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Author(s)	Peggy Freudenberg (TUD)
Participants(s)	DTU, RTU, AAU, UNIVPM, HES-SO
Internal reviewers	Morten Ørsager (EMA), Sébastien Lasvaux (HES-SO), Ernst Jan de Place Hansen (AAU)
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Abstract

The present report summarized the outcomes of case studies developed within the RIBuild project. These case study buildings were evaluated regarding the documented damages and damage indicators, the location characteristics (weather conditions), the usage (indoor climate, type), historic constructions and retrofit constructions as well as specific aspects of constructive problems (e.g. joist ends, tightness). Findings from the project-internal case studies are supplemented with published case studies from 2003 and onwards. Furthermore, the design of the monitoring systems of these buildings is summarized and non-destructive on-site test for the characterization of these constructions and materials are presented.

Keyword list: Case study buildings, internal insulation systems, Thermal bridges, Monitoring systems, Weather conditions, Indoor conditions, Non-destructive tests.

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1 Executive summary

The present report finalizes the measurement activities conducted in WP3. In a first deliverable (D3.1) of WP3, the focus was set on the hygrothermal performance of idealized constructions under laboratory conditions. The report on hand (deliverable D3.2) gives an overview of the hygrothermal performance in practice for a number of internally insulated case study buildings, either RIBuild-cases (14) or published (31) monitoring projects. They cover a wide range of weather conditions (locations), constructions (wall materials, wall thickness, type of constructive details) and typologies (office, residential and others). Different aspects have been analysed, e.g. performance risk factors addressing the construction (Section 3.1 and 3.3) or weather conditions (Section 3.4). Findings about the case studies are essential for the definition of planned simulation cases for the final guideline (WP6). The report provides furthermore an extension of material testing methodologies reported in D2.1 with test methodologies that can be done on site with a minimum destruction of the buildings (Section 4.3.1).

Among 31 case studies published since 2003 and 14 RIBuild case studies, only two damage cases occurred. However, critical moisture contents were measured in several projects for the first monitoring years; in 14 published case studies and five RIBuild case studies. In nine of these cases, critical moisture content could be attributed to a high built-in moisture of the system and the corresponding drying phase in the first year after installation of internal insulation. The length of the drying phase depends on the amount of built-in moisture, drying potential due to the vapour diffusion resistance and capillary activity of the system. Most of the projects with critical moisture contents showed a strong initial drying process with an acceptable moisture level in the wall after the first or the second year. Further reasons for high moisture levels in the construction were poor thermal resistance of the existing wall, a missing sealing of joist ends towards indoor air, a poor drying potential due to a high vapour resistance of the insulation system in combination with an insufficient wind driven rain protection or an inactive heating system. Other factors like the driving rain load or the air tightness of the construction are not documented in a comprehensive way for all cases.

The economic efficiency of internal insulation is not a focus of the present report. This aspect is analysed within deliverable D5.1 for selected case studies. The results showed an energy saving potential of about 30-70%, depending on the geometry of the building, the quality of the existing wall, the type and thickness of the insulation material, the kind of other energy saving measures etc.

In general, the following conclusions and recommendations can be derived about the hygrothermal performance from the measurement and simulation results in the present case study report:

- The thinner the existing wall, the lower is the possible damage-risk free thermal resistance resp. thickness of the added insulation system. A thin wall increases the condensation risk and the impact of driving rain on the construction.
- The lower the driving rain load (driving rain protection of façade or low driving rain load at the specific location), the more insulation systems are possible to use.
- The dryer and warmer the indoor air, the more insulation systems are possible to use. Especially the performance of capillary active systems (aka. condensate-toilerating systems) improves as these show a strong interaction with the indoor climate. Opposed to this, the behaviour of vapour-tight insulation systems (aka. condensate-preventing systems) (e.g. VIP) is only marginally depending on indoor climate conditions.
- A humidification potential from one side of the construction (e.g. moist indoor air or driving rain) requires an equivalent drying potential on, at least, the opposite side of the construction. This could be provided with a condensate-tolerating internal insulation system or avoided with a reduction of the moisture load (improved driving rain protection).
- The higher the built-in moisture, the higher is the required drying potential of the construction. Insulation systems with a high build-in moisture should therefore at the best be vapour-open and capillary active.
- The more vapour tight the insulation systems are, the more caution should be paid on proper workmanship at constructive details, connection jointing etc.

The detailed weighting of design factors (e.g. energetic, economic, comfort-related goals) for the analysed case studies is not explained in their documentation. Many of these projects are demonstration projects rather than being representative cases for building practice. This complicates the derivation of practice-relevant conclusions from these research projects. ***Nevertheless, involved people in the design process should be aware of the individual functionality and element interaction of each building. Any retrofit measure presumes an understanding of the existing construction and the expectable consequences for the whole building.***

2 Introduction

2.1 Actual performance of historic buildings

Internal insulation pursues different goals. The main application argument is the unification of measures, that allow the preservation of the historic building appearance and measures, which guarantee current thermal comfort and energy saving requirements. One inherent aspect of this approach is the assurance of condensate-free internal wall surfaces. Old buildings often include several thermal bridges that are subject to decreased surface temperatures and consequently risk of mould growth, surface condensation etc. The evaluation of these damage risks is a challenge.

Many conditions have changed for existing buildings compared to their original situation. This addresses the duration of the construction period (drying period) and the type of used materials, the change of climatic conditions and the indoor conditions. For instance, occupancy has changed essentially. Some of these changes might reduce the damage risks while others might strengthen them. There is, on the one hand, a tendency to an increasing living area per person for all types of buildings, furthermore a tendency to higher and consistent indoor air temperatures. These tendencies reduce the risk of a high indoor air relative humidity. On the other hand, an increased area of moist rooms and an increased number of vapour sources is given for modern buildings, compared to the occupancy decades or centuries ago, with shared bathrooms on each floor, joint washing and drying rooms in the basement, indoor plants being a rarity and so on. The impact of these changes is rather unknown and strongly depending on the interaction of the tenants with the building. An evidence about realistic occupancy conditions could only be given with measurement in refurbished buildings. These measurements are summarized and analysed in Section 4.

Another uncertainty for the actual performance of buildings is resulting from the interaction of internal insulation performance with other retrofit measures. One example is the renewal of windows, which provided originally high air change rates due to their leakages. This property provided a permanent removal of vapour and thus a dry indoor air during the heating season. New windows are tight and imply therefore the risk of vapour accumulation if the users do not follow a disciplined window-opening schedule. Some of these aspects are mentioned in the report. However, the interaction of these measures is a complex issue and cannot be analysed in a comprehensive manner in the frame of this report.

Beside these utilization characteristics, unknown material or construction properties, and local weather conditions are further uncertainty aspects to be mentioned. Although wall thickness and material of the walls are often known, the exact material properties are normally not known. The variety of brick types is huge, concerning not only the density and thermal conductivity but also the vapour diffusion resistance and liquid water conductivity. This is shown in Figure 1.

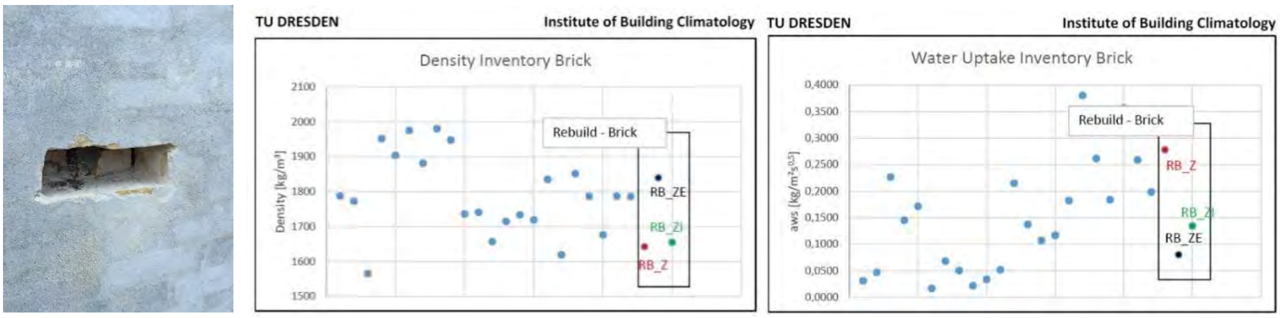


Figure 1: Sample extraction (left picture) from the case study building in Klitgaarden, Denmark. Diagrams in the middle and on the right show results of the laboratory measurements. Named dots in the frame are three different bricks extracted from Klitgaarden building, showing a huge variety of values.

Additionally, the brick types could vary within the wall cross section for thick walls. A change of wall materials with less liquid water conducting and more moisture resistant materials (e.g. natural stones like Travertine, Granite) in the basement and the plinth of the building was also common. The variety in the arrangements of construction parts (e.g. external wall with roof or ceiling) is manifold, too.

Usually, the building owner has only a vague idea about the embedded materials and details of his building. Clarity about these building properties is only provided by in-situ and laboratory material testing and systematic investigation of existing details (opening or endoscopic survey). A construction summary is part of Section 3.1 and Section 3.3. Investigative methods on site and in the laboratory are explained in Section 4.3.

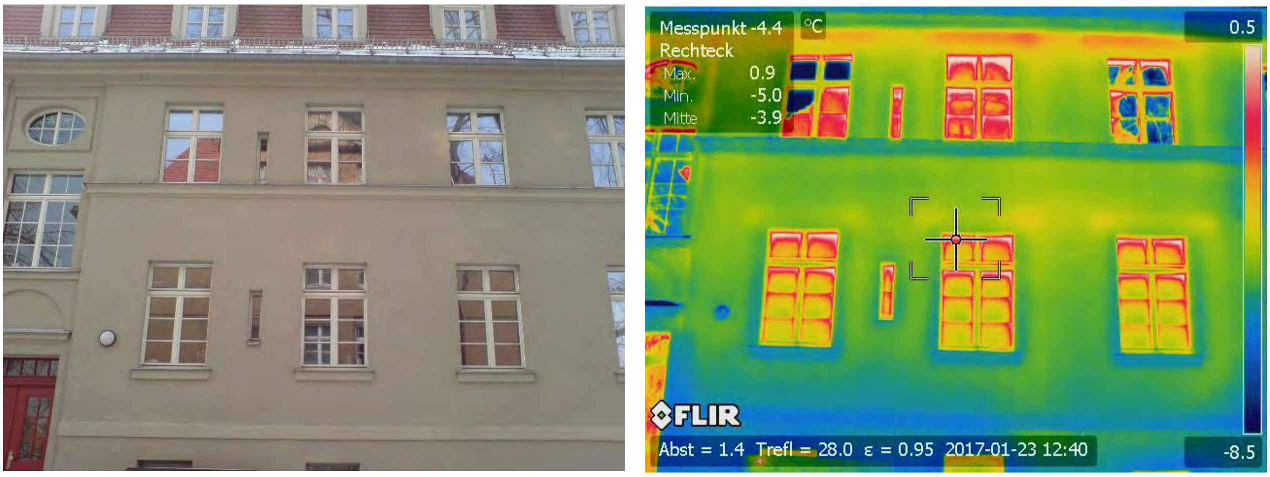


Figure 2: Photography and infrared image of the building façade taken from the case study building in Weimar, Germany. Thermal bridge areas around windows, ceiling, roof and inhomogeneity in the wall can be seen in the distribution of surface temperatures.

All these uncertainties aggravate the reliability of design calculations, which are conducted in advance of the retrofit construction works. An evaluation of realised projects therefore helps understanding the practical consequences associated with internal insulation.

2.2 Content of the report

The present report analyses hygrothermal and energy performance in practice. It covers a variety of case study buildings, including different construction traditions, usage types and ages, characteristics of the chosen insulation system (type, thickness, performance) and boundary conditions (local weather and indoor conditions) . Further, it includes not only RIBuild case study buildings, but also case study buildings from the literature. The case studies are presented in Section 2.3, Appendix I: Table of RIBuild Case Studies and Appendix II: Table of Published Case Studies.

Section 3 introduces risk factors known from literature, especially constructive risks of internal insulation and strategies to avoid them. These factors are investigated for the analysed case study buildings in the subchapters in regard to the historic wall constructions (Section 3.1), the chosen insulation type (Section 3.2), constructive details (Section 3.3 and 3.5) and the boundary conditions (Section 3.4). Further information about the case study building investigations, e.g. in-situ measurements and laboratory measurements are provided in Section 4. This included the development of monitoring systems and the conduction of non-destructive in-situ tests, as an addition to deliverable D2.1 (dealing with destructive laboratory tests).

2.3 Case Study Overview (published and RIBuild-internal)

A graphical overview of analysed case study buildings is given in Figure 3, set up as an interactive online map, which includes basic information about the case studies (Figure 4). Yellow house symbols are representing published case studies, while the red ones are representing RIBuild-internal cases. A number of 31 case study publications since 2003 was analysed. This includes 28 European projects, one Canadian (Toronto) and two US-American projects (Boston, Lawrence). The latter are also part of the map. As some of these projects were set up as test buildings with several test wall sections resp. insulation systems, in total there are 45 evaluated constructions. Twelve RIBuild case study buildings include 16 different constructions. This results in a sum of 43 analysed internally insulated buildings, comprising 61 different constructions.

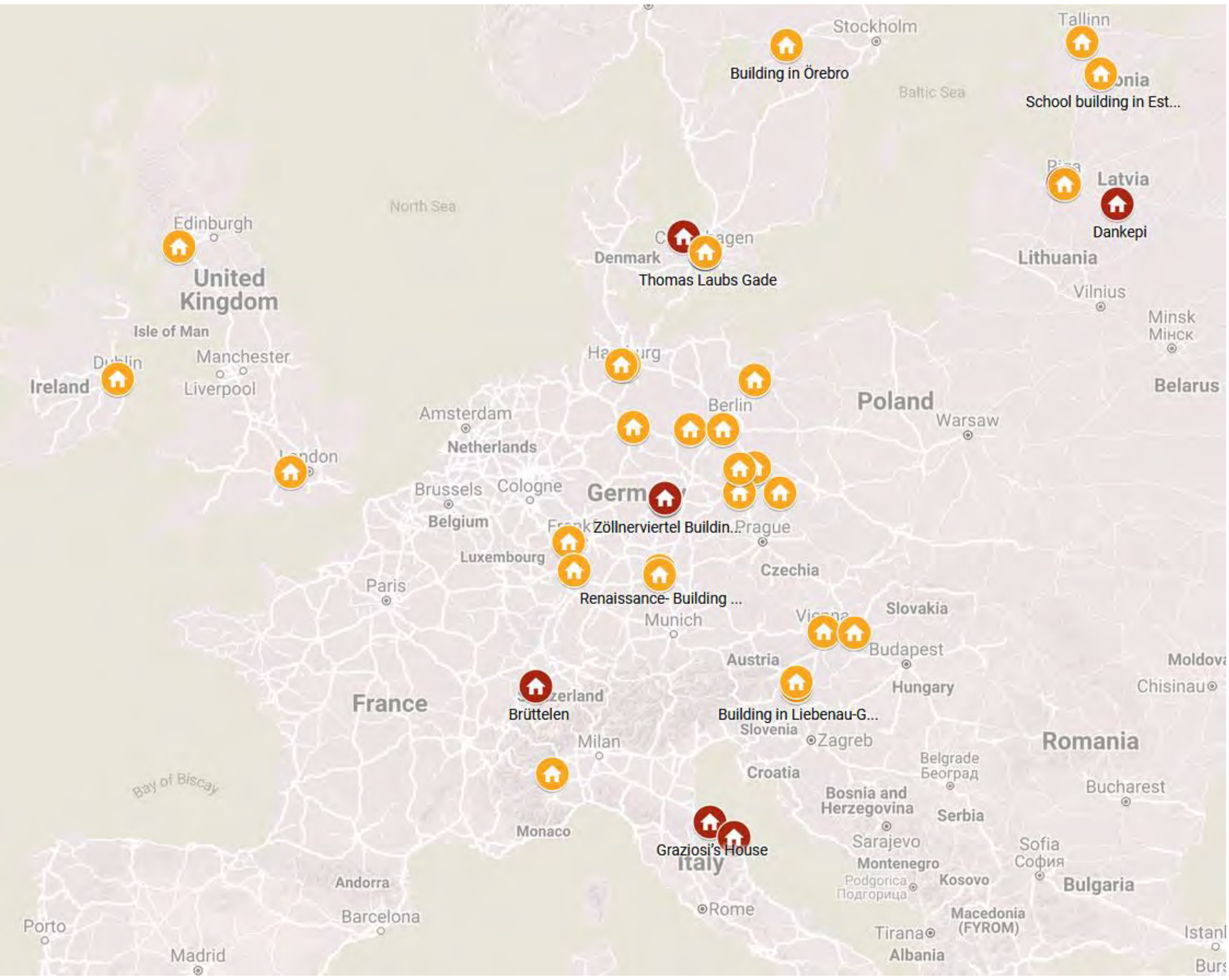


Figure 3: Map showing published case studies (yellow symbols) and RIBuild-internal case study buildings (red symbols). This is a section of the entire map excluding non-European projects.

Further information about wall constructions, the applied insulation systems, year of construction, monitoring period etc. is available in the map. The appendix of this report presents a more detailed summary of case studies including the description of the monitoring system, outcome of measurements and simulation, etc.

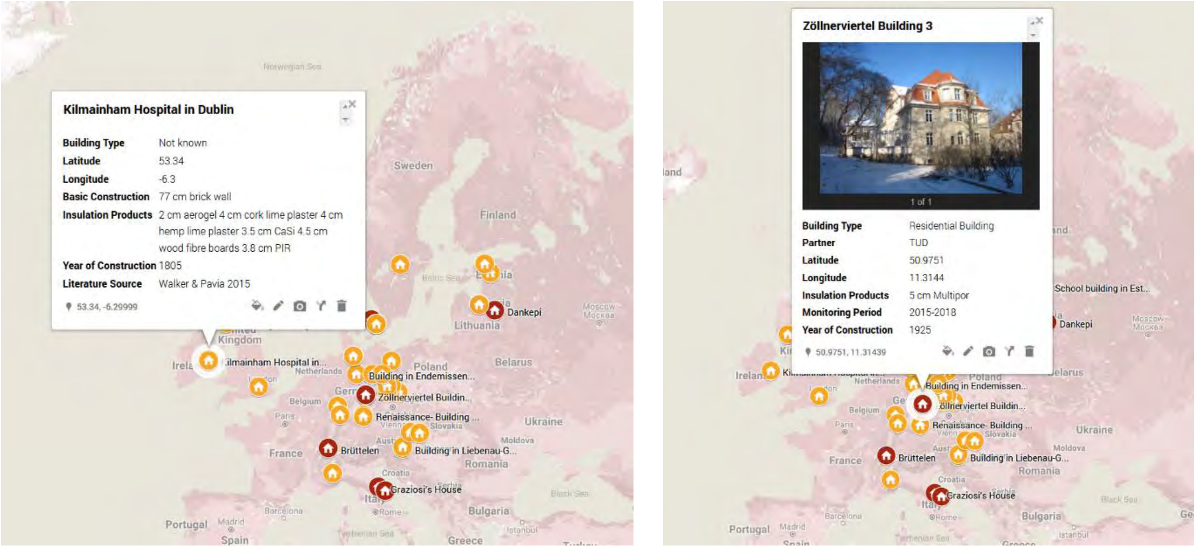


Figure 4: Interactive map showing detailed information for the published case studies (left) and the RIBuild case studies (right).

