall zone from the ceiling and ground and still harvest comparable energy savings. However, it is also noted that further investigations are necessary over a longer period of simulation time.

Stazi et al. (2014) studied thermal performance of an aged mineral wool insulation material applied on the interior side of an external wall. The insulation material in consideration has been installed for over 25 years. The methodology of the study comprises of several parts – ***laboratory***

tests to evaluate samples taken from the buildings and comparing them to new comparable insulation materials, monitoring in-situ thermal performance of the external wall with studies insulation material and ***analytical study with Energy Plus*** to carry out parametrical analysis to every season, as well as to asses different retrofit scenarios. It was concluded, that in fact some degradation of the heat insulation material was observed, which resulted in decreased hydrophobicity, which in turn was one of the main causes for the increase of thermal conductivity.

3.2.4 Economic assessment methods

The main goal of using economic assessment methods when internal insulation is applied in historic buildings, is minimisation of all costs, in particular energy and retrofit costs and life cycle costs. It may also consider costs associated with errors in decision making of appropriate retrofit measures and other costs relevant to specific case.

To evaluate the impact of uncertainties related to insulation material properties and insulation construction costs Aissani et al. (2014) added aspects such as environment, space and thermal comfort of occupants to the ***Life Cycle Cost method*** (LCC) as this often neglects the hidden costs of poorly installed insulation material, therefore as a consequence overestimating potential energy consumption reduction and leading to unexpected additional costs.

Different energy efficiency measures packages were analysed by Tadeu et. al. (2015) to evaluate their performance in three different climatic zones, which were quantified by different heating degree days – 987, 1302 and 1924. In total, 154,000 energy retrofit packages were calculated. Nine packages for each of the location were selected within cost-optimum range. The selection of packages was based on achieved construction U-values and heating degree days which gives a rough estimation on necessary heat energy amount for building space heating. Nine retrofit alternatives for each location were analysed via developed life-cycle model which consists of three main parameters – energy assessment, cost optimality assessment and environmental assessment. It was concluded that the optimal thicknesses for different climatic locations from cost-optimal point of view ranged from zero to 140 mm, which also is largely influenced by insulation material cost. Therefore in each separate case it is necessary to carry out a thorough assessment based on the specific location and insulation material cost. This also impacts total life cycle impacts for each of the locations studied. ***Genetic Algorithm for Energy Efficiency in Buildings*** (GAEEB) was used to find optimal solutions.

Study conducted by Friedman et al. (2014) evaluates different retrofit strategies to residential buildings in Israel. Regarding external wall insulation strategies both internal and external insulation strategies with varied insulation material thicknesses were considered. The study examined different retrofit strategies for building fabric retrofit and the energy simulations were done by ***EnergyPlus***. Cost-effective retrofit strategies depend on initial state of the building and local climate – even if the current thermal properties of existing building fabrics are poor, there may be low potential for energy efficient retrofit in mild climatic zones, e.g. Mediterranean climate regarding heating energy demand reduction.

3.2.5 Energy and heritage value appraisal methods

Both energy consumption reduction and heritage value are important criteria for decision making process. The main goal to be reached when these methods are applied is reduction of energy consumption while having no effect on heritage value.

Sahin et al. (2015) have investigated both improvement of energy efficiency and its impact on historic value of building. Transdisciplinary approach has been used. ***Building energy simulation tool*** was used to assess energy performance of building while ***risk-benefit analysis*** was carried out to select appropriate retrofit alternatives from the point of view of heritage value assessed as high risk, low risk, neutral, low benefit and high benefit of the building in case building in Izmir. Three different retrofit packages were compared and analysed. Results show that only targeting for major energy efficiency improvements, such as changing windows, external insulation of walls, solar panel application affect the historic, architectural and cultural values.

De Berardinis et al. (2014) have studied the compatibility of energy efficiency measures and damaged external historic building walls affected by earth quake. They have proposed a method based on energy saving calculation and level of transformability of masonry walls. First thorough ***field investigations*** accompanied with ***field measurements*** were made to acquire comprehensive data for masonry wall allocation into characteristic types. Method has been tested in Abruzzo region in Italy and results show that applicable energy solutions for masonry buildings damaged by earthquake improve their performance by over 50%. The developed methodology consists of a EE measure ***design guide summarized into table*** to facilitate decision making for retrofit measure selection. This approach seems to be valid in a certain region as the different parameters used in the method were validated against certain case studies in this region. For future work the method may be modified and applied in other regions.

3.2.6 Hygrothermal assessment approaches

The main goal for use of these methods is to help to decide whether internal insulation is applicable based on different hygrothermal properties of walls.

Several research groups have used ***simulation tool DELPHIN*** developed by Dresden University of Technology (Grunewald, 1999) to study hygrothermal processes in the external wall with internal insulation. Häupl et al. (2003) have investigated by performing calculations calcium silicate used as insulation on the interior side of external walls and compared the obtained results with field measurements. Klošeiko et al. (2015) have used DELPHIN to assess hygrothermal processes in brick wall with four types of internal insulation materials before tests are carried out. Steskens et al. (2013) have used DELPHIN to verify calculations carried out for internal insulation of external wall based on Glaser method according to ISO 13788 (see also Section 3.1.2.1.1).

Nielsen et al. (2012) have carried out sensitivity analysis to establish the parameters that are important when considering internal insulation of solid brick walls. The study was carried out in ***MATLAB***. Code23 was used to solve heat and moisture differential equation system. ***SIMLAB*** was used for statistical simulation while the ***Morris method*** was used for screening of important parameters. The ***Sobol method*** was used to determine the percentage of total output variance that each parameter accounts for.

Ibrahim et al. (2014) have used simulation tool ***WUFI*** to analyse transient heat and moisture transport in multi-layer building component for internal insulation with opaque and transluscent aerogel. Ghazi Wakilia et al. (2014) also report use of WUFI for assessment of hygrothermal processes in external walls with internal insulation. Johansson et al. (2014) have performed hygrothermal numerical simulations with simulation tool WUFI for internal insulation retrofit of a historic brick wall using vacuum insulation panels. WUFI was also used by Hall et al. (2013) with main goal to assess retroffiting measures in residential buildings. The main criteria defined by authors are hygrothermal properties, energy consumption, indoor climate, indoor air comfort, mould growth potential.

Vereecken et al. (2015) have used ***programme code HAMFEM*** (Janssen et al., 2006) as a tool for probabilistic approach for analysis of energy savings and the hygrothermal risks caused by internal insulation. HAMFEM solves the equations for energy and mass conservation based on a finite element method. Authors have compared two capillary active insulation systems (calcium silicate board, and a mineral wool combined with a smart vapour retarder) with two standard systems (a vapour tight XPS-system and a mineral wool combined with a traditional vapour barrier). Kočī et al. (2013) have studied internal insulation for autoclaved aerated concrete based walls. ***Simulation tool HEMOT*** based on the general finite element package SIFEL was used for hygrothermal analysis.

Mensinga et al. (2010) have developed a ***risk assessment methodology*** based on frost dilatometry to study the risk of frost damage of bricks subjected to freeze-thaw cycles in a retrofitted wall. The method allows to assess the critical level of moisture saturation for freeze-thaw damages.

Brunner et al. (2005) have investigated vacuum insulation panels in constant and dynamic conditions. Based on their findings they have developed an ***aging model***. It is ***based on the Arrhenius equation*** which means that the pressure and moisture diffusion doubles for each 10°C temperature increase. Brunner et al. (2008) have ***validated*** the model by two years measurements. This model was ***improved*** by Brunner et al. (2014) by including a third aging mechanism; long-term moisture induced changes of the interfacial contact areas between the fumed silica particles could increase the thermal conductivity through the solid. Based on Brunner et al. (2014) aging model, Johansson et al. (2014) have carried out 25 year simulation for vacuum insulation panels.

3.2.7 Holistic methods

This is a multi-objective complex approach where multiple factors are used as decision making criteria. Often these factors are in opposition, for example, minimise energy consumption and mould growth potential while maximise occupant comfort.

Musunuru et al. (2015) have developed the Measure Guideline to be used during decision making of internal insulation for masonry walls. Guideline takes into account a number of criteria: cost and performance, durability, constructability, freeze-thaw degradation risk, air leakage performance, and thermal performance. The ***BEopt tool combined with WUFI*** is used.

Grytli et al. (2012) developed an integrated analysis method. The method examined different short- and long-term impacts from various energy efficiency measures on a model building by ***combining life cycle assessment, energy calculations and heritage value assessment system***. For Life Cycle Assessment software ***SimaPro*** 7.1.8 Multi-user connected to the ***EcoInvent 2.0*** database was used. The functional unit was a building with case study's layout and volume. The service life was set to 80 years. Heritage was assessed based on relative scale. Energy calculations were performed with ***SIMIEN***. Authors list several problems, like uncertainties regarding results from the Life Cycle Assessment. Method requires more development on environmental impact from buildings, particularly concerning the development of a life cycle impact assessment method more adapted to the various regional conditions. Other type of uncertainties is related to input data for building energy calculations. Authors also mention that their approach was time consuming due to collection of data for both energy calculations and Life Cycle Assessment. In addition to that multidisciplinary methods require massive background knowledge and experience with software tools. Hence they conclude that holistic approach is very useful for historic building retrofit projects. Sensitivity analysis revealed that the length of service life for the building was crucial for the results obtained, in particular when comparing buildings with large variations in energy consumption.

Häkkinen (2012) has presented ***multi criteria decision making method***, focus on hygrothermal performance and life cycle aspects. ***SUSREF*** developed sustainable concepts and technologies for the refurbishment of building facades and external walls. Guidelines were given for the use of assessment methods especially regarding durability and life cycle impacts.

Kolaitis et al. (2013) have evaluated the performance of both external thermal insulation and internal thermal insulation configurations in residential buildings. Three interconnected parameters related to thermal insulation material application – heat losses, hygrothermal behaviour and economical aspects – were studied for external thermal insulation and internal thermal insulation case and compared to case with no insulation materials. Detailed numerical simulations of annual energy requirements and water vapour condensation potential were used to study heat loses and hygrothermal behaviour using ***TRNSYS and HETRAN***, respectively. It was concluded that both of the insulation material configurations provide considerable heat energy savings compared to base case when no insulation is considered. Moreover it was concluded that due to lower costs of internal thermal insulation installation the overall pay-back period for this configuration was lower compared to external thermal insulation configuration. The two studied locations also showed that depending on the climatic zone, different approaches to the internal insulation study need to be selected. Authors found that external insulation results in approximately 8% higher energy savings than internal insulation on an annual basis. Simulation results show that in internal insulation installed in the Mediterranean climate region negligible water vapour condensation potential is seen. In the Oceanic climate region, with low temperature and high relative humidity during the winter season, installation of internal thermal insulation may result in water vapour condensation incidents. This effect can be avoided by installing appropriate water vapour barrier layers.

Hall et al. (2013) have conducted a study to establish comprehensive approach for UK domestic buildings whish are considered to be ‘hard-to-treat’. The overall goal is the reduction in building operational energy consumption as well as increase of thermal comfort and desirability. A variety of energy efficiency improvement measures were analysed to establish preferable retrofit scenarios. To determine retrofit scenario relative effect on indoor air psychrometric conditions, external envelope (dynamic) heat transfer, operational energy efficiency, occupant comfort, and mould growth potential, the scenarios were modelled using energetic hygrothermics approach. The simulations were carried out via simulation tool ***WUFI***. It was concluded that in the specific retrofit cases, where a number of factors have to be taken into account reliable prediction of energy efficiency and risk analysis are essential components to decision making process in selecting and prioritising energy efficiency measures. It was also concluded that if aiming for low-energy retrofit projects, wall and ceiling insulation seems to be top priority.