2.4 RIBuild case studies

A brief description of each RIBuild case study building is presented in Table 1. Detailed information about the wall construction, the applied insulation system, the monitoring system etc. is provided in the Appendix (see Appendix I: Table of RIBuild Case Studies on page 71).

Table 1: Overview of RIBuild case studies with a short description of the buildings.

Building Name (RIBuild Partner)	Picture	Description
Dankepi (RTU) **[Monitoring from 2017-2018]**		The case study building was built in 1893 in Latvia. It was originally used as one family house for one farmer family. During the Soviet times, the basement was used as cattle shed which had led to severe damages of wooden beams and ground floor floors. In 1992, the building was denationalised and the ownership of the building was retrieved by the original owner's family. During the Soviet period the building was poorly maintained and worned out, and the building owner has decided to invest in the renovation of the building in 2006 and improved in 2015.
Spikeri (RTU) **[Monitoring from 2013-2017]**		The case study building was built in 1930 within in a historic red brick warehouse district built between 1864 and 1886 in Riga, Latvia. Before renovation, this naturally ventilated building was used as public restroom while during last years it was utilised as storage facility without heating. The building was poorly maintained for many years and walls were significantly affected by negative impact of weather, groundwater and humans. Renovation of the building was carried out in 2012 – 2013

Catholic Seminar (RTU) **[Monitoring from 2017-2018]**		Catholic seminar is located in Āgenskalns neighbourhood of Riga, Latvia. Āgenskalns is a unique example of architectural symbiosis of international Art Nouveau and buildings created by local German-Baltic architects. The case study building was designed by famous architects Heinrich Sheel and Freidrich Scheffel and was built in 1910. It was built as psychiatric clinic known as Sokolovskis' clinic. Since 1923, it is owned by Catholic church and used as Catholic seminar. During Soviet period, the building was used as hospital and elderly house. Renovation of the building is carried out in 2017
Thomas Laubs Gade (DTU) **[Monitoring from 2015-2017]**		The building is a multi-storey residential building from 1899. The building itself consists of 1300m² spread over 4 floors. The building is built in traditional Danish style, with solid masonry and embedded wooden beams and lath for floor separations. As the style prescribes, the thickness of the masonry is reduced for every floor. The case in question is an apartment on the 4th floor. During renovation in 2015, internal insulation was applied to eastern facade.
Haderslev (DTU) **[Monitoring from 2015-2017]**		The building is located in Haderslev, in the southern part of Jutland, the peninsula of Denmark. The building is located in a residential area with primarily one family houses. The building is a two-floor residential building with 130 m^2 living area, from 1932. The external walls are 1½brick (350 mm) solid masonry. The building is built in typical Danish style with gable roof with eaves, masonry and wooden beams as floor separations. The insulated room is on the 2nd floor.
Meinungsgade (DTU) **[Monitoring from 2015-2017]**		The case building is located in Copenhagen in the borough called Nørrebro. The building is a multi-storey residential building from 1877. The building itself consists of 790 m² spread over five floors. The building is built in traditional Danish style, with solid masonry and embedded wooden beams and lath for floor separations. During renovation in 2014, internal insulation was applied to south and southwestern facade.
Kildevældsgade (DTU) **[Monitoring from 2015-2017]**		The case building is located in Copenhagen, in the borough called Østerbro. Østerbro was created in the 1800s as Copenhagen expanded, and by the 1880s, the multi-story buildings were blooming in Østerbro. Kildevældsgade 69 is part of a project called Klimakvarter Østerbro. The building is a multi-storey residential building from 1905. The building itself consists of 700 m² spread over four floors. The building is built in traditional Danish style, with solid masonry and embedded wooden beams and lath for floor separations. During renovation in 2015, internal insulation was applied to northern facade.

Graziosi's House (UNIVPM) **[Monitoring from 2017-2018]**		Graziosi's House is a three-storey single-family house, which was built around 1935 in Cattolica, a small sized town next to the Adriatic Sea in Italy. A general retrofitting of Graziosi's House was performed in 2003, to improve the energy efficiency and the indoor comfort. Renovation included the internal thermal insulation of the envelope and other energy retrofit measures, i.e.: replacement of windows, insulation of roof and renewal of the heating and DHW equipment. The on-site experimental activity focuses on the impact of internal insulation on the building envelope, especially near the connection between the wooden beam and the insulated masonry.
Rectorate (UNIVPM) **[Monitoring from 2016-2018]**		Rectorate Palace is a Nineteenth-century palace built in 1866 in a Renaissance revival style in Ancona, Italy. The building has a rectangular shape, with a building base area of ca. 920 m², and it is structured around a central courtyard. The front of the building has a three-storey high façade, composed by a five arches arcade on the ground floor. The rest of the structure is five-storey high. After the earthquakes in 1930 and 1972, structural interventions were performed. During last intervention, plants were renovated. Thermal insulation operations were not actually carried out, but studies on their feasibility are programmed.
Zöllnerviertel 1 (TUD) **[Monitoring from 2015-2018]**		The building was erected in 1925 within a living quarter, which was built in the 1920th in South-West Weimar. It was originally used as residential building with living areas on two levels. The roof and the basement were originally not occupied. External walls in the basement are made of Travertine; walls in the upper floors are made of bricks. The retrofit of the building was carried out in 2015 with TecTem insulation of 70 mm thickness, a renewal of windows, heating system, domestic hot water system and mechanical ventilation.
Zöllnerviertel 2 (TUD) **[Monitoring from 2015-2018]**		The building was erected in 1925 within a living quarter, which was built in the 1920th in South-West Weimar. It was originally used as residential building with living areas on two levels. The roof and the basement were originally not occupied. External walls in the basement are made of Travertine; walls in the upper floors are made of bricks. The retrofit of the building was carried out in 2015 with Multipor insulation of 80 mm thickness, a renewal of windows, heating system, domestic hot water system and hybrid ventilation.
Zöllnerviertel 3 (TUD) **[Monitoring from 2015-2018]**		The building was erected in 1925 within a living quarter, which was built in the 1920th in South-West Weimar. It was originally used as residential building with living areas on two levels. The roof and the basement were originally not occupied. External walls in the basement are made of Travertine; walls in the upper floors are made of bricks. The retrofit of the building was carried out in 2015 with Multipor insulation of 50 mm thickness, a renewal of windows, heating system, domestic hot water system and mechanical ventilation.

Brüttelen (HESSO) **[Monitoring from 2014-2017]**		The building is located in the countryside around the commune of Brüttelen, in Canton Bern. It is part of a farm complex, as the main building. It was built according to the construction type of the time, in solid masonry, with the local rubble stones bounded with cement mortar. The roof has wide eaves to protect the facades against the rain. Due to the state of the hundred and forty-year-old building and the owner's demands the renovation was initiated. The building was very costly to heat. The complex was refurbished in 2014 as an accommodation place, to welcome a family in high standard housing. The building monitoring was realised between 2014 and 2017.
Klitgarden (IFLEX, AAU) **[Monitoring from 2017-2018]**		The building is located in Hundested, in the northern part of Zealand about seventy kilometres northwest of Copenhagen, Denmark. Klitgaarden is a free standing single-family house from 1875 in two stories with a total of 221 m^2. The building is erected with solid masonry walls and a foundation of granite boulders on top of a stone foundation. The renovation project of the building aimed for a minimum heating requirement and a preservation of original outdoor facade details. It was finished in 2016. The renovation was motivated by a very high-energy demand for heating and in general the fact that the house had not been used in twenty years.

3 Performance risk factors

The hygrothermal performance of internal insulation systems is depending on a number of conditions and properties related to the construction (initial conditions, properties of the existing wall, constructive joints etc.), the insulation system (built-in moisture, robustness etc.) and interior/exterior climatic boundary conditions. A summary of the risks related to these is given in this section and reviewed in the analysis of the project case studies and the published case studies.

3.1 Risk factors related to the existing wall

Some risk factors for internal insulation are given by the construction itself. The condensation risk within the wall increases with decreasing thermal resistance of the existing wall (small thickness or high thermal conductivity of the wall material) and increasing thermal resistance of the insulation system. This can be directly concluded from the impact of the insulation layer on the temperature conditions within the wall as shown in Figure 5 (left and right).

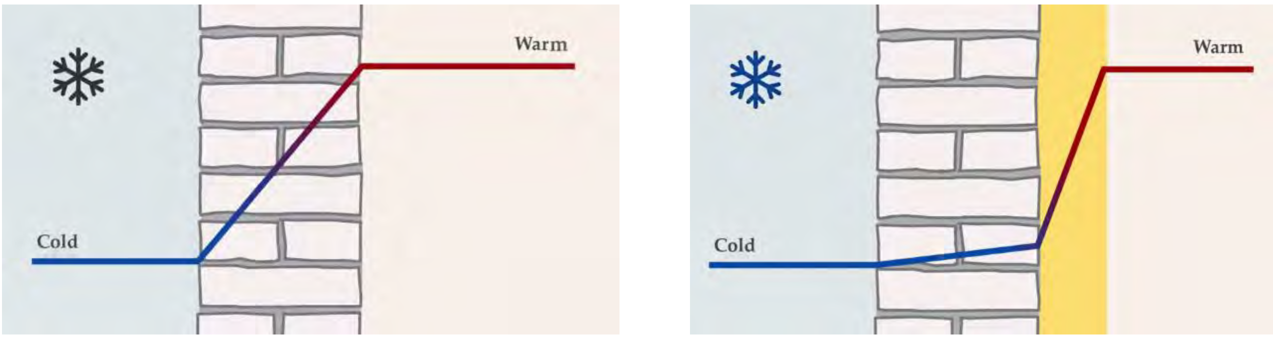


Figure 5: Comparison between the temperature profile of the uninsulated wall (left) and the internally insulated wall (right) (Figures from the RIBuild-video: https://www.ribuild.eu/news/video-internal-insulation-historic-buildings-desirable-risky)

Furthermore, the condensation risk increases with increasing capillary activity resp. capillary suction, addressing the impact of driving rain, which is intensified by low wall thicknesses. The more water is absorbed by the wall surface during driving rain events, the wetter the wall section becomes. A sufficient drying potential is required to eliminate this water. Otherwise, the façade has to be protected from high driving rain loads in a constructive manner (e.g. roof overhang) or with an additional material layer (exterior rendering). As the insulation typically hinders an inward drying process, water could be accumulated in the wall, reducing its insulation effect. This promotes damage processes like mould growth or frost weathering.

Other risk factors related to the original wall should be dealt with before installing internal insulation and are therefore not included in this report. They include salt load of the existing wall, rising damp, exterior rendering with cracks or damaged joints of the masonry.

Constructive details have to be treated in consideration of the whole refurbishment concept. Internally insulated buildings show a higher damage risk at these points as the insulation layer is interrupted by ceilings, partitions etc. In general, problems with these points could be reduced with additional insulation around the weak points. Furthermore, convective leakages at all constructive connections might cause problems as the warm and humid air could condensate at cold inner surfaces.

3.1.1 Wall constructions in published case study buildings

Basic questions of this subchapter are addressing the variety of historic constructions in different European countries (wall thickness, wall material, masonry properties) and according to this, the thermal improvement (thermal resistance of the insulation system). Not all of the listed publications included comprehensive information about the material properties and thicknesses. Therefore, missing values are filled with typical properties of similar buildings based on the provided information of the authors. Table 12 shows a list of analysed published case study buildings.

Table 2: List of published case study buildings with internal insulation. The projects are sorted by year of construction starting with the oldest building. The abbreviations in the column "Type" represent condensate-limiting insulation systems (CL), condensate-tolerating systems (CT) and condensate-preventing (CP).

Location city	Year	Insulation System	Type	Insulation Thickness [mm]	U-Value before [W/m²K]	U-Value after [W/m²K]
Maidenhead	1550	Timber fibre boards	CL	100	1.72	0.34
Torino	1580	Composite boards	CL	60	2.07	0.75
Nürnberg	1583	Calcium silicate	CT	28	2.38	0.97
Görlitz	1728	Calcium silicate	CT	50	2.40	0.74
Drebkau	1794	Perlite	CL	80	1.79	0.39
Dublin I	1805	Aerogel	CL	20	1.34	0.51
Dublin II	1805	Cork lime plaster	CT	40	1.34	0.73
Dublin III	1805	Hemp lime plaster	CT	40	1.34	0.83
Dublin IV	1805	Calcium silicate	CT	35	1.34	0.87
Dublin V	1805	Timber fibre board	CT	45	1.34	0.60
Dublin VI	1805	PIR boards	CL	38	1.34	0.54
Potsdam	1836	Mineral wool	CL	100	1.72	0.28
Eickenrode	1850	Calcium silicate	CT	2.	2.07	0.76
Liebenau I	1850	Cellulose plaster	CT	50	1.24	0.46
Glasgow	1850	PU	CL	125	1.83	0.26
Vienna II	1850	Timber fibre boards	CT	60	1.79	0.55
Örebro	1850	Mineral wool	CL	115	2.07	0.28
Dresden	1870	iQ-Therm	CT	50	1.40	0.43
Vienna I	1880	Reed	CT	50	1.24	0.60
Graz I	1885	Cellulose	CT	80	1.51	0.40
Graz II	1885	Perlite boards	CL	80	1.51	0.40
Graz III	1885	Thermo silit plastering	CT	120	1.51	0.40
Graz IV	1885	Wood fibre boards	CT	30	1.51	0.40
Graz V	1885	Reed	CT	100	1.51	0.40
Wiesbaden	1890	Polystyrene, extruded	CL	55	1.47	0.46
Copenhagen I	1896	Aerowolle	CL	40	1.51	0.40
Copenhagen II	1896	Vacupor	CP	20	1.51	0.60
Senftenberg	1900	Calcium silicate	CT	50	1.57	0.64
Hamburg II	1900	Klimasan	CT	55	1.48	0.72
Hruby Sur I	1906	Sheep wool	CL	130	1.37	0.17
Hruby Sur II	1906	Hemp	CT	130	1.37	0.17
Hruby Sur III	1906	Recycled timber	CT	130	1.37	0.19

Hruby Sur IV	1906	Crushed cork	CT	130	1.37	0.17
Hruby Sur V	1906	Cellulose	CT	130	1.37	0.17
Hamburg I	1907	Calcium silicate	CT	50	1.51	0.45
Wartin	1911	Cellulose	CT	80	2.38	0.46
Ludwigshafen	1912	Polystyrene, extruded	CL	80	1.60	0.34
Boston	1917	PU-foam	CL	75	1.30	0.35
Finsterwalde	1920	Multipor	CL	50	1.51	0.47
Copenhagen III	1920	Composite boards	CT	40	1.83	0.56
Güterfelde	1920	Multipor	CL	50	1.22	0.44
Lawrence	1930	EPS	CL	50	1.55	0.42
Riga I	1940	Aerogel mat	CL	20	1.83	0.27
Riga II	1940	VIP	CP	50	1.83	0.09
Toronto	1950	Spray foam	CL	50	1.20	0.33
Setu	2014	Mineral wool	CL	100	2.10	0.23

A first comparison shows the relationship between the year of construction of the published case study buildings and their heat transmission coefficients (U-value) (Figure 6). There is obviously no relationship between these parameters. The same statement is valid for the relationship between wall thickness, ranged between 260 and 800 mm, and building age as shown in Figure 7.

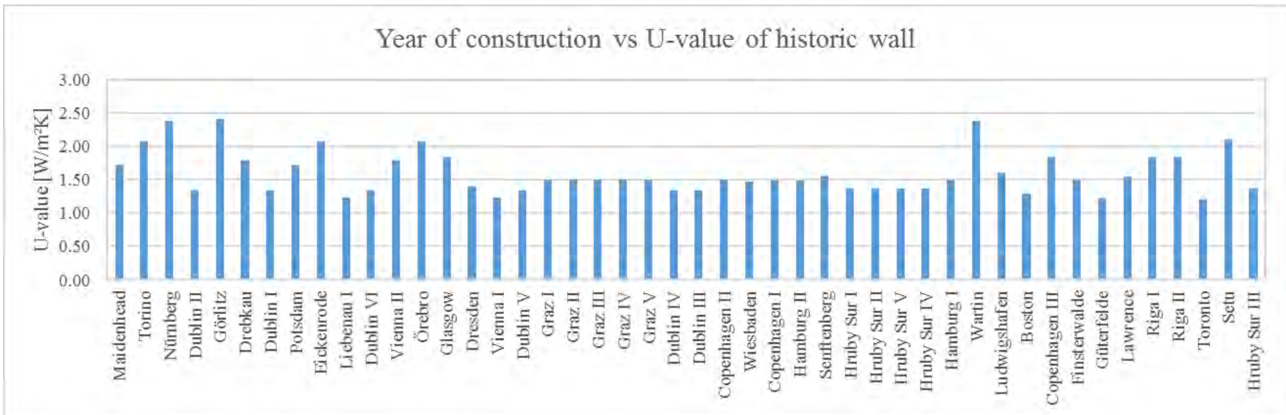


Figure 6: U-value (original historic construction) of published case study buildings ranked by their year of construction (starting with the oldest building from 1550).

Figure 7: Wall thickness (original historic construction) of published case study buildings ranked by their year of construction (starting with the oldest building from 1550).

The majority of buildings shows varying thicknesses for the floors. Most of the buildings were built of bricks in local standard format and at least plastered from inside. Thermal conductivity is mostly not mentioned in the articles but in many cases indirectly given with heat flux or U-value prior retrofit respectively after retrofit. The results of the estimated U-values of the historic construction in comparison with the thickness is presented in Figure 8.

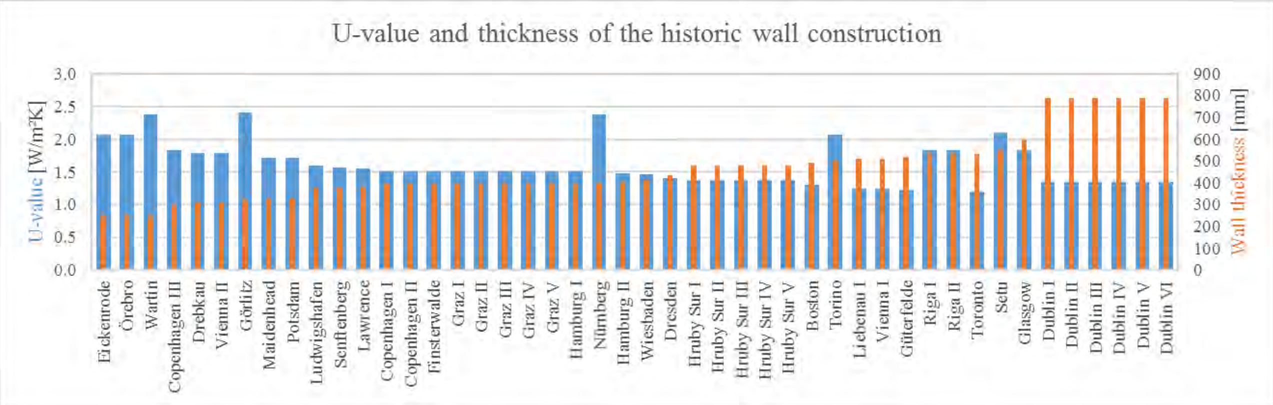


Figure 8: U-value of historic wall construction (blue bars) in published case study buildings compared with thickness of the historic wall construction (orange bars). Buildings are ranked by the wall thickness.