European project 3enCULT (Troy, 2014) wanted to provide an approach and a process that makes it possible to identify and integrate values of culture and energy in the conservation of built heritage. The work resulted in the ***3ENCULT methodology*** that identifies and balances culture and energy values, referring to cultural charters and conventions as well as to energy standards and directives. One of the deliverables of the 3ENCULT project was a handbook that summarises the principles for the energy retrofitting of historic buildings and describes the guiding methodology for survey, assessment and decision-making. The handbook includes steps from the first diagnosis to the adequately designed intervention: E.g. preservation of the historic structure, user comfort and energy efficiency, and provides design examples, calculations, and measuring results from eight case studies. The handbook also defines and illustrates some hygrothermal assessment methods for performance of all and roof constructions in historic buildings.

3.2.8 Overview of application of different methods and methodological approaches for internal insulation in historic buildings

Figure 3.6 gives an overview on application of methodological approaches within different categories of methods used for internal insulation of historic buildings described in details in the previous section. Details are presented in Appendix 2 and Appendix 3 of this report. The most used methodological approach is the numerical approach (one of the deterministic approaches), which is used for two purposes – building energy simulation and simulation of hygrothermal properties of walls. The second most used is a combined approach. One multi-criteria decision making approach and multi-objective programming case were found. Few cases with use of LCA and LCC tools are found. These findings correspond with Kolokotsa et al. (2009) stating that improvement of building performance is focused on specific actions and packages of actions and not on global approach, as holistic approach is very complex.

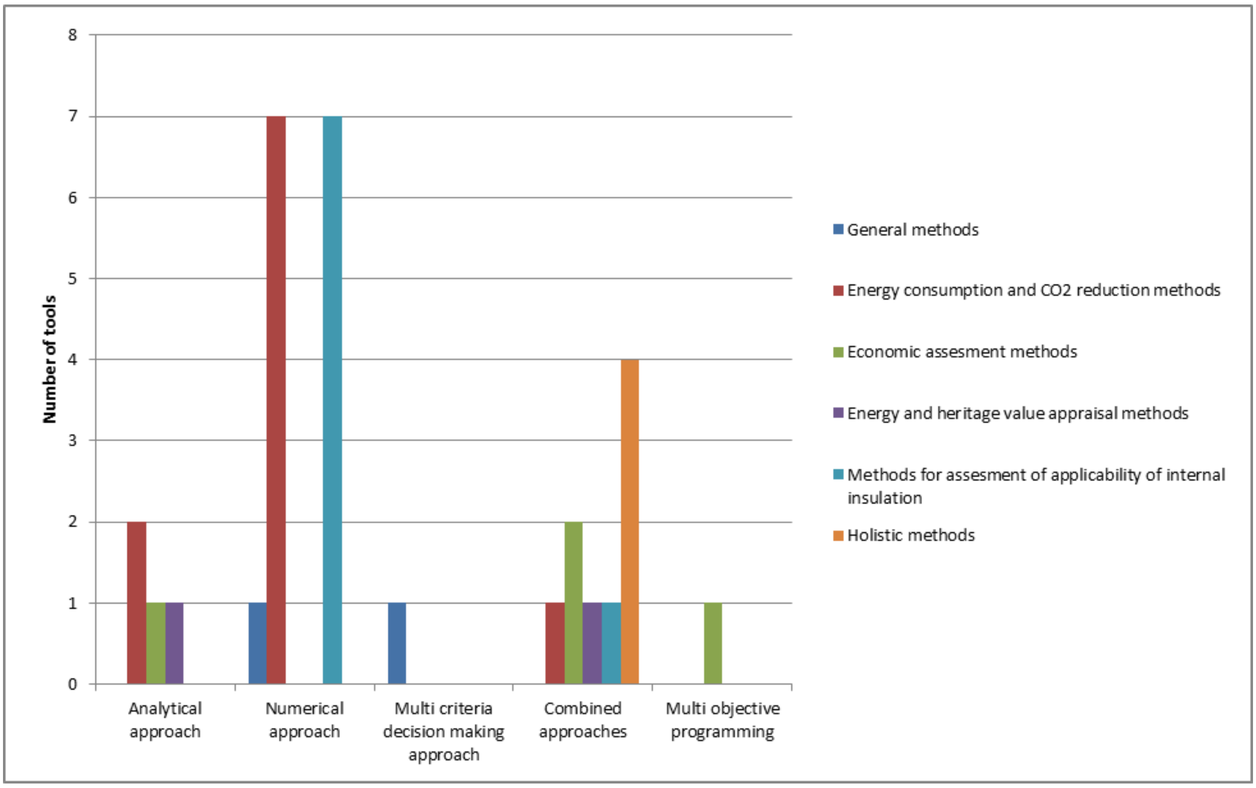

Figure 3.6. Overview of application of methodological approaches within different categories of methods for internal insulation in historic buildings

3.3 Conclusions and recommendations

3.3.1 General conclusions

The general conclusions are:

- The type and number of alternative solutions determines decision problems and the tools to solve these problems.
- *Global optimization of a building as a whole is a very complex problem* because of large number of parameters and variables, non-linear relations between variables, conflicting criteria and second-order effects. Hence holistic approach is very complex and in most cases improvement of building performance is focused on specific actions and groups of actions and not on global approach.
- *Process and decisions taken mainly depends on experience and the knowledge of building/energy expert and/or decision maker* when discrete decision approaches are used, the. It implies that decisions are based on predefined solutions and alternatives and not all feasible alternatives and criteria are taken into account.
- *A number of challenges to implement energy modelling tools exist*, e.g. unstructured nature of current design process, insufficient research on designers' decision making process in a highly changing design practice, insufficient communication between actors, lack of trust in modelling results and too little focus on the role of uncertainties.
- Most of the more than *two dozen existing hygrothermal simulation methods* are developed in the scope of either research project or PhD thesis and are not further developed and not used.
- *Applicability of hygrothermal calculations in retrofit decisions is limited* by various factors, including uncertainties for calculating impact indicators or simple lack of knowledge about boundary conditions (climate and exposure) and material properties – despite the use of sophisticated simulation tools. These tools requires experienced professional and, moreover the obtained results are sensitive to the assumption made by the program and modeller, therefore the results should be interpreted by a person with the specific background knowledge. A major question is what damage models or performance thresholds should be used to guide the interpretation of the model results.