The U-value prior retrofit ranges between 1.2 and 2.4 W/m²K. There is a dependency of this U-value on the thickness of the masonry, as the masonry properties did not vary that much in case of brick buildings. Exceptions are given for constructions made of natural stone, e.g. sandstone for the building in Nürnberg or rubble stone for the building in Torino.

The chosen insulation system (products and thicknesses) is supposed to depend on the local requirements about heat transmission coefficients in historic buildings. This assumption is checked in Figure 9 for the European published case studies and for the thresholds defined for new buildings in each national regulation. This is a consequence of some unclear national regulations resp. missing regulations for existing buildings.

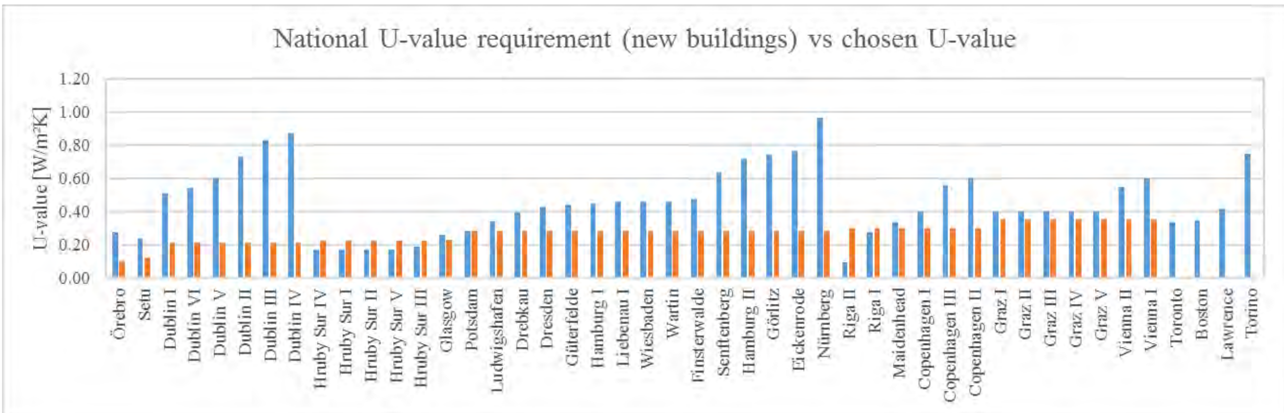


Figure 9: U-values required for newly erected buildings according to the national building regulations (orange bars) compared with U-values of the external walls after renovation of published case study buildings (blue bars). Buildings are ranked by the required U-values.

Apparently, there is also no dependency between these factors. This might be a consequence of the energy regulation diversity and could therefore not be analysed with these values. Firstly, the required values are based on the current standards while the buildings were erected several years ago (first articles from 2003). Secondly, the regulations include many specific determinations whose conditions cannot be validated for the published buildings with their rough descriptions. One example for this diversity could be given with the Swedish regulation (Swedish Regulation for Building Works 2014), which allow a higher U-value for small buildings (0.18 W/m²K) than for bigger ones (0.10 W/m²K). Another exception is provided in the Estonian regulation (Building Act of the Republic of Estonia 2002) according to the intended building usage (non-residential buildings 0.15 W/m²K, residential buildings 0.12 W/m²K). There is also an exception for heritage buildings, e.g. in the German building regulation (Energy Savings Ordinances 2016). Another exception is given in the Danish regulation in case of measures, which would not result in an economic efficiency of the retrofit concept.

The variety in the chosen insulation systems is great and results in U-values for the renovated constructions between 0.1 (VIP, Riga) and 1.0 (calcium silicate: Nürnberg) W/m²K. The planners might have chosen these U-values according to the quality of the existing building in order to limit the impact on thermal conditions within the wall. This assumption was checked in the following graph Figure 10 where the thermal resistance of the existing construction (R-value) is compared with the thermal resistance of the insulation system in the specific case.

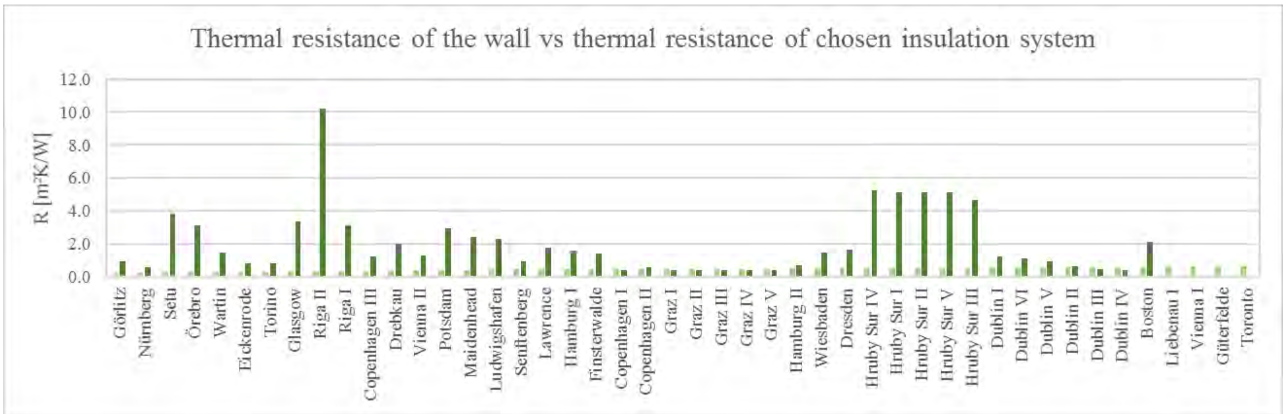


Figure 10: Thermal resistance (R-value) of the existing wall (light green bars) in published case study buildings compared with thermal resistance of the insulation system (green bars). Buildings are ranked by R-value of the existing wall.

There is obviously no relationship between these factors, although a cautious choice of insulation system resistance would be beneficial for a damage-free performance. The variety of chosen insulation products and thicknesses is huge for the analysed buildings. This is shown in Figure 11.

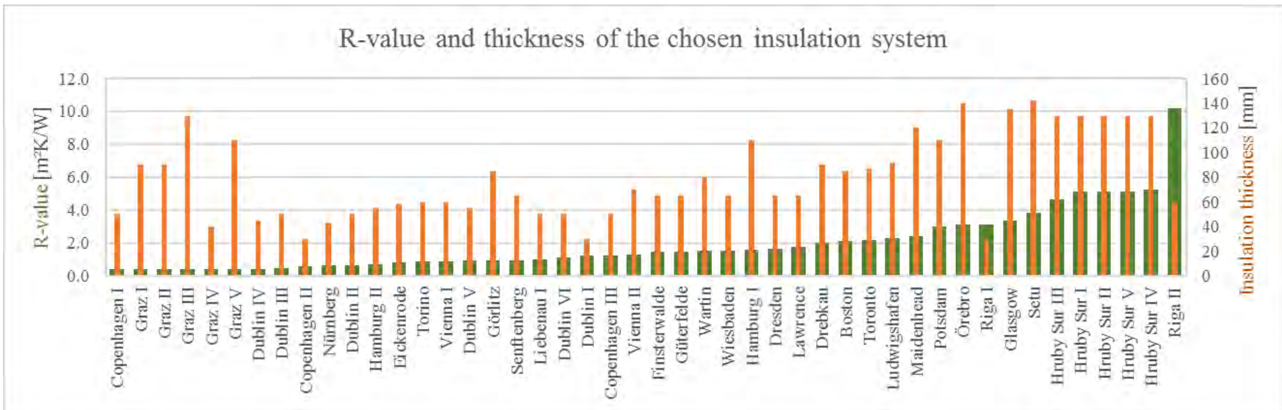


Figure 11: Thermal resistance (R-value) (green bars) compared with thickness (orange bars) of the chosen insulation system in published case study buildings. Buildings are ranked by R-value.

This comparison shows a basic dependency between both factors, although there are some outliers in form of well-performing insulation systems (e.g. Riga I: VIP) and some worse performing systems (Graz: natural materials like reed, cellulose).

3.1.2 Wall constructions in RIBuild case study buildings

Case study buildings included in the RIBuild-project cover a construction period from 1866 (Rectorate building in Ancona) to 1935 (Graziosi's house in Cattolica). Most of the case study buildings is used for residential purpose; some are used as office building or public building (Rectorate, Spikeri, Catholic Seminar).

Locations are spreading from Latvia (Riga, Sece Parish) in the North of Europe over Denmark (Copenhagen, Klitgaarden), Germany (Weimar), and Switzerland (Brüttelen) to Italy (Ancona, Cattolica) in South-Europe.

Table 3: List of RIBuild case study buildings with internal insulation. The projects are ranked by year of construction starting with the oldest building. The abbreviations in the column "Type" represent condensate-limiting insulation systems (CL), condensate-tolerating systems (CT) and condensate-preventing (CP).

Project Name	Year	Insulation System	Type	Insulation Thickness [mm]	U-Value before [W/m²K]	U-Value after [W/m²K]
Rectorate Palace Case A	1866	Calcium silicate	CT	130	0.94	0.28
Rectorate Palace Case B	1866	XPS	CL	80	0.94	0.29
Klitgaarden	1875	iQ-Therm	CL	80	2.02	0.18
Meinungsgade	1877	Kingspan K17	CL	60	1.89	0.27
Dankepi Case A	1893	Mineral wool	CL	150	2.15	0.21
Dankepi Case B	1893	Mineral wool	CL	150	2.52	0.21
Thomas Laubs Gade	1899	iQ-Therm	CL	30	1.89	0.64
Brüttelen	1900	Mineral wool	CL	160	2.43	0.20
Kildevaeldsgade	1905	Kingspan K17	CL	25	1.82	0.54
Catholic Seminar	1910	Mineral wool	CL	50	0.96	0.39
Weimar 1	1925	TecTem	CT	100	1.64	1.10
Weimar 2	1925	Multipor	CT	80	1.64	0.40
Weimar 3	1925	Multipor	CT	50	1.64	0.55
Spikeri Case A	1930	VIP	CP	50	1.24	0.14
Spikeri Case B	1930	PIR	CL	50	1.24	0.32
Spikeri Case C	1930	PIR	CL	100	1.24	0.19
Haderslev	1932	iQ-Therm	CL	80	1.89	0.32
Graziosi's house	1935	EPS	CL	60	1.76	0.48

A summary of U-value average prior retrofit gives 1.66 W/m²K, the value after retrofit is 0.37 W/m²K. This results in an average reduction of the transmission losses via shell constructions (without thermal bridges) of 78 %. However, as internal insulation decreases the temperature in the solid construction, a high impact of thermal bridges has to be expected. Therefore, the net transmission heat loss saving is expected to be much smaller.

Figure 12 shows the thermal quality of the historic constructions for all RIBuild cases in form of the heat transmission coefficients. The starting value ranges from 0.94 W/m²K for the Rectorate building in Ancona, Italy (770 mm of brick) to 2.52 W/m²K for the Dankepi building in Sece Parish, Latvia (600 mm of dolomite masonry). Most of the buildings show, in accordance to the published cases, a brick masonry with varying thickness from 250 over 360 to 770 mm. In the majority of RIBuild case study buildings, the thermal conductivity was measured in the laboratory and yielded values from 0.64 W/mK to 0.86 W/mK. There is no dependency of the existing wall U-value on the year of construction as Figure 12 shows.

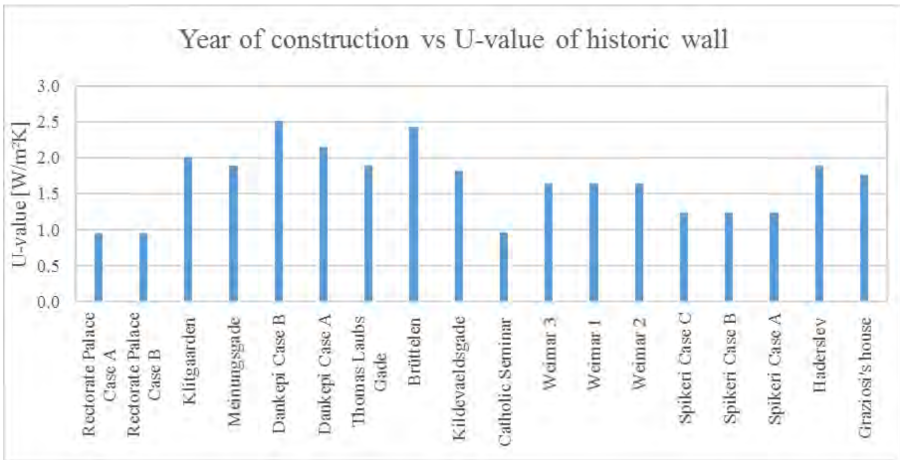


Figure 12: U-value (original historic construction) of RIBuild case study buildings ranked by their year of construction (starting with the oldest building from 1866).

There is no relationship between thickness of the construction and the year of construction as depicted in Figure 13. There might be a relationship between the location latitude and the construction thickness. Nevertheless, the number of analysed cases is too small for an approval of this statement. Further, the wall thickness often is decreasing, so that e.g. fifth floor has a thinner wall than second floor. In addition, not all buildings involved had the same number of storeys.

Figure 13: Wall thickness (original historic construction) of the RIBuild case study buildings ranked by their year of construction (starting with the oldest building from 1866).

As for the published case study buildings, Figure 14 shows that there is a relationship between masonry thickness and U-value of the historic construction because most of the buildings are made of masonry with a limited variation of thermal conductivity. Exceptions from this dependency are the building in Brüttelen (rubble stone) and the Dankepi project in Sece Parish (dolomite). Both constructions are made of a natural stone that has a high thermal conductivity compared to brick.

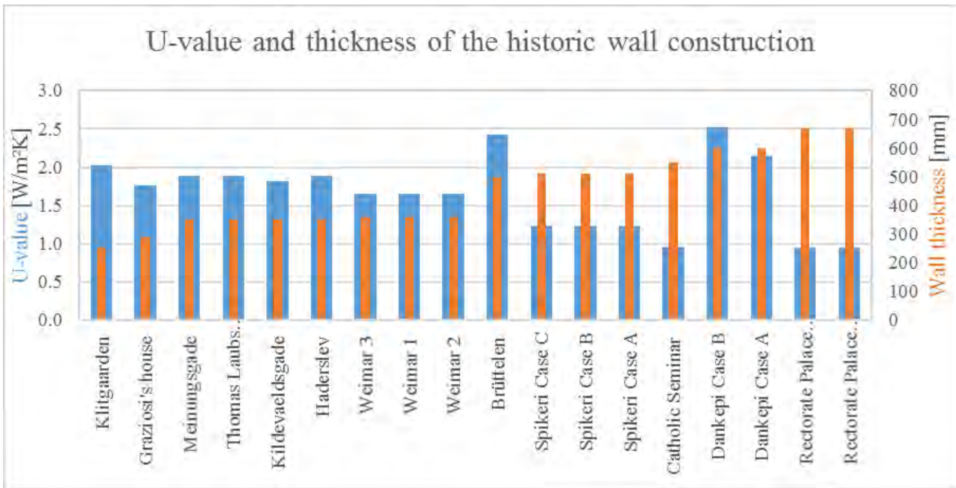


Figure 14: U-value of historic wall construction (blue bars) in RIBuild case study buildings compared with wall thickness (orange bars). Buildings are ranked by the wall thickness.

The chosen U-values in RIBuild case studies show, similar to the published cases, no dependency on the required national U-value for newly erected buildings. It was assumed that the relationship between the U-value thresholds for new buildings in the European countries equals the relationship of these values for building retrofit. However, as stated in the previous comparison for published case studies, these values underlay some exceptions according to the size of the building, the foreseen usage, the protection status etc.

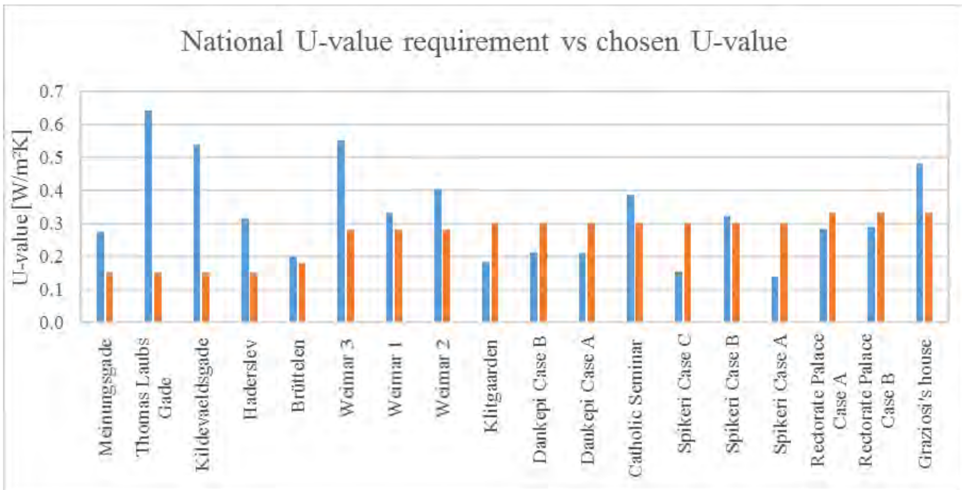


Figure 15: : U-values required for newly erected buildings according to national building regulations (orange bars) compared with U-values of the external walls after renovation of RIBuild case study buildings (blue bars). Buildings are ranked by the chosen U-values.

Figure 16 shows a comparison between the thermal resistance of the existing wall and the chosen thermal resistance of the insulation material. Again, as in Figure 10 on page 16, there is no relationship between both parameters. This could be different in building projects from the practice, where the variety of chosen materials and the caution of the building owners and planners is higher. In these research cases, where high-performance insulation systems were applied (e.g. Spikeri: VIP) and huge thicknesses were chosen (e.g. Brüttelen: > 10 cm mineral wool), the thermal resistance of the existing wall was not an important factor for the choice of the insulation standard.

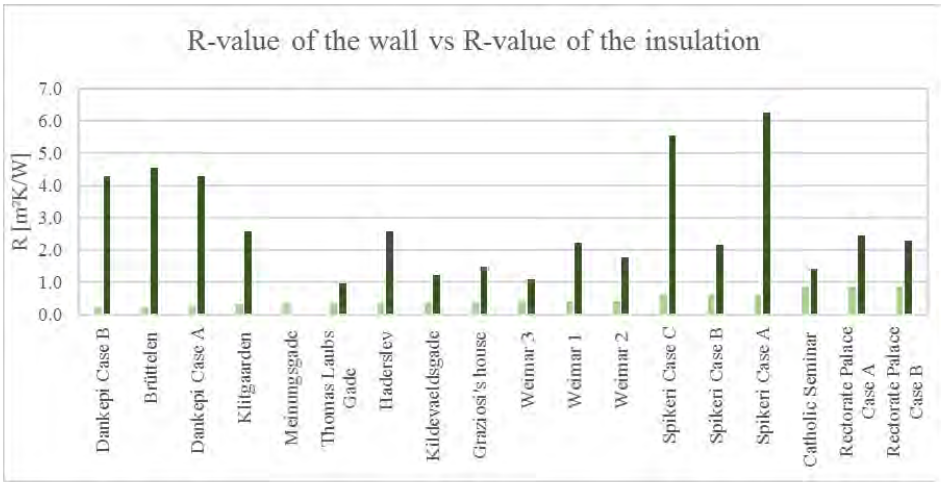


Figure 16: Thermal resistance (R-value) of the existing wall (light green bars) in RIBuild case study buildings compared with thermal resistances of the insulation system (green bars). Buildings are ranked by R-value of the existing wall.