3.3.2 Recommendations for WP2

The main objective of WP2 is to provide data for material properties and threshold values for historic building materials and existing insulation materials as a background for material characterization models and guidelines for safe renovation measures. One of the tasks to reach the goal is evaluation, refinement and validation of material characterization models which is based on evaluation and comparison of existing models for calculating the effect of adding internal insulation on the hygrothermal conditions of external walls. The following recommendations based on literature review for WP2 are:

1) Number of analytic and numerical hygrothermal, thermal and energy tools used for internal insulation application have been found and listed. More detailed analysis of application has to be carried out in WP2 to decide how to fit the RIBuild project needs. It could be based on Table 2.1. (Assessment tool for the applicability of internal insulation).
2) Hygrothermal modelling tools are described in Section 3. Not all the tools described are applied in studies carried out with internal insulation materials, e.g. Computational Fluid Dynamics tools.

3.3.3 Recommendations for WP5

The main goal of WP5 project is to develop a probabilistic assessment methodology of the environmental impact and costs/benefits of internal insulation solutions, based on Life Cycle Assessment (LCA), Life Cycle Cost (LCC) and Cost-Optimal (CO) analysis. The following recommendations are an outcome from the literature review:

- *Hidden costs of poorly installed insulation material should be taken into account* in Life Cycle Cost method (LCC) as they are often neglected and hence as a consequence LCC is overestimating potential energy consumption reduction and leading to unexpected additional costs.
- *Life Cycle Assessment (LCA) often is used as a deterministic approach* to provide useful information related to environmental impacts. However, the deterministic format sometimes leads to widespread environmental impacts according to the studies' modelling assumption, background data and environmental impact assessment method. It is thus *necessary to switch from deterministic approach to probabilistic approach* in order to capture, as much as possible, the range of possible environmental impacts. Based on such probabilistic approach, transparent and conclusive decision support tools will be possible and their robustness will enable a widespread use of LCA for building renovation strategies and policies. It is not the purpose of the WP5 to tackle the uncertainty related to LCIA method since it implies several research field (substance transfer into various media, toxicological dose response models, etc.). However, uncertainties related to modelling assumption and background data could be addressed comprehensively partially in partnership with WP4 objectives.
- *Life Cycle Assessment used as deterministic tool does not have ability to be used as a decision making optimization tool* as it is mainly used as an instrument to quantify inflows and outflows and environmental impacts. If optimisation of different criteria is used in WP6, it should be discussed how LCA can be adopted for optimisation tool.

3.3.4 Recommendations for WP6

The objective of WP6 is to develop and to assess guidelines for a renovation of historic buildings with internal insulation, based on the methodologies developed in WP4 and WP5. The purpose of these guidelines is to help decision making regarding e.g. whether internal insulation is relevant at all or not, and whether it is affordable to make a detailed calculation.

Due to the complexity and many potential risks and uncertainties of applying internal insulation there is a need for practical guidelines that are simple in relation to what to do when internal insulation is to be considered in a specific situation. Some manufactures of insulation materials and systems do have some simple guidelines but there is a need for neutral, non product-specific and comprehensive guidelines. The applicability of the methodology and the guidelines is evaluated and validated on demonstration projects, where the methodology is used as a basis for decision making. This will help to optimise the design and implementation of internal insulation to increase the energy efficiency of and comfort in historic buildings in an economical and environmental friendly way.

The following findings from literature review can serve as the basis or inputs for development of guidelines within WP6:

- If building physics is taken into account, the best solution for wall insulation can be found by optimising:

  - *thermal performance* of the envelope: reduction of the heat losses through the envelope, minimising thermal bridges
  - *moisture performance* of the envelope: ensuring drying capacity, avoiding condensation
  - *durability* of the constructions: reduction of the risk for mould, decay, frost and corrosion
  - *indoor air quality and comfort*: thermal symmetry, no draft, control of humidity (Hakinnan, 2012)
- *Holistic or systemic methodologies* developed are based on deterministic approach and methods for *assessment of different criteria are not interlinked*. Additional study has to be carried out to find a tool or method that can link together hygrothermal simulation with energy simulation, LCA, LCC and other tools. One option could be application of evolutionary computation techniques, such as genetic algorithms where internal insulation is globally optimized from the viewpoint of energy use, ecological impacts, and costs.
- Holistic methods can be used as a *basis for an intelligent risk management strategy*
- *Tools based on stochastic approach should be considered* instead of a deterministic approach
- *Combination of multi-objective modelling and multi-criteria decision analysis can be used*, starting with finding the Pareto front by means of multi-objective modelling and followed by multi-criteria analysis to find optimal solution. Alternatively, evaluation process can start with multi-criteria decision analysis providing aggregated score for all alternatives and followed by multi-objective modelling to find optimal solution
- *Research on developing weighting factors for historic building retrofit decision making should be part of RIBuild*. From the literature review it became clear that there is a considerable gap in this field. Different parameter weighting factors for Multi-criteria analysis to support internal insulation of external wall could be obtained from further WP's, when the consortium will evaluate different parameters related to internal insulation material use. Thoroughly evaluated and scientifically justified weighting factors may be a part of the decision making tool for historic building internal insulation decision making process.