The last comparison addresses the variability of insulation materials as it compares the chosen insulation thickness with the achieved thermal resistance. This comparison in Figure 17 shows the strong dependency of both properties. The bigger the length difference between both bars, the better (green bar much longer than orange bar) respectively worse (green bar much shorter than orange bar) the insulation system is. Despite some exceptions with comparatively low thermal conductivity (e.g. VIP, PIR in Spikeri, TecTem in Meinungsgade) and comparatively high thermal conductivity (e.g. calcium silicate in Rectorate Palace), the thermal conductivity shows a relatively low variation of around 0.033 W/mK from about 0.31 to 0.45 W/mK.

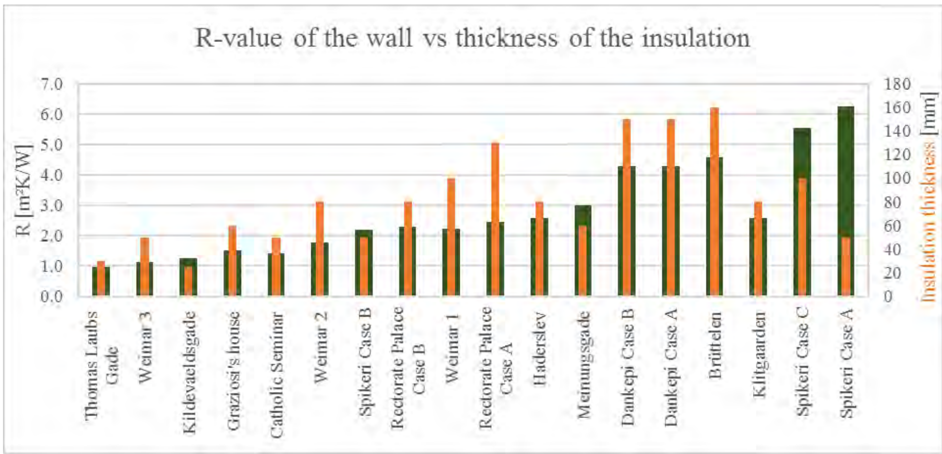


Figure 17: Thermal resistance (R-value) (green bars) compared with thickness (orange bars) of the chosen insulation system in RIBuild base study buildings. Buildings are ranked by R-value.

3.1.3 Conclusions about the case study constructions

The construction evaluation of published and RIBuild case studies yielded an insight into some of the wall and insulation characteristics. They show the variability and the typical properties of historic wall constructions prior retrofit, the variability of chosen insulation systems, the typical reduction of U-values and its comparisons with national requirements. Some of these values are summarized in Table 4.

Table 4: Key characteristics of historic wall construction and refurbished construction properties in published and RIBuild case studies.

Characteristics		Published case studies	RIBuild case studies
Historic construction	Share of brick constructions [%]	93.3 %	83.3 %
	Share of exposed brickwork [%]	35.5 %	33.3 %
	Share of plastered brickwork [%]	64.5 %	66.6 %
	Average U-value [W/m²K]	1.60 W/m²K	1.66 W/m²K
	Average masonry thickness [mm]	465 mm	452 mm
Refurbished construction	Average U-value [W/m²K]	0.46 W/m²K	0.33 W/m²K
	Average insulation thickness [mm]	66.0 mm	82.5 mm
	Average insulation R-value [m²K/W]	1.97 m²K/W	2.94 m²K/W
	Share of capillary active systems [%]	52.2 %	38.9 %
	Share of vapor retarding systems [%]	43.5 %	55.6 %
	Share of vapor tight systems [%]	4.3 %	5.6 %
	Average U-value reduction [%]	70.8 %	79.4 %

The majority of analysed buildings (93 % in published case study buildings, 83 % in RIBuild case study buildings) was built of brick with a plastered brickwork (65 % published, 67% RIBuild). In some cases, the basement resp. first floor walls were made of natural stone and only the upper floors consisted of pure brick masonry. In this case, applied natural stones were sandstone and rubble stone. The masonry thicknesses varied between 250 and 790 mm with an average of 465 mm (published) resp. 452 mm (RIBuild). The average U-value of published cases was 1.60 W/m²K for the historic constructions and 1.66 W/m²K for RIBuild case studies. This equals an R-value of 0.48 m²K/W (published) resp. 0.49 m²K/W (RIBuild). A graphical evaluation of the dependency between year of construction and U-value as well as thickness of the historic wall constructions yielded a random distribution. The same is supposed for the dependency on the location latitude. On the other hand, the material properties of the historic constructions show a low variability with mainly brick masonry that showed a thermal conductivity of about 0.65 to 0.85 W/mK. Walls made of solid natural stone like rubble stone or sandstone with a considerably higher thermal conductivity of about 2 W/mK are an exception.

Achieved insulation levels for the retrofitted constructions differ more between published and RIBuild-internal case studies. The provided reduction of transmission losses through undisturbed constructions (U-value reduction) is about 80% for the RIBuild cases, while the published cases showed an average reduction by ca. 71 %. As the original transmission coefficients of the wall are nearly the same, this is a consequence of a higher insulation layer thickness (about 66 mm in published cases, about 83 mm in RIBuild cases). Finally, provided U-values of the retrofitted walls are on average 0.46 W/m²K for the published cases and 0.33 W/m²K for the RIBuild cases. The maximum U-value was realized in a comparatively early case study project from 2003 in Nürnberg. It shows a value of 0.97 W/m²K with a small insulation layer of less than 30 mm calcium silicate. The minimum value was provided by a comparatively new case study building from 2014 resp. 2017 via vacuum insulation panel (VIP) system and a value of less than 0.095 W/m²K.

For selected constructions of both case study types (published and RIBuild), comparisons between calculated and measured U-values were performed. The result was diverse as some of the values showed a small deviation to the calculated values, e.g. Dankepi in Sece Parish, Latvia (measured for PIR construction: 0,19 W/m²K, calculated: 0,21 W/m²K) while others were far away from the calculated level, e.g. Adjutant General's Building in Dublin, Ireland (measured for PIR construction: 0,54 W/m²K, calculated: 0,41 W/m²K, (Walker & Pavia, 2015)). This could be attributed to different reasons, e.g. the selection of the measurement period, the irregularities in the wall, the calculation assumptions (brick-mortar fraction, surface transfer coefficients etc.) or euphemistic thermal conductivity data provided by the producers or testing institutions.

An evaluation of the constructions resulted furthermore in the statement that chosen thermal resistance of the insulation system was not defined in the context of existing wall thermal resistance. This is surprising as the relationship between these values is decisive for the change of thermal conditions in the wall and thus the potential damage risk. A possible dependency of the chosen insulation resistance on the level of driving rain protection of the existing wall (e.g. provided via exterior rendering, hydrophobizing, clinker brick cover) cannot be evaluated for all cases, especially for the published ones, as this information is mostly not provided. Probably, this was considered because all constructions with resistances higher than 4.3 m²K/W provided either a constructive driving rain protection (e.g. Brüttelen: roof overhang, protecting landscape) or a hydrophobizing layer (e.g. Spikeri in Riga) or a renewed exterior rendering (e.g. Hruby Sur: lime plaster outside). Some showed even a combination of several factors (e.g. Brüttelen: also exterior rendering).

3.2 Risk factors related to the insulation system

3.2.1 Principles of insulation systems

According to the moisture and heat transport processes in the construction, different insulation systems induce different damage risks. International literature mentions three different principles of insulation systems: condensate-preventing systems, condensate-limiting systems and condensate-tolerating systems. The first type is vapour tight and prevents vapour diffusion through the construction completely. Examples for this type are foam glass, which is a vapour tight material itself and vacuum insulation panels, which is tightened and evacuated by the help of foil layers around a stable base material.

The second type comprises systems, which reduce the vapour transmission into the insulation material with an additional foil that is placed at the inner side of the insulation material. The level of vapour transmission is limited in order to keep the threshold values for vapour accumulation within the materials. This limitation is necessary, as the drying potential of these constructions is strongly reduced towards room side and anyway outwards. Examples for this system are mineral wool and EPS. Both insulation materials are widely used. They are relatively cheap in relation to their thermal performance.

The third group of insulation materials are capillary active materials. They tolerate a vapour diffusion into and thus water accumulation in the wall as they allow a distribution and drying of accumulated condensate within the wall construction and backwards to the room air through its small capillaries and its high vapour permeability.

Some benefits and risks for the use of the different types of insulation systems are given in Table 5.

Table 5: Advantages and disadvantages (including damage risks) for three different types of interior insulation systems according to their transport characteristics.

	Advantages / Disadvantages	Risks
Condensate-preventing insulation systems	+ Enables dry constructions without condensate accumulation + Independent on room climate (also functioning with high indoor air moisture load) − Expensive materials/systems − Labour-intensive workmanship − No vapor drying potential in case of moisture loads in the wall − No liquid water distribution in case of local water accumulation	• Misjudgement of historic construction properties (rendering, masonry) and thus moistening of the wall (e.g. driving rain) • Retention of high moisture content in the existing construction (e.g. due to rising damp and low drying potential) • Improper workmanship resulting in leaky board joints and air stream behind the insulation layer

Condensate-limiting insulation systems	+ Cheap solution + Case adapted selection of vapor permeability (foil) + Usually no built-in moisture from the insulation system − Labour-intensive workmanship − Reduced vapor drying potential in case of moisture loads in the wall − Strong reduction of moisture and heat buffering effect of the walls − No liquid water distribution in case of local water accumulation	• Misjudgement of historic construction properties (rendering, masonry) • Retention of high moisture contents in the existing construction (e.g. due to rising damp) • Retention of high built-in moisture contents from the insulation system • Improper workmanship resulting in leaky board joints and air stream behind the insulation layer • Insufficient durability of sealing tapes and sealing masses and thus leakages and air stream behind the insulation • Perforation of foils by the tenants or workmen and thus leakages and air stream behind the insulation
Condensate-tolerating insulation systems	+ Robust system in case of improper workmanship or local damage spots (distribution of condensate) + Moisture and heat buffering effect of the walls kept − Labour-intensive workmanship to prepare the plane and smooth ground, place the boards etc. − High effort for the system design by the engineers (simulations) − Not suitable for permanently high vapor loads in the room air − Reduced thermal performance (higher thermal conductivities) compared to other systems − In many cases high built-in moisture loads (mortars, plasters)	• Misjudgement of historic construction properties (rendering, masonry) • Retention of high built-in moisture contents from the insulation system • Improper workmanship resulting in inconsistent connection of the system layers and thus interrupted capillary contact with reduced distribution of condensate or even convection behind the boards and thus condensate accumulation • Perforation of the boards by dowels or other elements and thus local thermal bridges • Selection of unsuitable interior finishing material and thus prevention of vapour exchange with room air

In addition to these specific risks, general risks have to be considered. One of these risks is the misjudgement of the historic construction. This includes properties of the masonry that influence the performance of the insulation system remarkably, e.g. the liquid water absorption coefficient or the vapour permeability of the masonry and the mortar. It addresses furthermore the properties of the insulation system ground, which has to provide a sufficient bearing capacity and a resistant surface (e.g. not sanding). Another practical risk is the underestimation of required drying times. Adequate drying periods are necessary if additional moisture is added to the construction, for example via levelling rendering of uneven walls or a renewal of interior rendering in general. In particular, it is required for historic constructions that show a high moisture load and for retrofit constructions that include themselves water, e.g. insulation rendering.

3.2.2 Systems in detail

Condensate-preventing insulation systems avoid water vapour diffusion from the indoor air into the wall completely. They include a layer acting as a vapour barrier and are also known as vapour tight systems. The vapour barrier layer has to be placed close to the innermost side of the construction in order to provide a low vapour pressure level in the insulation layer, where the strong temperature drop is given. There are several product options for the vapour barrier layer. It could be a vapour tight insulation (e.g. cellular glass boards connected with bitumen) or a tight internal facing shell (e.g. aluminium foil at the room side of a condensate-limiting insulation material). There are furthermore composite boards, which include a core insulation material (e.g. Perlite in some VIP boards) and an additional vapour barrier around (e.g. for VIP an aluminium foil, which is furthermore preserving the vacuum).

Condensate-preventing insulation systems disable the exchange of vapour and liquid water between the construction and the room air. Therefore, it is primarily applied for building resp. room types with a high vapour pressure level of the indoor air, e.g. indoor swimming pools or bathrooms. It could also be used for the avoidance of water transfer in the opposite direction, e.g. if moisture from the construction is to be expected. Indeed, the missing interaction between construction and room climate also means, that there is nearly no re-drying potential of the construction towards room air. This might be a problem in case of increased water loads from outside (e.g. driving rain) and furthermore for the stability of the indoor air climate.

A condensate-preventing insulation system is therefore also vulnerable for leakages and a resulting unwanted convective vapour penetration. This requires a careful execution of details (e.g. connections at windows, ceilings) and a sufficient driving rain protection of the façade.

Condensate-limiting insulation systems reduce the water vapour diffusion from indoor air into the wall by the help of a vapour retarding layer. The properties of this layer resp. foil is defined in terms of condensate limitation in the interstitial condensation layer. According to the national standards, different threshold values are used, e.g. one kilogram condensate per square meter wall construction in the German standard for common materials. Timber materials require more strict thresholds. The limitation of vapour diffusion implies a drying potential of penetrated moisture from the wall into the indoor air and a hygrothermal interaction between wall construction and indoor climate. A moisture buffer effect is therefore present, although small.

Condensate-limiting insulation systems show a wide variety of material resp. system properties. Furthermore, there are special types of vapour retarding layers, one of which are moisture-adaptive vapour retarders. These foils provide a higher vapour diffusion resistance if indoor air is humid and the wall is dry than for the opposite situation. This promotes drying of the construction during summer time or other beneficial weather periods. The typical condensate-limiting insulation system consists of a facing shell (e.g. gypsum plasterboards), a vapour retarder, and a substructure (e.g. wooden stud frame) with the embedded insulation mats, that is fixed to the existing wall. Another type is composite boards with a vapour retarder lamination on top. Some insulation materials provide the vapour retarding function themselves and do not require an additional foil.

The difficulty of both condensate-limiting (vapour tight) and condensate-preventing insulation systems is the number of connections within the system (e.g. board joints) and with the adjacent constructions (e.g. windows). This implies several risks of leakages, especially those resulting from bad workmanship and insufficient durability of the connection materials. Both prerequisites, precise workmanship and durability of applied materials, is necessary for the provision of airtight connections for all linked constructions and elements within the system. In case of leakages, warm and humid room air would penetrate the construction and flow behind the insulation system, where it cools down and condensates. Suchlike introduced condensate masses provoke a fast and risky moisture accumulation that presents a multiple of the possible vapour diffusion condensate in these constructions. Another risk of these systems is given by its sensitivity for room-side mechanical manipulation. This could be a consequence of further building work (e.g. electric installation) or utilization (e.g. drill holes for pieces of furniture).

Condensate-tolerating or capillary active insulation systems show a very low resistance to water vapour diffusion. In case of a high vapour pressure difference between indoor and outdoor air, this results in condensation between insulation layer and the existing wall. The applied materials of these systems show a multitude of pores with small diameters, which approve an efficient suction and distribution of condensate within the insulation system. Consequently, a fast drying process from the boards to the room air is promoted whenever the indoor air relative humidity is low enough. There is consequently a strong interaction between wall and indoor air. The moisture buffer effect in both directions (drying of the wall towards indoor air and moisture absorption from indoor air by the wall) is the highest of all three types of insulation systems.

Moreover, this type of insulation system is very robust. It functions without a foil that could be destroyed by penetrations made by construction workers or tenants. In case of voids, convective inlet is limited.

In contrast to condensate-limiting and condensate-preventing systems, capillary active systems are always fixed the existing wall over the whole surface. This could be done with a glue mortar or by the system itself (plaster insulation systems). It is the basic requirement for the capillary connection from the insulation system to the construction. This characteristic avoids, in case of proper workmanship, any convective inlet of room air behind the insulation system. To ensure that these systems maintain their capillary-active behaviour, the use of a diffusion-open paint or similar at the inner surface is required and in some cases, special arrangements are needed for hanging heavy things upon the walls, e.g. TV screens.

3.2.3 Insulation systems in published case studies

The majority (52.2% resp. 24 out of 46 constructions) of evaluated published case studies represents the group of condensate-tolerating insulation systems (Figure 18). Within this group, mainly calcium silicate, timber fibre and cellulose are applied. With the exception of mineral plaster and calcium silicate, insulation material of this group contain organic, natural ingredients. Some of them consist of a base rendering material, which is supplemented with insulating entrapments. This is true for reed, hemp, cork and cellulose. The other insulation products (timber fibre, calcium silicate) are boards.

The group of condensate-limiting systems (share of 43.5%) shows a huge variety of products compared to the group of condensate-tolerating systems. There are eleven different products out of 20 cases in this group compared to seven different products out of 24 cases for the group of condensate-tolerating resp. capillary active materials. Mostly used products are mineral wool, polyurethane, extruded polystyrene. The group of composite boards includes systems that combine different products and partially different principles (e.g. iQ-Therm with a combination of Polyurethane with capillary active cores).

Among the group of condensate-preventing systems, only vacuum insulation panels were applied in two cases out of 46 constructions, representing a share of 4.3%.

Figure 18: Sunburst diagram showing the share of different insulation systems in published case studies grouped by their insulation system class: condensate-tolerating (green), condensate-limiting (blue) and condensate-preventing (orange).

A comparison of average thickness and average thermal conductivity in the published case study buildings show the smallest dimension (35 mm) and lowest thermal conductivity (0.006 W/mK) for the group of condensate-preventing systems, in this case the two VIP constructions (Figure 19). Condensate-tolerating systems show in comparison, a smaller thickness (65 mm) of the insulation layer and paradoxically also a higher thermal conductivity (0.042 W/mK). This leads to the conclusion that the lower thermal performance of these condensate-tolerating systems is not balanced with an increased thickness. The fact that many of these capillary active insulation systems are rendering systems with a limited possible thickness might play a role in this context. Condensate-limiting systems used in the published case study buildings did have an average thickness of 71 mm and shows an average thermal conductivity of 0.033 W/mK.