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Appendix 1. Insulation materials and material systems for internal insulation

Condensate-preventing materials and material systems (adopted from Arbeiter (2014))			
Materials/material system	Producer name and product	λ [W/mK]	μ [-]
Foam glass based Systems	FOAMGLAS: FOAMGLAS T4+	0.04	∞
Aluminium foil-laminated	RECTICEL: Eurothane GK	0.024	combined
Vacuum insulation boards	SAINT-GOBAIN ISOVER: Kontur VVP 007 and HVP 007	0.007	$>10^6$
	VARIOTEC: Universal VIP/ QASA-Elemente	0.007	$>5*10^5$
	Barsmark: Vacupour	0.007	$>10^6$
Condensate-limiting materials and material systems (adopted from Arbeiter (2014))			
EPS- based systems	Danogips: DANO Dämm PS	0.04	40
	Glutolin: Depron Dämmplatte	0.03	650
	Knauf: Knauf InTherm (System)	0.032	combined
	Saint-Gobain: System Rigitherm 032	0.032	55
	Saint-Gobain: System Rigitherm 032	0.040	40
	Saint-Gobain Weber: weber.therm 507	0.07	15
PUR based systems	Linzmeier (Linitherm PAL SIL):	0.024	combined
	RECITEL: Eurothane GK	0.024	combined
Mineral wool based systems	ROCKWOOL: Aerorock	0.019	>3
Glass foam granulated	KlimaTec: KP 2500+	0.086	10
	KlimaTec: LP 1000+	0.086	10

Wood fibre based	Pavatex: Pavatex Pavadentro	0.045	163
Textile fiber based	KlimaTec: KlimaTec KV 600	0.04	15
Other synthetic foam systems	Kingspan: Kingspan Kooltherm Resolhartschaum K12	0.022	38
	Kingspan: Kingspan Kooltherm Resolhartschaum K17 (with gypsum board)	0.022	538
Composite boards	Knauf Insulation: Tektalan TK- DB (integrated vapor bake)	0.038	combined
	Remmers: IQTherm	0.033	27
	Wedi: Wedi Bauplatte Premium (XPS based)	0.04	100
	Condensate-tolerating products (Arbeiter, 2014)		
Calcium silicate based boards	ALLIGATOR: ALLFAtherm	0.042	2-3
	Calsitherm: Calsitherm Klimaplatte	0.06	3-6
	CASIPLUS: Casiplus Klimaplatte	0.062	3
	Epasit: Spezialbaustoffe, Calciumsilikat	0.067	3
	FEMA: FEMA Maxipor Mineraldämmplatten	0.042	3
	FEMA: FEMA KlimaPlus Sanierungsplatten	0.07	5
	HASIT: HASIT MULTIPOR	0.042	3
	Isotec: ISOTEC Klimaplatte	0.06	3
	Redstone: Masterclima	0.063	4.61

	Remmers: SLP	0.063	4.6
	Microterm: Mircrotherm plates	0.067	
	ZERO-LACK: ZEROTHERM MSP-System	0.060	6
Wood fiber based boards	CLAYTEC: Claytec Pavadentro	0.045	5
	Conluto: Conluto Internal insulation system	0.045	5
	GUTEX: Gutex Thermoroom	0.04	3
	Hock: Opti Plan universal	0.047	3
	HOMATHERM: ID_Q11 standard	0.047	3
	INTHERMO: INTHERMO HFD-Interior Clima	0.05	5
	SCHOMBURG: Thermolut	0.045	5
	UNGER_DIFFUTHERM: UdilN System	0.045	5
	UNGER_DIFFUTHERM: UdilN RECO System	0.041	5
Clay based boards	Haacke: Cellco Wärmedämmlehm-Platte (WDP)	0.07	10
Other organic based boards (e.g. cork, hemp, cellulose)	Haacke: Cellco Kork- Dämmplatte (EKP)	0.04	25
	Hock: Thermo- Hanf premium	0.04	1
	Hock: Thermo- Hanf PLUS	0.04	1
	ISOCELL: Renocell	0.052	2.4

	UNGER_DIFFUTHERM: UdiCLIMATE	0.049	5
Other mineral based boards	HECK WALL: Heck IDP MS	0.042	5
	Getifix: ambio hydrophil	0.042	5
	Keimfarben: Keim iPor-Mineraldämmplatte	0.042	3
	Knauf Aquapanel: TecTerm Insulation Board Indoor (Perlite)	0.045	5
	Quick-mix Gruppe: Mineraldämmplatte MI-XI	0.042	2
	Krautol: INSO:BLUE 60/80 Innendämmplatte	0.04	2
	Redstone: Pura hydrophil	0.042	5
	SAINT-GOBAIN: Akustic VP	0.035	1
	Saint-Gobain: System Rigitherm MW	0.04	1
	Saint-Gobain: weber therm MD 042	0.042	3
	Xella: Ytong multipor	0.045	3
	ZERO-LACK: ZEROTHERM MSP-System	0.042	5
Insulating plastering	HECK WALL: Heck DP MIN	0.09	7
	HECK WALL: Heck DP MIN	0.07	8
	Getifix: WD	0.077	7
	Haacke: Cellco	0.07	9
	Redstone: Senso (Perlite)	0.077	7

	Sto AG: StoTherm In Comfort (Perlite based)	0.045	6
Aerogel	Sto: StoTherm In Aevero	0.016	10
	Aspen Aerogels: Spaceloft	0.016	10
	Thermablok Aerogel: ThermaSlim IWI Board	0.016	10
PUR-based system	i-Qtherm	0.031	

Appendix 2. Decision making methods and tools for internal insulation of historic buildings