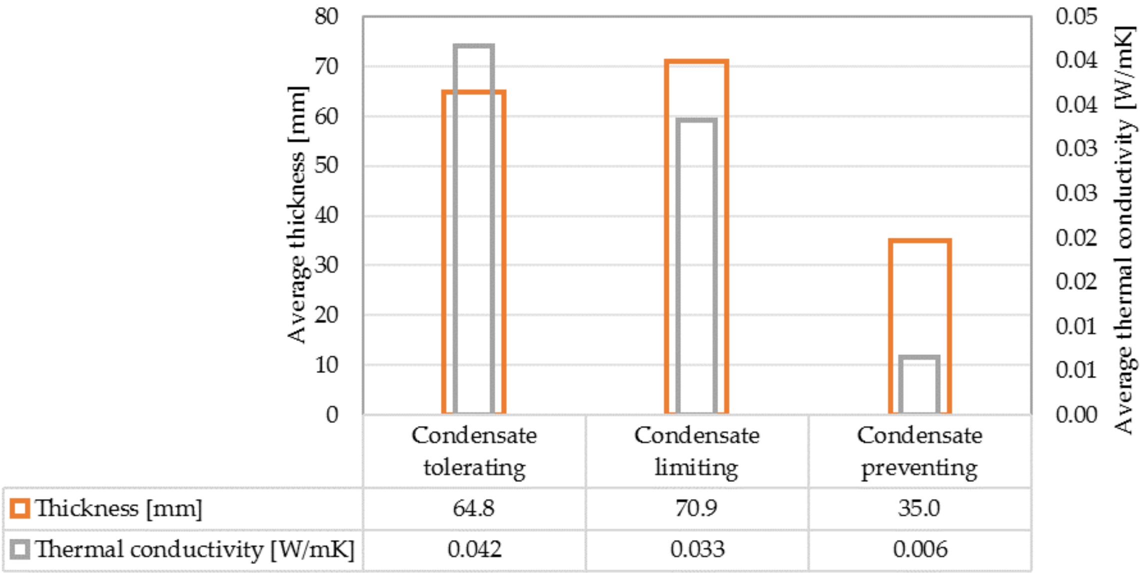


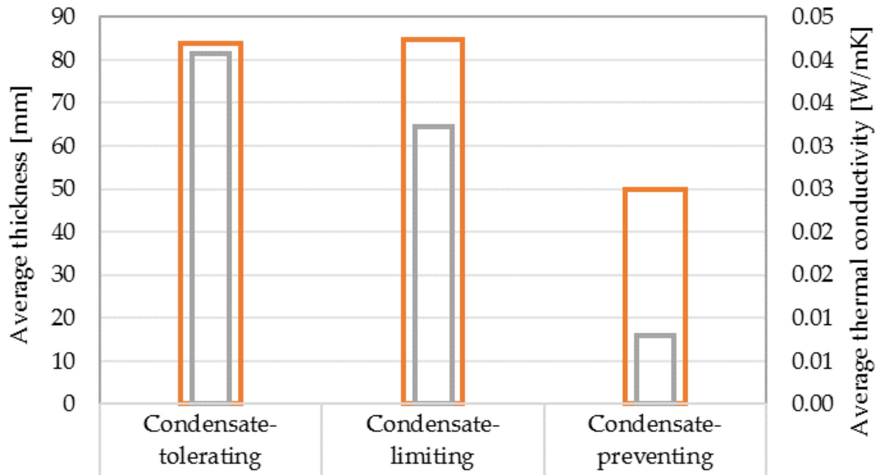
Figure 19: Average thickness and average thermal conductivity for published case studies sorted by insulation group.

3.2.4 Insulation systems in RIBuild case studies

RIBuild case studies show a majority (72.2%) of condensate-limiting insulation systems in contrast to the published case studies. Again, the product variety among this group is high (Figure 20). In addition to the published case studies, two projects applied resol rigid foam insulation boards (Kingspan, Denmark). These boards are made of Bakelite and provide a low thermal conductivity of about 0.021 W/mK. The other products, composite boards (Mineral wool, iQ-Therm, EPS, PIR) were already applied in published cases. Again, mineral wool is the most frequently used (22%). Among the condensate-tolerating products, calcium silicate and mineral boards (products Multipor and TecTem) were used. However, the share of capillary active materials in RIBuild projects is less than one quarter (22.2%).

Figure 20: Sunburst diagram showing the share of different insulation systems in RIBuild case studies grouped by their insulation system class: condensate-tolerating (green), condensate-limiting (blue) and condensate-preventing (orange).

The comparison of thickness and thermal conductivity for each insulation group shows the same relationship as for the published case studies. The lowest thermal conductivity and thickness is given by the condensate-preventing products (Figure 21). Again, this group is solely represented by vacuum insulation panels of a thickness 50 mm and a thermal conductivity of less than 0.01 W/mK. In contrast to the published cases, the thickness difference between condensate-tolerating and condensate-limiting systems is neglectable and ranges around 84 mm. This is much more than for the published cases with an average thickness of 66 mm. Eventually, this can be attributed to the retrofit year, as the RIBuild cases are younger and definitely following the tendency of an increasing insulation standard. Nevertheless, the average thermal conductivity among the condensate-limiting systems (0.032 W/mK) is definitely lower than for the condensate-tolerating systems (0.041 W/mK). Both values are slightly lower than for the published case studies (0.033 and 0.042 W/mK) and show the same relationship as for these cases.



	Condensate-tolerating	Condensate-limiting	Condensate-preventing
Thickness [mm]	83.75	84.62	50.00
Thermal conductivity [W/mK]	0.041	0.032	0.008

Figure 21: Average thickness and average thermal conductivity for RIBuild case studies sorted by insulation group.

3.2.5 Conclusions about the case study insulation systems

The analysis of published and RIBuild internal case studies provided an overview of applied insulation systems, insulation thicknesses and thermal conductivities. It was concluded that among all projects, condensate-limiting systems are most frequently used (ca. 50%). Condensate-tolerating systems are also common (ca. 45%) and condensate-preventing systems are rare (ca. 5%).

The analysed cases included only vacuum insulation panel projects for the group of condensate-preventing systems. These VIPs showed the best thermal performance of all insulation systems with an average thermal conductivity below 0.01 W/mK and furthermore the smallest mean insulation thickness of about 40 mm.

Condensate-limiting systems showed a medium thermal conductivity of 0.032 W/mK and an average thickness of about 77 mm. This average thickness differs among published and RIBuild case studies. For the latter, about 85 mm were common; while for all published cases, 71 mm were typical. In comparison to condensate-tolerating systems, this group of materials shows both, lower thermal conductivity and higher insulation thickness. Therefore, the thermal resistance of these products is remarkably better than for the group of condensate-tolerating insulation products in the actual cases studied. As mentioned at the beginning, most common material in this group is mineral wool. Further frequently used condensate-limiting products are EPS (expanded polystyrene), XPS (extruded polystyrene), PU (polyurethane), composite boards and perlite insulation. Most of them are condensate-limiting insulation materials, supplemented with a vapour regulating foil and an interior finishing.

Capillary-active resp. condensate-tolerating products are applied in a medium thickness of 68 mm within all analysed case studies. Again, the typical thickness is higher for the RIBuild-internal case studies (84 mm) than for the published cases (65 mm). The average thermal conductivity is about 0.042 W/mK. Most common materials of this group are calcium silicate, timber fibre, cellulose and mineral boards. These systems require suitable levelling mortars, glue mortars and interior finishing ensuring the capillary connection within the envelope construction.

3.3 Risk factors related to constructive details

A ruling risk in the application of internal insulation is the interruption of the insulation layer by all embedded constructive details like ceilings, windows, partitions, roof etc., exemplified in Figure 22.

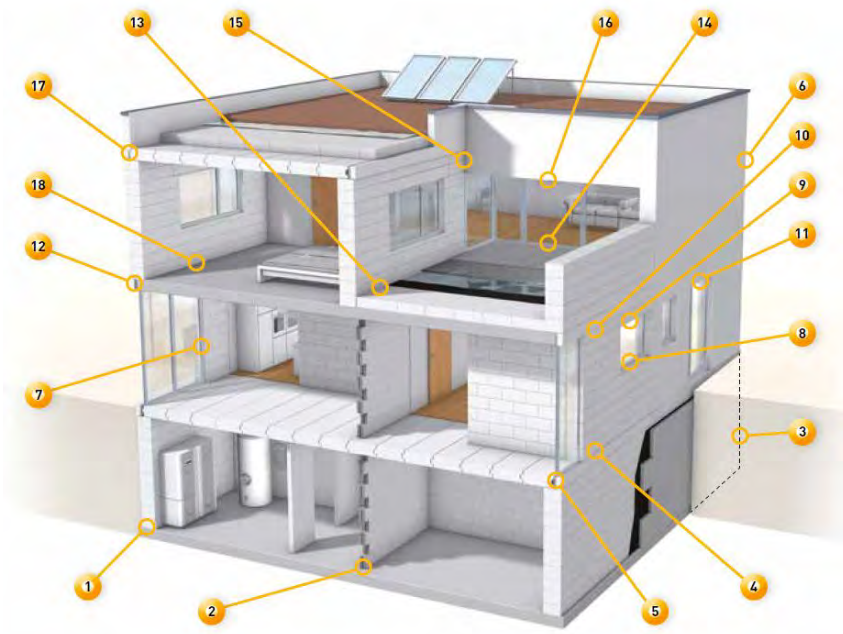


Figure 22: Overview of possible thermal bridges resp. constructive joints in (internally insulated) buildings, e.g. residential buildings (Griebel, et al., 2015)

This interruption of the insulation layer by linked constructions provokes two main differences in comparison with externally insulated buildings. Fist consequence is the higher construction work effort for the provision of a closed airtight envelope at these connective points in order to prevent convective heat losses. The second consequence is the thermal treatment of these details in order to prevent high transmission heat losses. External insulation leads to a warm-up effect of the existing wall construction as the insulation is placed outside. Additionally, external insulation is added in a relatively continuous layer around the buildings without being interrupted or penetrated by constructive elements apart from windows and similar. The impact of thermal bridges is therefore also present to a less extent than for the uninsulated building. In contrast, internal insulation results in a colder existing wall construction. It leads furthermore to an interruption or reduction of the insulation at these constructive connection points. Both factors provoke an increased heat loss via thermal bridge areas. Damage risks like surface condensation inside are therefore higher than for externally insulated buildings.

3.3.1 Constructive risk factors in published case studies

Table 6 provides an overview of published case studies concerning the thermal bridge points. Evaluated details in these projects are mainly three, the exterior wall corner, joist ends of the ceiling construction in the masonry and connections around windows (windowsill, window reveal). Table 6 lists analysed details in the projects and the outcome of this analysis. Each evaluated construction is marked with a symbol for critical conditions in the constructions (-) and one for uncritical conditions (+). According to the analysed case studies, critical conditions could be a permanently high relative humidity level above 80% or a permanently high moisture content in the wooden parts above 20 Vol-%. These critical conditions could be measured permanently (entry “-“) or only during the drying phase within the first years of measurements (entry “-(ini)”). There might also be cases, in which high, but uncritical conditions were measured in the drying-out phase and reduced levels were recorded later on (entry “+(ini)”). There is no documentation of cases, where uncritical conditions were measured initially and conditions that are more critical developed afterwards.

Table 6: List of published case studies with a summary of documented damage resp. damage indicators in different construction types. The projects are ranked by thermal resistance of the applied insulation layer (Rins).

Project	R_{ins} [m²K/W]	Analysed constructive points			
		Wall	Wall edge	Joist end	Window
Riga II	5.15	-			
Hruby Sur IV	5.15	Only temperature measurements			
Hruby Sur V	5.15	Only temperature measurements			
Hruby Sur II	4.68	Only temperature measurements			
Hruby Sur I	3.84	Only temperature measurements			
Hruby Sur III	3.38	Only temperature measurements			
Setu	3.12	-		-	
Glasgow	3.11	-(ini)			
Riga I	2.97	-			
Örebro	2.40	+			
Potsdam	2.30	+			
Maidenhead	2.18	-(ini)			
Ludwigshafen	2.13	+(ini)			
Toronto	2.00	+			
Boston	1.76	-			
Drebkau	1.63			+	
Lawrence	1.57	-			
Dresden	1.50	+		+	
Hamburg I	1.50	+			+
Wiesbaden	1.44			+	
Wartin	1.44	-(ini)	+(ini)		-(ini)
Finsterwalde	1.27	+			
Güterfelde	1.25	+(ini)	-(ini)	-(ini)	
Vienna II	1.21	-(ini)			
Copenhagen III	1.11			+	
Dublin I	1.00	+		+	
Dublin VI	0.93	+		+	
Liebenau I	0.93	-(ini)			
Görlitz	0.92	+			
Senftenberg	0.86			-(ini)	
Dublin V	0.86	+		+	
Vienna I	0.83	-(ini)	-(ini)		
Torino	0.71	+			
Eickenrode	0.62	+		+	
Hamburg II	0.61				
Dublin II	0.60	+		+	
Nürnberg	0.46	+	-(ini)		
Copenhagen II	0.40			+	
Dublin III	0.40	+		+	
Dublin IV	0.40	+		+	
Graz IV	0.40	+(ini)		+(ini)	
Copenhagen I	0.40	-(ini)	-(ini)	-(ini)	
Graz I	0.40	+(ini)		+(ini)	
Graz II	0.40	+(ini)		+(ini)	
Graz V	0.40	+(ini)		+(ini)	
Graz III	0.40	+(ini)		+(ini)	

The list of risk evaluation outcome for the published case studies shows the type of analysed constructions and general results of the assessment. In the majority (40) of these cases, undisturbed walls have been equipped with measurement tracks. Unfortunately, the tracks in the Hruby Sur project did not comprise hygric measurements. A risk evaluation was not a focus of this project. The remaining 35 projects combined these wall measurements mainly (17) with tracks in the joist ends, partially with tracks in the exterior wall edge (5) or around the window (2).

In the majority of cases with critical conditions (10 out of 15), there is only an initial exceedance of the threshold values for relative humidity resp. wood moisture content in the drying period (first years) of the montioring phase. The remaining five cases showed critical conditions for the whole phase. Nevertheless, in some of these permanently critical cases, the measurement period is not exceeding the expected drying phase and the further development was consequently not recorded. Therefore, uncritical conditions are also possible in the sequel of the building usage for these projects. Nevertheless, 25 of all evaluated constructions showed uncritical conditions, 10 showed only initially critical conditions and 5 cases were problematic.

A closer look to the insulation materials of critical projects show a huge variety with VIP, mineral wool, Aerogel, PU and EPS. Not all of these materials are belonging to the group of condensate-tolerating resp. capillary active materials. Nevertheless, this could be a consequence of the higher thermal conductivity of these materials. A desired high thermal resistance of the insulation system would yield a wider insulation thickness and thus a loss of indoor space. There is also a huge material variety for less critical projects with only initially high moisture levels. The applied materials among these projects are PU, timber fibre boards, reed mats, cellulose boards, Multipor (mineral boards), cellulose plaster, calcium silicate and Aerowolle (mineral wool and aerogel). This list includes materials of all both groups, the condensate-limiting and condensate-tolerating types.

A direct relation between thermal resistance of the insulation system and critical conditions was not observed. On the other hand, a concentration of critical cases for the projects with higher insulation resistance is obvious. This property should therefore be considered as an essential risk indicator.

3.3.2 Constructive risk factors in RIBuild case studies

RIBuild case studies provided the opportunity of consistently documented monitoring projects. The duration of the monitoring phases is, by the majority, longer than the drying phase. This allows a more extensive comparison.

Again, the list of cases in Table 7 is sorted by the thermal resistance of the applied insulation systems. At first sight, the thermal resistance values are higher than for the published case studies with an average of 2.8 m²K/W compared to 1.98 m²K/W for the published cases. The potential risk of damage might therefore be higher as well. Surprisingly, the documented critical cases (marked in red below) are not those with the highest thermal resistance. Indeed, all cases on top of the list (thermal resistance higher than 3 m²K/W) show high short-time values of the relative humidity. However, these values occur during condensation periods in winter, when the temperature in the interstitial condensation area is far below the mould growth level (about 10°C) and they are only given for short time periods.

Table 7: List of RIBuild case studies with a summary of documented damages resp. damage indicators in different construction types. The projects are sorted by the thermal resistance of the applied insulation layer (Rins).

Project	R_{ins} [m²K/W]	Analysed constructive points			
		Wall	Wall edge	Joist end	Window
Spikeri Case A	6.25	+			
Spikeri Case C	5.56	+			
Brüttelen	4.57	+			
Dankepi Case A	4.29	+			
Dankepi Case B	4.29	+			
Meinungsgade	3.00	+		- (ini)	
Haderslev	2.58	-		-	
Klitgaarden	2.58	-			-
Rectorate Palace Case A	2.45	+			
Rectorate Palace Case B	2.29	+			
Weimar 1	2.22	+ (ini)			+
Spikeri Case B	2.17	+			
Weimar 2	1.78	+ (ini)			+
Graziosi's house	1.50	+			
Catholic Seminar	1.43	+			
Kildevaeldsgade	1.25	+		+ (ini)	
Weimar 3	1.11	+ (ini)			- (North)
Thomas Laubs Gade	0.97	- (ini)			

There are only two severely critical cases, both located in Denmark. In both cases, permanently high moisture levels were measured in the wall and in the monitored details (joist end resp. window lintel). None of these buildings offers a constructive driving rain protection. One building has at least an exterior rendering. One aspect, that both buildings have in common, is the type of insulation. Both buildings applied a relatively diffusion-tight and capillary inactive material in form of composite boards with capillary active channels. Moreover, the insulation system is mounted with a glue mortar, which causes additional water load to the construction.

Drying process of the captured built-in moisture was confined in the winter period for the Klitgaarden project, as the heating system was partially inactive for the first year after the retrofit (winter 2016/2017) and for the following winter season (2017/2018). Indoor conditions for the Haderslev-building were rather typical with consistent heating and indoor relative humidity of less than 65%. In this case, the driving rain protection of the façade was completely missing (exposed brickwork, no additional measures). This was also the case for the “Thomas Laubs Gade” project, the last entry in the table with critical conditions as well but a visible drying process. These factors might be the reasons for the drying time prolongation for the critical cases. This argument is supported by the stable high-moisture-level characteristics (Figure 23).

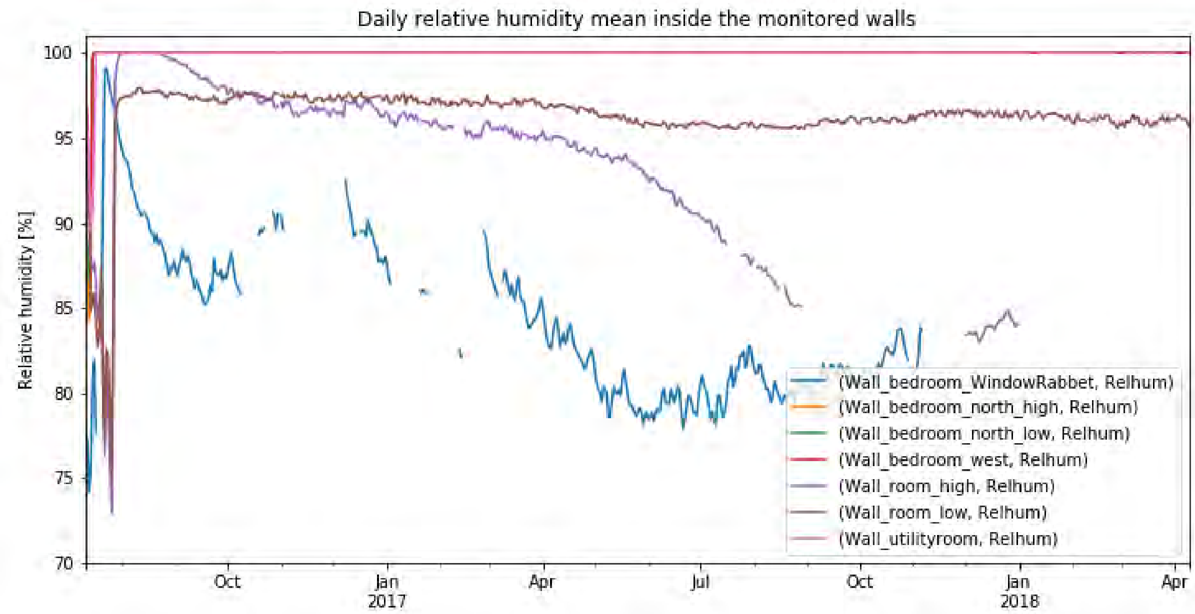


Figure 23: Extract of the measurement results for the building in Klitgaarden, Denmark for the winter period 2017-2018. The majority of the sensors (four out of seven) record a permanent moisture level of 100% (it was questioned where some of these had defects as single-point measurements showed lower values). Three sensors show a drying tendency towards summer.

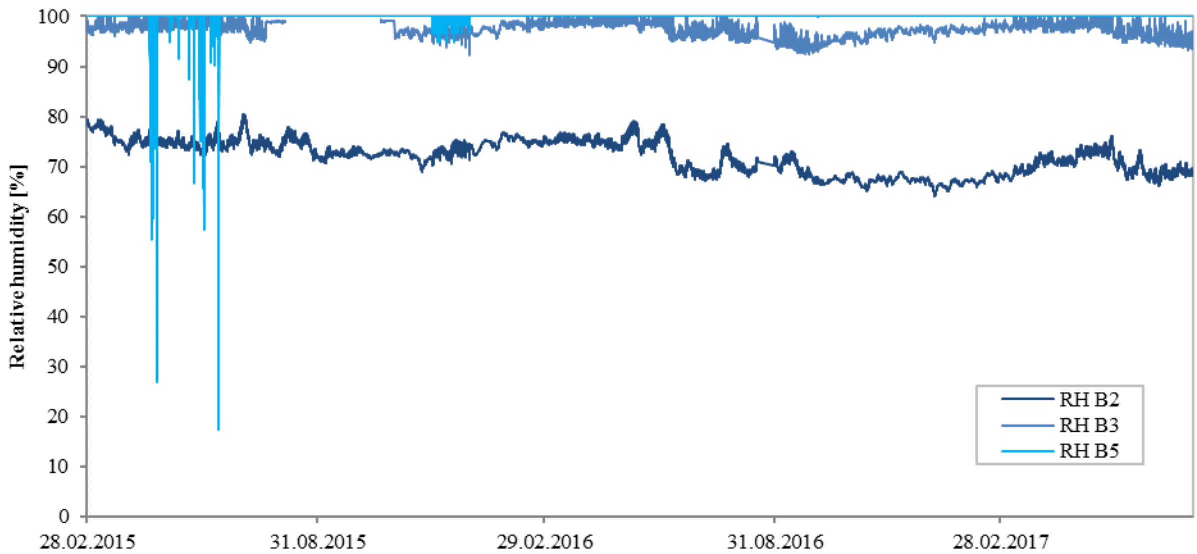


Figure 24: Extract of the measurement results for the building in Haderslev, Denmark for the period from winter 2015 until winter 2018. Two (B5 and B3) out of three sensors record a permanently high moisture level of around 97%. The third sensor (B2) shows a small drying tendency

A grouping of the simulation systems in combination with the measured conditions resulted in the conclusion that none of the capillary active systems showed critical conditions in the last monitoring year. The highest relative humidity level was measured in the case study building in Ancona (Rectorate) with short-time values slightly above 80% for the relative humidity in the wall, just one and a half year after termination of the retrofit measures and with sequential inactivated heating system during the monitoring phase. A further reduction can be expected for this project.

If the projects are analysed according to the thermal resistance resp. thickness of the existing wall, none of the European projects with a historic wall R-value higher than 0.5 m²K/W is documented with critical conditions. The same conclusion is not possible for the published case studies, where several critical cases occurred for buildings with a thick wall resp. high thermal resistance of more than 0.6 m²K/W. However, the reliability of these values is not that high, as the source for the specification of the existing wall, thermal resistance was not mentioned in the majority of published cases. Partially the values were not given directly and had to be estimated based on the material specifications, thicknesses in the reports. The second factor, the driving rain protection of the facades was also not explained for most of the published monitoring projects.

3.4 Boundary and initial conditions risk factors

3.4.1 Boundary and initial conditions in general

Weather conditions and indoor climate conditions provide the main source for vapour (from indoor air), liquid water (wind driven rain) and heat losses. All these conditions promote damage processes. Increased vapour inlet from indoor air might be possible for special room types (e.g. bathrooms). Temperatures and wind driven rain loads are location dependent. Buildings close to the sea and buildings in the mountains are vulnerable to heavy rain loads while locations in northern-European countries and in the mountains experience low outdoor air temperatures. The boundary conditions in the published case studies can only be estimated from the locations as the typical weather conditions at the building location (mean annual temperature and relative humidity, annual precipitation sum, wind conditions etc.) are not mentioned in any of the articles. This estimation is done based on map data for the published case studies and it was done on the basis of location data for the RIBuild cases.

Driving rain load in combination with the properties of the existing wall is mentioned as an important factor for the performance of internal insulation in several literature sources, e.g. (Morelli & Svendsen, 2012), (Harrestrup & Svendsen, 2016). Especially the joist end performance is influenced as the joist ends are placed about 100 mm into the wall and will therefore quickly react on moisture from the exterior surface. In any case, external coatings, reducing the rainwater penetration while marginally influencing the vapour permeability are advisable. A special attention should be turned to (embedded) wooden constructions. As the timber dries over time and develops gaps at the joints with the solid construction parts and furthermore cracks in the material itself, a direct water transport via air is possible. The same is true for façade masonry with defective joints or faulty hydrophobizing coatings that could be permeable for rainwater.

The driving rain load is generally dependent on the amount of horizontal precipitation (rain load) and the local wind conditions. Figure 25show that the annual rain load is varies a lot in Europe, e.g. being less than 500 mm per year in some areas of eastern Germany and in central parts of Spain, while the rain load is more than twice as high in the Alpine region, West England, and the Western part of Norway. However, precipitation is to be evaluated in conjunction with wind speed. In contrast to the precipitation level, which is mainly depending on the altitude of the location, wind conditions are stronger ruled by the closeness to the sea.

Exterior boundary conditions are only one field of the damage risk indication. Interior boundary conditions are also relevant. This addresses the emitted vapour, e.g. by tenants, and furthermore the temperature level. Both factors result in a vapour pressure level of the indoor air. The lower this level is and the more condensate-limiting the system is, the higher is also the drying potential towards room. This drying potential defines furthermore, how long the built-in moisture, which might be added with a renewal of the interior rendering or with the insulation system itself (e.g. adhesive mortar), is captured in the wall. Unfortunately, the indoor climate conditions are only mentioned in a few cases of the published buildings.

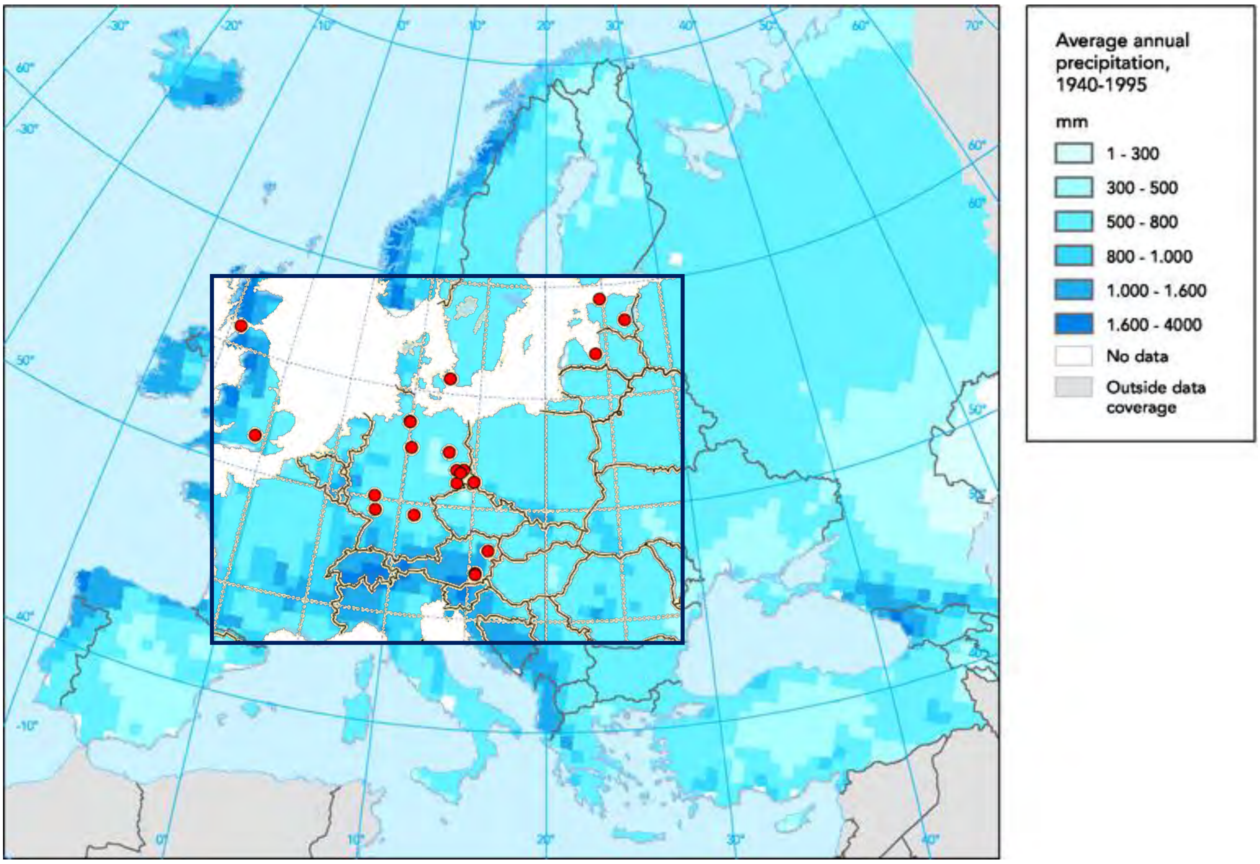


Figure 25: European precipitation map complemented with selected locations of published cases studies, Owner: University of East Anglia, Climate Research Unit, Processor: European Environment Agency (EEA), Permalink: http://www.eea.europa.eu/data-and-maps/figures/ds_resolveuid/872B55F3-B1F7-4277-8668-891AF213B314

3.4.2 Boundary and initial conditions in published case studies

Figure 26 shows the average wind speed for the period of 2000-2005. It gives a reason for the accumulation of critical constructions around the sea as these areas show the highest wind speeds of more than 7 m/s. A more obvious visualization of the weather conditions impact is given by combining Figure 26 with Figure 25. Four of the five northernmost locations reported critical conditions for the case study buildings. Most of these locations (Estonia, Latvia, Sweden, England) show average annual wind speeds of more than 6 m/sec and an annual precipitation level of about 500 to 800 mm. An exception is Glasgow, which is characterized by a very high rain load of more than 1000 mm. Initially critical conditions were furthermore given in the buildings in Maidenhead (England), located in an area with high wind speed of more than 6 m/sec and moderate precipitation level, Liebenau and Vienna (both Austria), located in a region with high precipitation load of more than 1000 mm per year.

This dependency of critical conditions on the location characteristics leads to the suspicion of insufficient driving rain protection of the facades in the reported critical cases. Unfortunately, this is not documented in detail. However, an analysis of the existing constructions shows that driving rain protection in form of exterior rendering is not the case for the majority of these critical buildings, as most of them have exterior walls made of exposed brickwork. However, constructive driving rain protection in form of roof overhangs or protected locations is not mentioned in any of the reports. The same is true for the quality of external rendering. Especially for buildings, which featured the original historic exterior rendering, characteristics of the plastering would be of special interest. At least the water absorption coefficient should be tested.

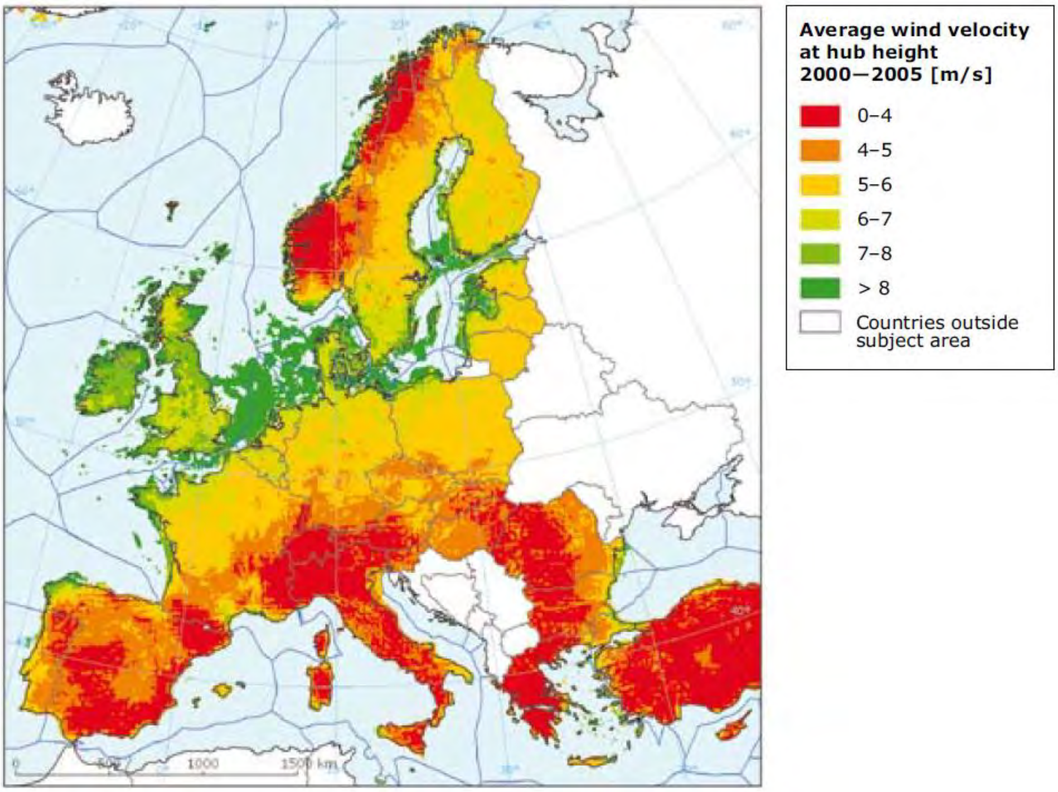


Figure 26: European average wind speed map for the period 2000-2005. Owner: University of East Anglia, Climate Research Unit, Processor: European Environment Agency (EEA)

Besides exterior boundary conditions, internal conditions resulting from the usage of the building are of interest. Especially for insulation systems with a strong hygrothermal interaction between insulation system and indoor climate (capillary active systems), the usage conditions might be crucial for the performance and damage risk of the insulation system. In the majority of published case studies, only the type of usage is mentioned. An explanation or even an analysis of resulting indoor relative humidity and temperature conditions is only given for a few buildings. An analysis is therefore not possible. Anyway, most of these published buildings are used as residential buildings (16 cases), followed by educational purpose (6 cases) and office buildings (4). For the rest of the case study buildings, the usage was either a special one (e.g. museum) or not explained at all.

Surprising is furthermore the fact, that many of the studied case studies were not in use during the monitoring period (9) or used in an intermitted way (4). This is an unsatisfying situation, as the first months after retrofitting are decisive for how fast built-in moisture is reduced. This drying process depends strongly on the heating and ventilation strategy in this period. A conclusion or even comparison of the built-in moisture in published case studies is therefore not possible. Moreover, information about moisture loads, resulting from the construction works, e.g. renewal of interior rendering, is not given in the articles. The same is true for the initial state of the walls, as moisture content measurements are not reported as well.

3.4.3 Boundary and initial conditions in RIBuild case studies

RIBuild case study buildings provide the opportunity of more detailed boundary conditions information compared to the published case studies. This addresses both the weather conditions and the indoor conditions. The data was partially provided by the partners and partially adopted from databases, e.g. climatecharts.net.

An analysis of risk indication, derived from the previous paragraphs, and the corresponding climate conditions for each location is given in Table 8, which is sorted by the average annual rain load (precipitation level) of each location based on long-time measurement analysis provided for the regions by the national weather services. According to this table, there is obviously no relationship between precipitation level and identified risk indicators in the case study buildings.

Table 8: List of RIBuild case studies with the risk indicator adopted from Table 7 and the annual characteristics of local weather conditions: average outdoor air temperature (T) and relative humidity (RH), sum of precipitation (P) and the direction of the measured wall (N=North, E=East, S=South, W=West). Projects are sorted by precipitation level.

Project	Uncritical conditions	Weather condition factors			
		T (°C)	RH	P (mm)	Direction
Weimar 2	+	7.9	79%	492	N, S-W
Weimar 1	+	7.9	79%	492	N, S-W
Weimar 3	-	7.9	79%	492	N-E, N -W, S
Haderslev	-	9.0	82%	595	S, W
Klitgaarden	-	7.4	82%	612	N, E, S, W
Meinungsgade	-	8.6	79%	636	S, S-W
Thomas Laubs Gade	+	8.6	79%	636	E
Kildevaeldsgade	+	8.6	79%	636	N
Graziosi's house	+	11.8	78%	658	N-E
Rectorate Palace Case A	+	15.0	75%	658	N-W
Rectorate Palace Case B	+	15.0	75%	658	N-W
Spikeri Case C	+	5.9	81%	667	W
Spikeri Case B	+	5.9	81%	667	S-W
Spikeri Case A	+	5.9	81%	667	N-W
Catholic Seminar	+	5.9	81%	667	N, W
Dankepi Case B	+	6.7	82%	690	N-E
Dankepi Case A	+	6.7	82%	690	N-E
Brüttelen	+	9.9	76%	1187	N-W, S-W

This long-time weather data is not necessarily representative for a given location and especially not for the analysis of a certain measurement period. Table 9 shows high variations among the years for the location of Haderslev. The differences are considerable compared to the given average in Table 8. Following these weather conditions for the measurement period, the building in Haderslev shows a high precipitation load, which is definitely promoting the damage risk of the construction. The same could be assumed for the remaining Danish case studies, as the measurement periods are similar.

Table 9: Weather data as local measurements for Haderslev for the years of 2015-2017. Extracted from the DTU-Report about Haderslev (source: http://www.dmi.dk/vejr/arkiver/normaler-og-ekstremer/kommuneklimadata-2006-15/)

	2015 (1-3-2015 – 31-12-2015)	2016 (1-1-2016 – 31-12-2016)	2017 (1/1-2017- 1/3-2017)	Average Values
Annual precipitation [mm]	826,2	743,8	1100,5	896[a]
Annual number of frost days []	21	74	30	
Average annual temperature [°C]	10,35	8,87	10,58	8,9
Average annual relative humidity [%]	83,43	85,21	89,84	85

Three of the risky buildings are located in Denmark. Two of them show furthermore a high vulnerability against driving rain (Haderslev, Meinungsgade) as they do not feature a constructive protection in form of exterior rendering or roof overhang. However, the remaining two buildings (Weimar 3, Klitgaarden) show at least an intact exterior rendering and are thus not vulnerable to driving rain load.