Categories	Subtype of categories	Goal to be reached by applying method	Criteria	Methodo-logical approach	Simulation/ calculation tool	Description of method/tool	Source
General methods	Effective choice method	To assist in making effective choices, thus seeking to combine the designer's, client's or user's intentions	• indoor temperature, • heat buffering in the walls, • energy demand for heating and cooling • costs	Numerical simulation	Capsol by Physibel	Objective is not to dictate an optimised solution, but rather to assist effective choices. Program calculates the thermal dynamical behaviour using the heat balance equation, indoor temperature and heat buffering the walls.	Refurbishment of residential buildings: a design approach to energy-efficiency upgrades Konstantinou et. al. (2011)
General methods	Multi criteria decision making method	Selection of the best alternative for brick wall insulation from inside	• cost of the material, • complexity of the installation, • heat transfer coefficient, • loss of space when installing additional insulation layer • hydrophobic/moistu re properties of insulation layer	Multi Criteria Decision Analysis	TOPSIS Grey numbers method	Method is based on the grey number criteria values. In this research the universal method for selecting the best alternative for brick wall insulation from inside is developed and it can be used when deciding which new insulation material for the refurbishment of historic building to select.	Thermal insulation alternatives of historic brick buildings in Baltic Sea Region Zagorskas et. al. (2014)
Energy consumpti on and CO2 reduction methods	Local regulations method	Energy consumption after retrofit complies with national regulations	• annual primary energy consumption (kWh/(m2a)) • use of delivered energy for space heating and heating of ventilation air, the delivered energy includes also energy for heating of domestic hot water, fans and pumps (kWh/(m2a)) .	Analytical simulation	Validated energy consumption calculation tool based on ISO 13790	Energy renovation measures are selected on significantly different bases when following the local regulations.	Renovation alternatives to improve energy performance of historic rural houses in the Baltic Sea region Alev et al.(2014)
Energy consumpti on and CO2 reduction methods	Energy and environmental appraisal tool	Preserve architectural features and artistic value of the building and improving its thermal performance	• non-renewable primary energy input, • environmental indicator of global warming potential, • environmental indicator of acidification potential.	Analytical simulation	Environmenta l indicator OI3KON	Comparison of different types of insulating materials, incl. commercially available, and environmentally friendly materials applied to case study.	Technological aspects of reconstruction of historic buildings Hočova et al.(2015)
Energy consumption	Energy and environmenta	Reduce energy	• heating energy savings,	Numerical simulation	Software programme	Energy analysis and refurbishment	Energy analysis and

and CO2 reduction methods	l appraisal tool	consumption and protect heritage value	• carbon emission reduction • return on investment period		Toplinska zaštita Novolit 2009 and HRN ISO 13790	strategy for Zagreb University building with heritage value of building exterior was carried out.	refurbishment strategy for Zagreb University buildings: Former Faculty of Technology in Zagreb by Alfred Albini Ostojič et. al. (2015)
Energy consumption and CO2 reduction methods	Energy appraisal method	Reduce energy consumption	• U-values	Analytical simulation	U-value estimation	U-values of different internal insulation methods are calculated.	Analysis of the possibilities of improving timber-framed wall thermal insulation with regards to historic buildings Hola et. al. (2015)
Energy consumption and CO2 reduction methods	Thermal properties of wall and energy performance of building	Reduce energy consumption	• U-value • Energy performance of building	Numerical simulation	Knauf TERM 2 PRO	This article aims at investigating the potentials and limitations for energy refurbishment of the building heritage dating before the World War One. Thermal properties of applied structures, as well as energy performance of the analysed buildings were calculated by using non-commercial software, which is based on requirements and settings of the relevant thermal regulations.	Potentials and limitations for energy refurbishment of multi-family residential buildings built in Belgrade before the World War Dukanovič et. al. (2015)
Energy consumption and CO2 reduction methods	Thermal properties of wall and energy performance of building	Reduce energy consumption and CO2 emissions	• gas consumption, • electricity consumption, • energy savings • carbon savings	Numerical simulation	Integrated Environmental Solutions (IES) software, Standard Assessment Procedure (SAP) and Passive House Planning Package (PHPP)	The aim is to evaluate the potential contribution retrofit adaptations can make to reducing energy use and CO_2 emissions.	The use of Passive House Planning Package to reduce energy use and CO_2 emissions in historic dwellings Moran et. al. (2014)
Energy consumption and CO2 reduction methods	Thermal properties of wall and energy performance of building	Reduce energy consumption	• Energy savings	Numerical simulation	HEAT2, HEAT3	Analyses of potential energy savings of a typical section of the outer masonry wall. The coupling coefficient analyses are made in two dimensions	Internal Insulation of Masonry Walls with Wooden Floor Beams in Northern Humid

						and three dimensions, using the heat transfer programs HEAT2 and HEAT3.	Climate Morelli et. al. (2010)
Energy consumption and CO2 reduction methods	Performance analysis tool	To evaluate the insulation conservation state after 25 years, to assess the actual indoor thermal comfort and to compare different retrofit interventions	• PPD and PMV values; • Operative temperature; • Energy consumption for heating and cooling	Combined approach	EnergyPlus, PMVModel (EN ISO 7730), the adaptive model (EN ISO 15251)	EnergyPlus is used to assess the decrease of the performance of insulation layer inside the cavity of an external wall after 25 years, considering both the hygrothermal performance of the wall and the internal thermal comfort level, and to identify the better retrofit scenario between two different solutions.	Assessment of the actual hygrothermal performance of glass mineralwool insulation applied 25 years ago in masonry cavity walls Stazi et. al. (2014)
Economic assessment methods	Life Cycle Costs method	To study impact of uncertainties related to insulation properties and cost estimation errors	• direct costs • indirect costs of environment, space and thermal comfort of the occupants	Analytic simulation	Indirect costs method	In addition to traditional direct costs decision making criteria of thermal insulation, indirect costs of environment, space and thermal comfort of the occupants are considered.	Cost model for optimum thicknesses of insulated walls considering indirect impacts and uncertainties Aissani et. al. (2014)
Economic assessment methods	Life-Cycle method	To identify cost-optimal solutions based on an occupancy pattern and to assess whether these solutions also ensure low life cycle environmental impacts	• energy consumption, • cost optimality, • environmental considerations	Combined approach	Energy calculation with EnergyPlus, LCA, life-cycle model	Life-cycle model was used to investigate optimal energy efficiency measure retrofit packages in different locations. Life-cycle model assessed such factors as energy consumption, cost optimality, environmental considerations. In total nine different retrofit strategies were analysed for each of the three different locations with different heating degree days.	Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions Tadeu et. al. (2015)
Economic assessment methods	Cost-benefit analysis	To determine direct economic and external benefits to society arising from electricity conservation resulting from such retrofit	• Energy consumption • Energy costs • Energy efficiency measures costs • externalities	Combined approach	EnergyPlus, calculation of externalities of electricity production	Energy balance is calculated with EnergyPlus. The external benefits of reduction in demand for electricity were calculated.	Energy retrofit of residential building envelopes in Israel: A cost-benefit analysis Friedman et. al. (2014)
Energy and heritage value	Energy-heritage value assessment tool	Reduce energy consumption and protect	• reduction in total annual primary energy consumption,	Combined approach	BES tool, risk-benefit analysis tool	Transdisciplinary methodology in order to reduce the energy consumption	A transdisciplina ry approach on the energy

appraisal methods		heritage value	• total annual primary energy consumption. • U values, • material changes on the construction, • visual change on the building appearance. • Costs • Durability • Moisture • Mould risk			of the building in heating season without unacceptable impact on the historic heritage values. Building energy simulation tool for energy calculations and risk-benefit analysis for historic heritage value assessment.	efficient retrofitting of a historic building in the Aegean Region of Turkey Sahin et. al. (2015)
Energy and heritage value appraisal methods	Technical and economical compatibility appraisal method	Energy consumption reduction and heritage value	• economic feasibility of the internal insulation alternatives • transformation level of masonry.	Combined approach	Evaluation matrix	Criteria are the economic feasibility of the internal insulation alternatives and transformation level of masonry.	Improving the energy-efficiency of historic masonry buildings. A case study: A minor centre in the Abruzzo region, Italy De Berardinis et al.(2014)
Hygro-thermal assessment approaches	Hygrothermal processes	To assess the impact of an internal insulation retrofit on the hygrothermal performance of a brick wall	• relative humidity between materials • temperature on the surface and between materials	Numerical simulation	Delphin	In this study, four solutions of internal thermal insulation for the brick wall are tested. An analysis was carried out to assess the impact of an internal insulation retrofit on the hygrothermal performance of a brick wall.	Hygrothermal performance of internally insulated brick wall in cold climate: A case study in a historic school building Klošeiko et. al. (2014)
Hygro-thermal assessment approaches	Hygrothermal processes	To present an assessment tool for the building facade in order to help the building designer to which serves as a basis for the selection and design of an appropriate internal insulation system.		Combined approach	Glaser method and Delphin	The tool helps the building engineer and designer to analyse and diagnose whether internal insulation is applicable, given the state of the existing facade.	Interior insulation of masonry walls – Assessment and design Steskens et. al. (2013)
Hygro-thermal assessment approaches	Hygrothermal processes	To establish the parameters that are important when considering internal insulation of solid brick walls	• Insulation thickness • Insulation conductivity • Air-change rate • Wall orientation • Driving rain	Numerical simulation	Matlab coupled with Simlab	In order to find the parameters that are important to consider when insulating solid brick walls internally the statistical simulation is done with	Use of sensitivity analysis to evaluate hygrothermal conditions in solid brick walls with interior

			• Vapour barrier			SIMLAB coupled with the MATLAB model is done. The Morris method and the Sobol methods are used.	insulation Nielsen et. al (2012)
Hygro-thermal assessment approaches	Hygrothermal processes	To analyse transient heat and moisture transport in multi-layer building component for internal insulation	• assembly water content, • drying rate, • mould growth, • condensation risk, • ASHRAE-160 criterion, • heat losses	Numerical simulation	WUFI	Examination of the hygrothermal performance of walls with new rendering and to compare different thermal insulation configurations.	Hygrothermal performance of exterior walls covered with aerogel-based insulating rendering Ibrahim et. al. (2014)
Hygro-thermal assessment approaches	Hygrothermal processes	To analyse transient heat and moisture transport in multi-layer building component for internal insulation	• Internal and external surface temperatures • moisture content within the stone wall	Numerical simulation	WUFI, VOLTRA	The performance and applicability of a newly developed high efficiency insulation material to retrofit old buildings was investigated.	Efficiency verification of a combination of high performance and conventional insulation layers in retrofitting a 130-year old building Ghazi Wakili et al. (2014)
Hygro-thermal assessment approaches	Hygrothermal processes	To assess hygrothermal performance of building envelope	• moisture diffusivity, • water vapour diffusion resistance factor, hygroscopic moisture content	Numerical simulation	HEMOT (HEat and MOisture Transport)	The computer simulation tool HEMOT (HEat and MOisture Transport), which is based on the general finite element package SIFEL (SImple FInite Elements), was used for the assessment of hygrothermal performance of the analysed building envelope. Künzel's mathematical model of coupled heat and moisture transport was implemented in HEMOT for the calculations. A computer aided design is to be adopted for the achievement of both satisfactory hygrothermal performance and acceptable service life of the envelope.	Computer aided design of interior thermal insulation system suitable for autoclaved aerated concrete structures Kočī et. al. (2013)
Hygro-thermal assessment approaches	Hygrothermal processes	To design an innovative internal thermal insulation system on the basis of hydrophilic	• condensate annual balance of the structure • heat and moisture transport and storage properties • of hydrophilic	Numerical simulation	TRANSMAT computer simulation tool	An innovative internal thermal insulation system on the basis of hydrophilic mineral wool is studied. TRANSMAT model of coupled heat and	Hygrothermal performance study of an innovative interior thermal insulation system