The direction of the monitored walls could influence the damage risk as well, as the distribution of wind directions over the year differs. This is briefly evaluated for the risky buildings by the help of the local wind roses in Figure 27 for the three locations of Weimar, Haderslev and Copenhagen. The graph for Weimar shows a very small precipitation level for the northern sector, although this is the direction of the critical wall in this project. Of course, not only the wind and precipitation levels indicate risky conditions. The drying potential of the solar radiation is also important and nearly absent for the northern sector. The same direction is also rated as risky in the Klitgaarden project that featured an exterior rendering as well. Indeed, all other wall directions are moist in this building (Klitgaarden) as well, despite the intact (renewed) exterior rendering of that building.

Wind roses for the three locations show a small variability of main wind directions among the locations. This is also the case for the remaining locations of RIBuild case study buildings. Most of them show a main wind direction from west respectively South-West and a slightly increased wind load from the opposite direction. There is only a fundamentally different characteristic for locations in the alpine region.

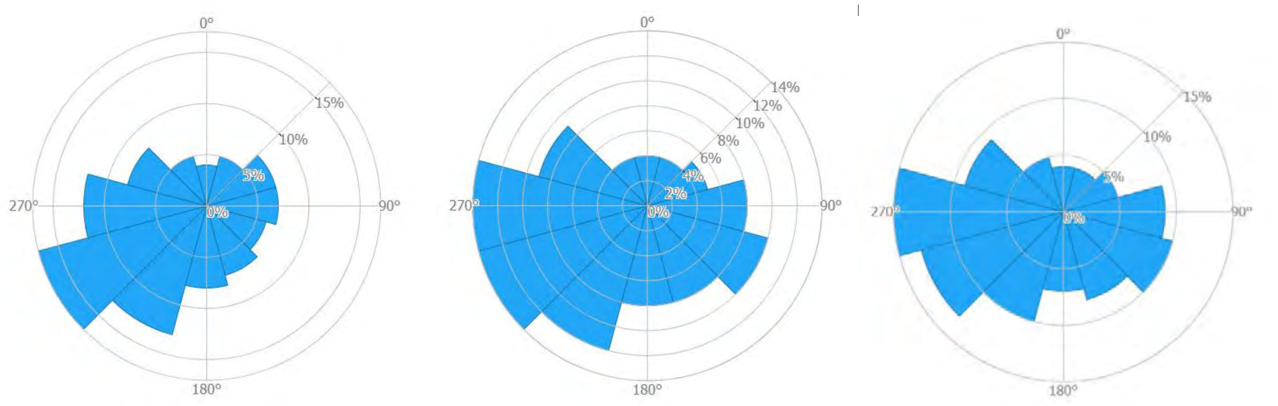


Figure 27: Wind roses for the critical cases in Weimar (left), Haderslev, Denmark (center) and Copenhagen, Denmark (right) according to the data provided by DTU in 2018 on https://globalwindatlas.info.

Case study buildings were predominantly occupied during the measurement period. In some cases, a usage established some month after installation of the monitoring system (Weimar, Germany and Brüttelen, Switzerland). In one case, the heating system was contemporarily inactive due to technical issues (Klitgaarden, Denmark). Only in one case (Catholic Seminar, Latvia), the heating system was permanently off during the measurement period. Fortunately, the refurbished walls of this building (mineral wool) did not cause a built-in moisture load. For all other buildings, the temperature levels during measurement periods were comparable with values of approximately 16°C to 23°C in winter and more than 30°C in summer. The interior conditions key values are summarized as follows. The column "built-in moisture" relates to the insulation system itself and its mounting technique. If the insulation system includes any process or material that causes additional water load of the construction (e.g. insulation systems including an adhesive mortar), then the built-in moisture is raised and marked as "yes" in this column.

Table 10: List of RIBuild case studies with the risk indicator adopted from Table 7 and the usage characteristics in form of built-in moisture from the insulation system, the occupancy density based on the number of tenants and the area of the building resp. apartment and the measured indoor relative humidity. The table is sorted by occupancy density.

Project	**Uncritical conditions**	**Further conditions**		
		Built-in moisture	**Occupancy density** [person/m²]	**Indoor relative humidity** [%]
Dankepi Case B	+	no	0.018	40-70% (plus peaks, bath)
Dankepi Case A	+	no	0.018	40-70% (plus peaks, bath)
Weimar 3	-	**yes**	0.021	45-50%
Weimar 1	+	**yes**	0.021	45-50%

Klitgaarden	-	**yes**	0.023	40-60%
Haderslev	-	**yes**	0.023	35-65%
Meinungsgade	-	**yes**	0.025	30-65%
Weimar 2	+	**yes**	0.028	30-45%
Thomas Laubs Gade	+	**yes**	0.030	40-60%
Graziosi's house	+	**yes**	0.031	40-60%
Brüttelen	+	no	0.031	30-70%
Kildevaeldsgade	+	no	0.046	< 80%
Rectorate Palace Case A	+	**yes**	0.054	40-60%
Rectorate Palace Case B	+	**yes**	0.054	40-60%
Spikeri Case C	+	no	0.062	20-95%
Spikeri Case B	+	no	0.062	20-95%
Spikeri Case A	+	no	0.062	20-95%
Catholic Seminar	+	no	0.083	30-75%

The raises the suspicion of relation between estimated occupancy density and the maximum indoor relative humidity. Some exceptions are given for special rooms, e.g. the bathrooms in Dankepi, Latvia. In addition, the building no. 2 in Weimar, equipped with a controlled ventilation system, is an exception. It shows a normal density but a lower relative humidity. A similar case of relatively high occupancy density but low relative humidity was given for the Catholic Seminar, where the number of occupants was likely misjudged.

The course of relative humidity for a winter period for one case study building is illustrated in Figure 28 for the example of Dankepi in Latvia. Obviously, the relative humidity level of indoor air is low and ranges around 50%. All longer usage periods of the bathroom cause short-time-peaks in this curve and a slightly increased level of the indoor air in the living room during non-occupied hours. These peaks are not affecting the damage risk of the construction behind in a significant way and can be balanced by the construction.

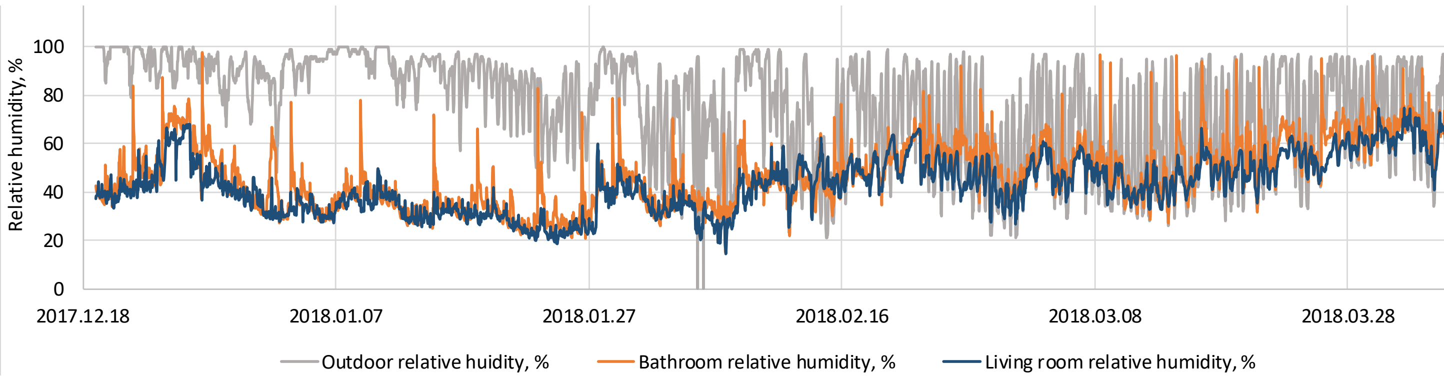


Figure 28: Outdoor and indoor relative humidity for two rooms in the test case building in Dankepi, Latvia. The values for the bathroom are on the average on a typical level but show regular peaks due to the usage

Much more influential than short-time moisture loads is the temperature level of the indoor air. The temperature level is influenced by the seasons (heating period or free-running period) and by the heating characteristics during the cold season of the year. Both factors were analysed in the Italian case study buildings (Rectorate and Villa Graciosi).

The seasonal variations and their impact on the temperature conditions is shown in Figure 29 for the Villa Graciosi. Three phases were chosen for the comparison, two cold seasons with activated heating system (Periods P1 and P3) and one phase in the summer (Period 2), where the heating system was inactive. The temperature box plots in Figure 29 show already a huge range of measured indoor air temperature in the warm season and a remarkably higher temperature level within the construction (red boxes in Figure 29). The corresponding moisture level in the wall is consequently much lower.

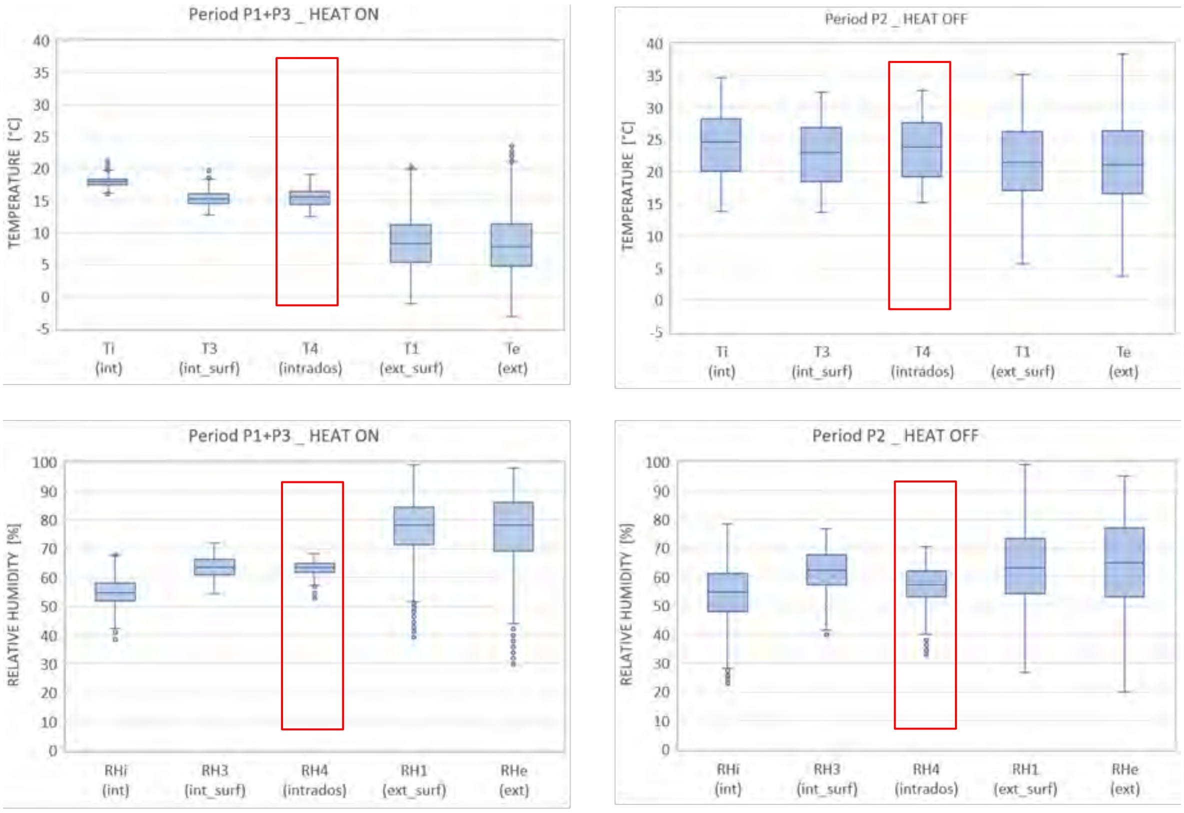


Figure 29: Temperature (upper graphs) and relative humidity (lower graphs) conditions for the heating season (left graphs) and for the free-running season (right graphs) in the RIBuild case study building Villa Graciosi in Ancona.

The heating settings resp. the level of heating during the cold season is decisive for the damage risk potential of internally insulated buildings. This was analysed for the Rectorate building in Italy (Figure 30 and Figure 31). The building was not directly in use during monitoring but instead heated in an experimental way with heating-on and heating-off phases. The comparison between the free-running phase with an inactive heating system (period 2) with a constantly heated phase (period 3) shows a remarkably higher indoor moisture level for the first phase. The resulting measurement points in the graph are compared with a mould growth risk indicator, the isopleths (Sedlbauer, Krus, & Zillig, 2003). The unheated phase dot cloud (upper and lower left graph) is much closer to that risky line than the heated phase (upper and lower right graph) values, especially for the calcium silicate construction, which is more vapour permeable and thus stronger linked to the indoor climate.

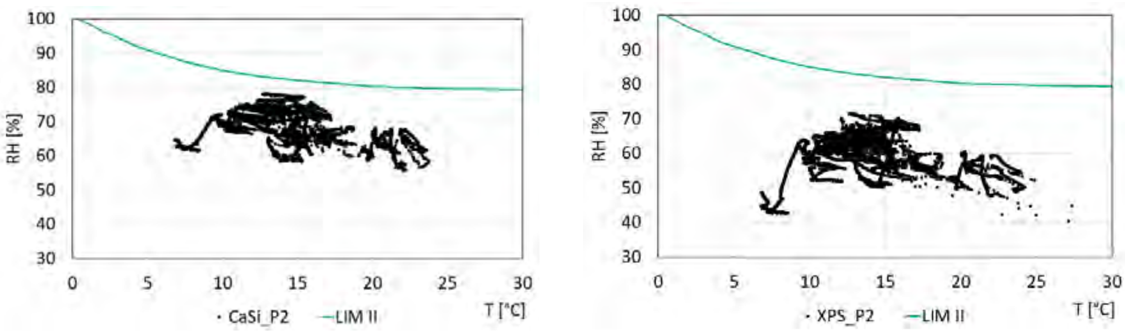


Figure 30: Mould risk evaluation with Sedlbauer isopleths (LIM II: common building materials) for CaSi (left) and XPS (right) insulation systems in period 2 (unheated phase). RIBuild case building Rectorate (Italy)

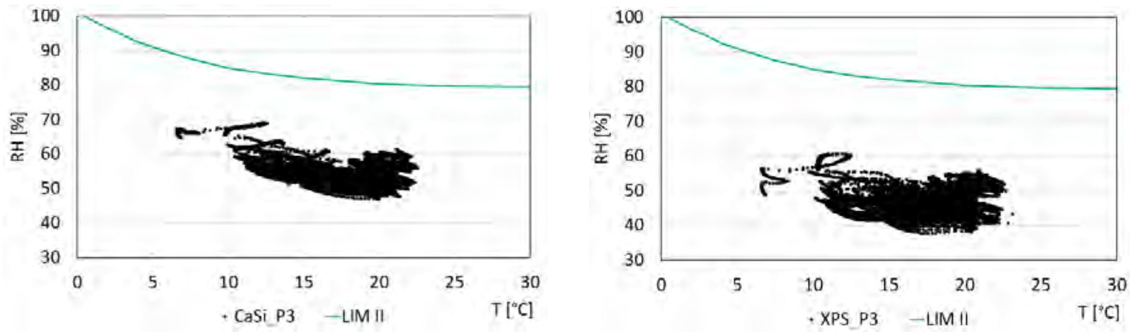


Figure 31: Mould risk evaluation with Sedlbauer isopleths (LIM II: common building materials) for CaSi (left) and XPS (right) insulation systems in period 3 (heated phase). RIBuild case building Rectorate (Italy)

A proper estimation of the resulting indoor climate in hygrothermal simulations is still a challenge. The case study results for Italy have shown that both summer and winter conditions influence the wall behaviour essentially. During a year, the moisture content of indoor air is assumed to depend on the outdoor air temperature as the moisture content depends on the temperature level. Furthermore, the ventilation behaviour of building occupants is dependent on the season. EN ISO 13788 describes both aspects by means of humidity classes. In order to give a recommendation for the practical assessment of these constructions, the existing model has been compared with measurement results for the case study building 3 in Weimar. Figure 32 shows that measured indoor air values for this building are within the limit of humidity class 2.

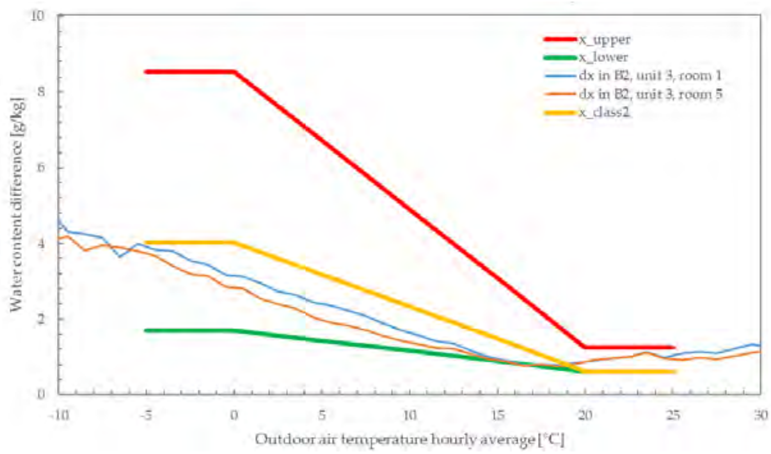


Figure 32: Measured indoor air values in case study building Weimar 3, Germany compared with upper limit curves for humidity class 1 (green), class 2 (yellow) and class 4 (red) according to (EN ISO 13788: 2013). Indoor air value is represented by water content difference (g/kg) between indoor and outdoor air.

3.4.4 Conclusions on boundary and initial conditions

The analysis of weather conditions and reported damages or damage indicators yielded a link between location, especially the closeness to the sea (high average wind velocity) and the annual precipitation sum, with reported risks for the published case studies. Four of the five northernmost locations in the published case studies were rated as risky due to high measured moisture levels in the walls. Some of them did not feature an adequate driving rain protection. In general, information about the driving rain protection, the quality of the external rendering etc. were not found in the published cases. Four of the RIBuild case study buildings were reported with damage risk indicators. Two of them did not have a proper driving rain protection (e.g. exterior rendering or roof overhang), three of them were exposed to high precipitation levels during the measurement period, and all of them showed additional moisture load based on built-in moisture of the insulation system (at least adhesive mortar, partially renewed interior rendering).

Interior boundary conditions are a second aspect of boundary conditions. They were unfortunately only documented in form of usage types for the majority of published case studies. Most of the buildings were used for residential purposes, some as educational buildings and office buildings. A relevant number of them was not permanently used or discontinuously used. Key values of the indoor climate were mostly not listed or explained. A link between usage types and the reported damage indicators was consequently not possible for the published case studies.

A better documentation was available for RIBuild case studies. The indoor climate was measured and ranges of the relative humidity and the temperature level could be summarized. During heating season, the temperature level was different with margins from 15 to 23°C. This affected the relative humidity level as well. For most of the buildings, the resulting relative humidity level and the occupancy density were in a good accordance. Exceptions were identified for a moist room, a building with a mechanical ventilation system and a non-residential building. For one residential building with natural ventilation, the annual characteristics of moisture content showed a good accordance with humidity class 2 in ISO 13788. Another comparison was provided for the impact of the heating season temperature level on the risk indicators. The lower temperature level showed a relevant increase of the moisture level in the wall.