		mineral wool	thermal insulation material and water vapour retarder			moisture transport in multi-layered building envelope systems formulated by Kunzel.	Pavlik et. al. (2009)
Hygro-thermal assessment approaches	Hygrothermal processes	To assess the critical level of moisture saturation for freeze-thaw damages	• moisture contents of the brick masonry	Numerical simulation	WUFI	An alternative approach and laboratory methodology has been suggested: frost dilatometry can be used to determine the critical degree of saturation at which freeze-thaw damage is likely to occur. The testing methodology described has shown that a relatively fast and simple test protocol can provide the critical degree of saturation for clay brick materials.	Assessing the Freeze-Thaw Resistance of Clay Brick for Interior Insulation Retrofit Projects Mensinga et. al. (2010)
Hygro-thermal assessment approaches	Aging model	To determine yearly pressure increase rate	• Pressure increase rate • Moisture content	Analytic simulation		An aging model was developed which take into account the gas and moisture diffusion into the VIP.	In situ performance assessment of vacuum insulation panels in a flat roof construction Brunner et. al. (2008)
Hygro-thermal assessment approaches	Hygrothermal processes	To assess retroffiting measures in residential buildings	• hygrothermal properties, • energy consumption, • indoor climate, • indoor air comfort, • mould growth potential	Numerical simulation	WUFI, WUFI Bio v3.1	Each retrofit scenario was modelled using an energetic hygrothermics building performance simulation approach to determine the combined effects of retrofit packages on indoor air psychrometric conditions, external envelope (dynamic) heat transfer, operational energy efficiency, occupant comfort, and mould growth potential.	Analysis of UK domestic building retrofit scenarios based on the E.ON Retrofit Research House using energetic hygrothermics simulation – Energy efficiency, indoor air quality, occupant comfort, and mould growth potential Hall et. al. (2013)
Hygro-thermal assessment approaches	Probabilistic approach	To carry out analysis of energy savings and the hygrothermal risks caused by internal insulation	• Total heat loss • Number of moist frost cycles per year • Moisture level in construction (between masonry and insulation)	Numerical simulation	HAMFEM with Monte Carlo analysis	An in-house programme code that solves the equations for energy and mass conservation based on a finite element method.	Interior insulation for wall retrofitting – A probabilistic analysis of energy savings and hygrothermal risks

			• Moisture level in construction (wooden beam ends) • RH on the indoor surface (mould growth)				Vereecken et. al. (2015)
Holistic methods	Performance analysis tool	To assess use of internal insulation for masonry walls	• cost and performance, • durability, • constructability, • freeze-thaw degradation risk, • air leakage performance, • thermal performance	Combined approach	BEopt, WUFI	Criteria include cost and performance, durability, constructability, freeze-thaw degradation risk, air leakage performance, and thermal performance.	Measure Guideline: Deep Energy Enclosure Retrofit for Interior Insulation of Masonry Walls Musunuru et. al. (2015)
Holistic methods	Energy calculations, hygrothermal processes	To investigate the main parameters affecting the efficiency of installing thermal insulation for energy efficiency purposes in residential buildings	• annual heating and cooling energy requirements, • transient thermal behaviour, • potential risk for water vapour condensation • payback period. • climate region • occupant behaviour	Combined approach	TRNSYS and HETRAN codes, Dew Point Method	A comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings has been performed by means of detailed numerical simulations of annual energy requirements and water vapour condensation potential.	Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings Kolaitis et. al. (2013)
Holistic methods	Multi criteria decision making method, focus on hygrothermal performance and life cycle aspects	Analysis of refurbishment projects of building facades and external walls	• Durability. • Impact on energy demand for heating. • Impact on energy demand for cooling. • Impact on renewable energy use potential. • Impact on daylight. • Environmental impact of manufacture and maintenance. • Indoor air quality and acoustics. • Structural stability. • Fire safety. • Aesthetic quality. • Effect on cultural heritage. • Life cycle costs. • Need for care and maintenance.	Combined approach	SUSREF	SUSREF developed sustainable concepts and technologies for the refurbishment of building facades and external walls. Guidelines were given for the use of assessment methods especially regarding durability and life cycle impacts.	Systematic method for the sustainability analysis of refurbishment concepts of external walls. Häkkinen (2012)

			• Disturbance to the tenants and to the site. • Buildability				
Holistic methods		To bridge the gap between conservation of historic buildings and climate protection	• preservation of the historic structure, • user comfort • energy efficiency	Combined approach	3ENCULT methodology (based on different methods); Calculation tool for the certification of historic buildings	3ENCULT methodology that identifies and balances culture and energy values, referring to cultural charters and conventions as well as to energy standards and directives. A handbook that summarises the principles for the energy retrofitting of historic buildings and describes the guiding methodology for survey, assessment and decision-making.	European project 3ENCULT (Efficient Energy for EU Cultural Heritage)

Appendix 3. Overview of application of methodological approaches within different categories of methods for internal insulation in historic buildings

Categories	**Methodological approach**					
	Simulation based approach		**Multi criteria decision making approach**	**Combined approaches**	**Multi objective programming**	**Continuous or mixed decision problem approaches**
	Analytical approach	**Numerical approach**				
General methods			TOPSIS Grey numbers method			
		Capsol by Physibel				
Energy consumption and CO_2 reduction methods	OI3KON	Toplinska zaštita Novolit 2009		EnergyPlus, PMVModel (EN ISO 7730), the adaptive model (EN ISO 15251)		
	U-value estimation	Knauf TERM 2 PRO				
		Energy consumption calculation tool based on ISO 13790				
		Integrated Environmental Solutions (IES)				
		Standard Assessment Procedure (SAP)				
		Passive House Planning Package (PHPP)				
		HEAT2, HEAT3				
Economic assessment methods	Indirect costs method			Energy calculation with EnergyPlus, life cycle costs model	Genetic Algorithm for Energy Efficiency in Buildings (GAEEB)	
				EnergyPlus, calculation of externalities of electricity production		
Energy and heritage value appraisal methods				BES tool, risk-benefit analysis tool		
	Evaluation matrix					
Methods for assessment of applicability of internal insulation		Delphin		Glaser method and Delphin		
		WUFI, WUFI Bio v3.1				
		Matlab coupled with Simlab				
		WUFI, VOLTRA				
		HEMOT				
		TRANSMAT computer simulation tool				

		HAMFEM with Monte Carlo analysis				
Holistic methods				TRNSYS and HETRAN codes, Dew Point Method		
				SUSREF approach incl.WUFI, LCA, LCC, mould growth model etc.		
				3ENCULT methodology (based on different methods); Calculation tool for the certification of historic buildings		
				SimaPro 7.1.8 Multi-user, connected to theEcoInvent 2.0 database; mass calculation with 3D models in ArchiCAD; energy calculations with SIMIEN		