It is therefore highly recommended, especially for buildings with a high built-in moisture content, to fully heat and ventilate the refurbished rooms after termination of the retrofit measures. This assumes also a high vapour permeability of the interior insulation system to decrease the built-in moisture level in the wall. All four documented risky RIBuild cases showed a moisture load caused by built-in moisture of the insulation system. Three of these insulation systems showed a low vapour transmission resistance factor of 20-30. All of them showed a small capillary activity.

3.5 Specific aspects of interior insulation application

In the following paragraphs, certain aspects of internal insulation are analysed. This analysis was not possible solely based on published and RIBuild case studies, as the depth of documentation was not allowing this for the majority of buildings. Therefore, further literature sources for selected construction types or analysis aspects were included and partially supplemented with outcomes and examples of the RIBuild and published case studies. These aspects include the untightness of the construction, thermal bridges and risks related to exposed brickwork. Untightness could cause a convective air stream and thus an increased moisture load in the wall.

3.5.1 Vapour ingress due to convection

In practice, internal insulation is often applied at uneven historic building surfaces. If the workmanship is not done precisely and gaps are left between insulation system and the existing wall, convective inlet might be a consequence. This is usually excluded with a firm air tightness layer around the whole construction including all constructive junctions. In case of leakages, the resulting damage risk is high if unwanted air connections are given at several points within a wall construction and a closed air loop between cold downwards sinking air from the cavity and warm air from the room develops. Cold air from the cavity enters the room at the bottom area and leaves it heated-up on top of the wall towards cavity. The insulation system is consequently undermined, as the warm air releases its heat directly to the cold wall. Furthermore, the developing convective airflow will continuously transport moisture into the historic wall construction. The moisture transported due to convective flow could be a multiple of diffusion-related ingress. The corresponding damage risk is therefore very high (Jenisch, 1996, S. 72-74).

There is no documented case of convective air inlet in the analysed case study buildings. This could be traced back to the limited monitoring period of these buildings. In some cases of increased moisture content in the wall, convective inlet due to leakages of the vapour retarder might be supposed. For example, this is the case for the case study building Meinungsgade in Denmark. The measured fluctuations of relative humidity behind the 60 mm insulation layer is very high. This is untypical for such an insulation system. Compared to another building with similar construction properties in Kildevaeldsgade, the amplitude of the relative humidity seems exceptionally high. This is shown in the comparison below. As this construction is also a facebrick wall, fluctuations might also be promoted by the driving rain load through the masonry and eventually cracks in the joints. This is not evaluated for the given construction.

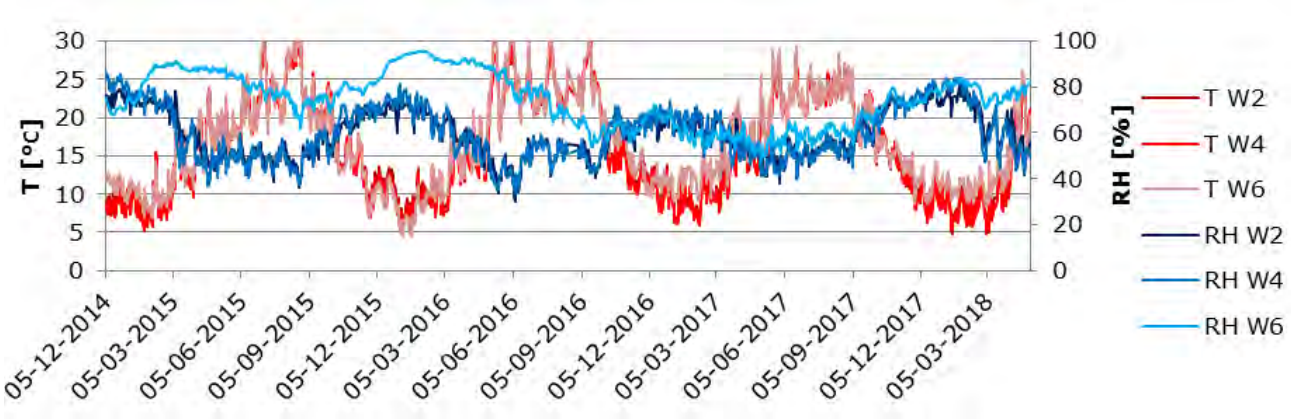


Figure 33: Relative humidity and temperature between insulation and historic wall construction measured in the case study building in Meinungsgade, Copenhagen. Relative humidity shows strong fluctuations, which are untypical for a construction with a vapour barrier.

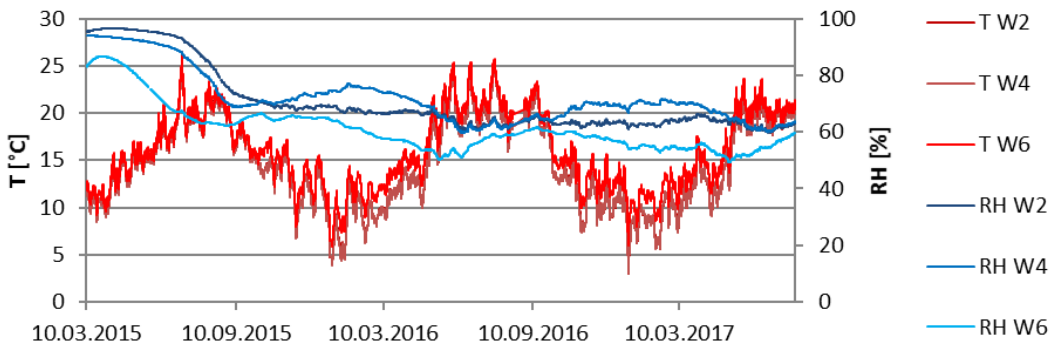


Figure 34: Relative humidity and temperature between insulation and historic wall construction measured in the case study building in Kildevaeldsgade, Copenhagen. Relative humidity shows small fluctuation. The wall construction is the same as for the building in Meinungsgade except a lower insulation thickness (25 mm compared with 60 mm in Meinungsgade).

Cavities might appear in capillary active, vapour-open systems (condensate-tolerating systems cf. Section 3.2) as well as in systems involving a vapour-retarder or vapour-barrier (condensate-preventing and condensate-limiting systems). Capillary active systems might show cavities if insulation boards are mounted point-wise with lumps of mortar or if the boards are fixed on a very uneven surface without a previous levelling of the underground. The main leakage sources for vapour retarding systems are workmanship-related issues, e.g. a leakage in the foil layer, and design-related issues, e.g. a non-continuous air tightness layer. A proper air tightness concept in combination with an inspection on the construction site helps reducing these risks. It comprises the definition of the airtight layer all around the building and the design of constructive details for all envelope intersections, gaps and connections. The detail design part is not only a theoretical one as it includes the description of practical realization and applied materials.

A more specific manual for retrofit projects is for example provided by the engineering association WTA in form of three codes of practice for the concept design (WTA 6-09), detail design plus realization (WTA 6-

010) and the airtightness measurement procedure. This measurement is recommended for the pre-intervention state to identify problematic connection points as well as for the post-intervention state to verify a precise workmanship in accordance with the planned concepts.

Consequences of vapour transport through gaps, cracks, connections etc. might be condensation, mould growth and increased energy consumption. The latter is especially relevant for cases in which openings in the masonry are given in addition to the connection between interstitial condensation plane and room air. In this worst case, airflow through the whole construction occurs (Oswald & Zöller, 2010). Locating these untight points or areas is possible with infrared imaging as shown below for the example of power sockets perforation.

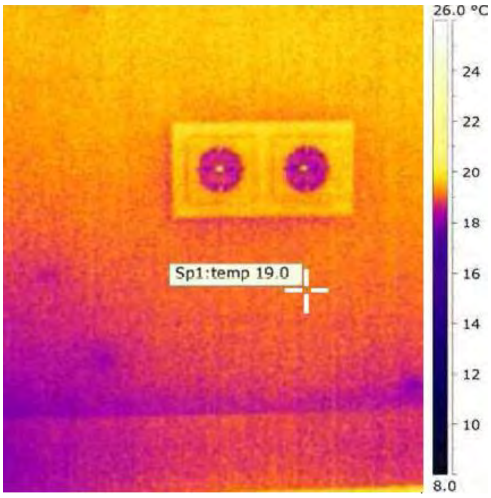


Figure 35: Impact of insulation system perforations on the temperature field. The wall was supplemented with power sockets that degrade the insulation layer. Dark areas in this infrared image show areas of lower temperature and give a hint to thermal bridges resp. leakages (Oswald, Zöller, Liebert, & Sous, 2011).

3.5.2 Thermal bridges

Thermal bridges are a challenging field, whenever internal insulation is applied in historic buildings. Insulation layers added at interior surfaces are several times crossed by ceilings, partition walls and other construction parts. An installation of internal insulation results in a colder masonry resp. solid structure, which causes higher heat fluxes through all non-insulated areas of the building like thermal bridges. For that reason, thermal bridges have to be eliminated as far as possible. Problems occur additionally due to punctual fixation of internal insulation system, electrical installation and insulation board joints. Solutions are provided by insulation system producers or distributors, e.g. fixations made of materials with lower conductivity or reduced fixation depth.

There is often a combination of promoting material-related and geometrical constellations (e.g. solid internal walls, external walls of different materials, window reveals etc.) for linked constructions. Furthermore, interior fittings have to be integrated into the insulation layer. In many cases, thermal bridge effect can be avoided via conductive elements (e.g. metal corner), insulation cages, insulation wedges/slats at internal walls, decoupling of linked constructions (e.g. partitions) or punctual heating. In the case of insulation slats, there is a risk of high temperature differences at the end of the slat towards room side, which should be avoided (Jenisch, 1996, S. 49-56), (Oswald, Zöllner, Liebert, & Sous, 2011, S. 42).

3.5.2.1 Floor joist ends

Problematic joints are often documented for timber floors. This concerns mainly floor joist bearings in external masonry walls which show cold joist ends, a strong influence of wind driven rain loads through the masonry (reduced thickness) and sometimes convective moisture loads due to leakages in the external wall and/or at the joints surrounding towards inside. (Oswald, Zöllner, Liebert, & Sous, 2011, S. 63)

Concerning the proper evaluation of joist ends, two aspects were seen as substantial constraints. There was firstly a need for commercial HAMT simulation tools for the comprehensive assessment of joist ends, including three-dimensional hygrothermal transfer and storage processes. This lack is partially solved. A simulation engine was developed in the frame of a research project (Vogelsang & Nicolai, 2014). The remaining obstacle is the modelling software for engineers, a user interface that enables the graphical creation of three-dimensional project files with an integrated geometry and boundary conditions check and furthermore an equivalent graphical output analysis.

The second field of research activity was the obtainment of firm monitoring data, spanning several years and including relevant positions, comparative points, different occupancy patterns and constructions. This was tackled via combined measurements and hygrothermal simulations in several projects. One major aim was the evaluation of wood rot risk, resulting from the application of internal insulation. Outcomes of these summaries showed that practice-established threshold values are reliable. Experiences with joist ends in internally insulated masonry are for example summarized in (Kehl, 2014) for Germany, Austria and Switzerland. The author emphasizes the impact of driving rain on the joist end conditions. The summary includes 14 monitoring projects with a diversity of constructions, insulation products, locations etc. The author attested uncritical conditions for constructions with external plaster and low driving rain loads if water absorption is low enough and diffusion permeability is high enough for the given construction. Approaches for the required relationship between water absorption coefficient (A_W) and diffusion equivalent air layer thickness (s_d) relationship are specified in the literature (e.g. DIN 4108-3, WTA MB 6.5)

Analysis of measurement results in (Kehl, 2014) shows disagreement about damage risk thresholds. In the case of decay resp. rot risk, the assessment approaches are ranging from simple models, e.g. DIN 68800 with a threshold of 20 % mass-related moisture content, to advanced models, e.g. by Viitanen including also material specifications and temperature levels. Due to an incomplete documentation of the published cases, a sound comparison and evaluation of these models was not possible. Moreover, the threshold values for the allowed wood moisture content were exceeded in some cases. However, damage was not visible in several of these cases. One the one hand, the mentioned threshold value seemed to include a safety margin. On the other hand, the temporal cycles between wet and dry periods seem to be important and not covered by the models.

There are not only measurements, which evaluate the damage risk approaches but also measurement that analyse the spatial distribution of damage risk within the building and within the beam end itself. Measurements showed that the critical situation for wooden joist ends varied among different azimuth directions of the facades and between different positions within the beam end. A remarkably higher risk was given for beam-ends that suffer a reduced solar radiation (local shading, north direction etc.). Small-scale spatial distribution within the joist end is shown in Figure 36, where two samples from a southeast façade were extracted from a case study building. Higher moisture contents (red IDs) are given for the lower measurement points close to contact face with the masonry. Less critical is the upper area of the beam end and the front face.

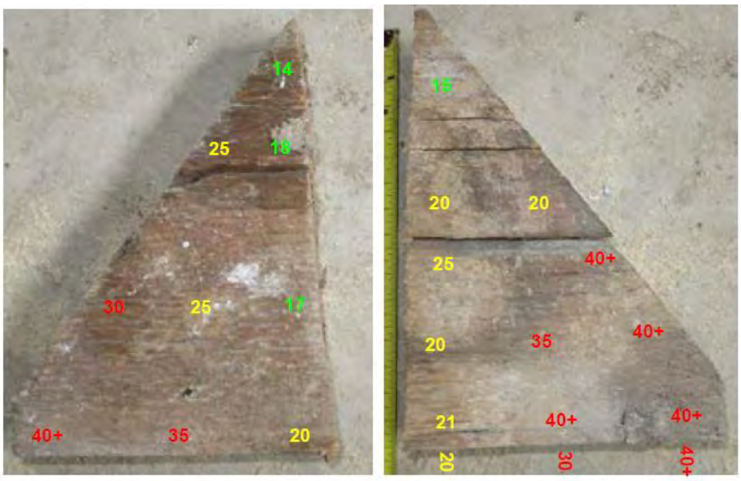


Figure 36: Moisture content in southeast oriented joist end faces in a case study building located in Ottawa, Canada. IDs represent measurement points with a colour-decoded moisture content (red= high, yellow= moderate, green= low). The bottom side of the samples was the horizontal bearing surface. The samples show left and right side of the beam end. The beam ends were bevelled cut off at an angle of 45° and the long side was placed on the masonry, thus the long sloped side is was the front face (in contact with cavity air) of the beams in the masonry. All red (critical) points are located outwards (closest to the outer surface of the wall).

Another issue is the difficulty of sealing at the connection area between joist end and the wall construction. Joist ends underlay a shrinkage process. After installation, the usage conditions are typically dryer. In case of renewed beams, the initial moisture of the wood is higher and a drying process follows as well. The same is true for the masonry joints, which underlay the shrinkage process, too. Both shrinkage processes (in the masonry: joints and the wood: longitudinal and radial within the timber) cause cracks and thus an infiltration air change. This risk of unwanted air inlet is normally reduced with (precompressed) joint tapes, filling material insertion, collars etc. for the joist end connection. (Scheffler, 2016) The masonry quality (joints) should be inspected and improved additionally.

Drying process of eventually moist joist ends should be enabled into the room and/or towards outdoor air. Internal insulation systems reduce inward drying potential and cause furthermore decreased temperature levels in the existing masonry wall. Both factors could raise the moisture content in wooden beam-ends. Thus, additional moisture input, e.g. convective loads from indoor air caused by leakages at the joint or rising moisture from the ground, must be avoided. One risk mitigation method can be seen in a heat flux reduction at the flanks of the beam.

Other approaches prefer local heating of the joist end, intensive warm airflow into the cavity or heat conducting elements at the joist ends. There are further approaches, which modify the beam end construction and the correlating load transfer. A heat flux reduction can be achieved with a continuously realised insulation layer, which is also pursued in the slab level. There is a disagreement on the treatment of the ceiling construction itself. Some authors suggest an interruption within the ceiling area while some recommend a continuous insulation layer. Another disagreement can be denoted for the treatment of the cavity around the joist end bedding. Some prefer a filling with insulation material and others prefer an empty cavity. (Bräunlich & Kaufmann, 2013) (Kehl, 2014)

Some authors suggest raising the joist end temperature level by use of direct or indirect heating. A solution is given with flow line pipes or heat pipes placed at the joist ends. This should be combined with the removal of insulation around the joist ends. The expected drying process could be initiated with the placement of heating pipes beside the beam end. The disadvantage of this method is an estimated additional heat loss of 10% (Stopp, Strangfeld, Toepel, & Anlauft, 2010). The resulting long-time behaviour is shown in Figure 37.

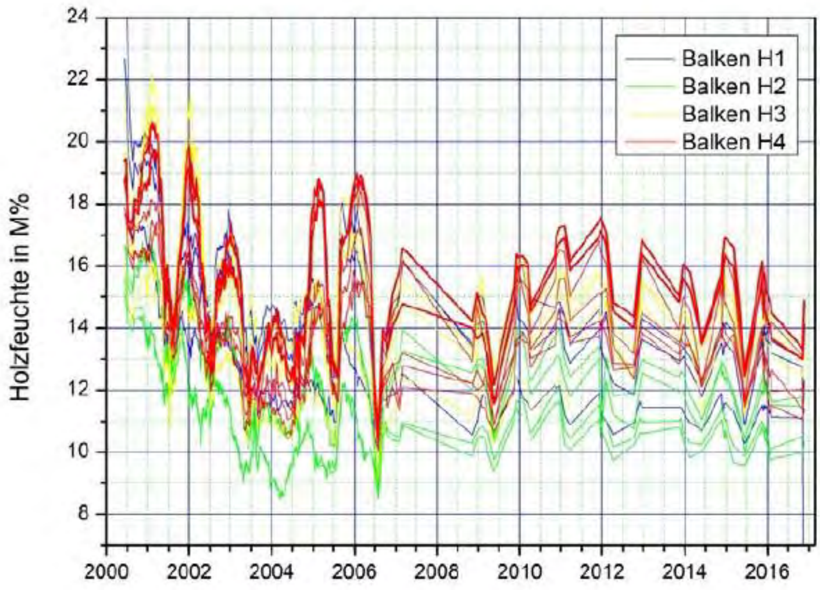


Figure 37: Moisture content (weight-% in wood) in joist ends in a case study building located in Senftenberg, Germany. Different graphs represent different measurement points at the North-West-Façade within four different joist ends. All joist ends were equipped with a heat source in form of different heating pipe solutions that provided different levels of permanent heat inlet over the cold period of the year. (Stopp, Strangfeld, Toepel, & Anlauft, 2010)

The estimated increased energy demand using direct/indirect heating in this case compared with a completely insulated and non-heated wall is about 10%. Another solution makes use of heat conducting elements, connecting flow line pipes to the joist end. Alternatively, well-conducting materials could be used to replace the insulation material around the wooden beam end. Further solutions without heating include insertion of thermal insulation behind the front face of the beam end (between beam end and exterior masonry), combined with moisture absorbing materials in cavity around the beam end (side areas of the beam end in the masonry). (Stopp, Strangfeld, Toepel, & Anlauft, 2010) (Strangfeld, Staar, & Stopp, 2012).

Another approach of indirect heating was evaluated in Danish test houses (Morelli & Svendsen, 2012), (Hansen, Bjarlov, Peuhkuri, Harrestrup 2018). The authors left an air gap around the beam end of about 30 cm without insulation but covered by boards, to increase the local temperature around the joist end. These cases did not combine the omitted insulation with local heating. A similar strategy was also realized in Danish RIBuild cases, e.g the case study building in Meinungsgade, Copenhagen (Figure 38).

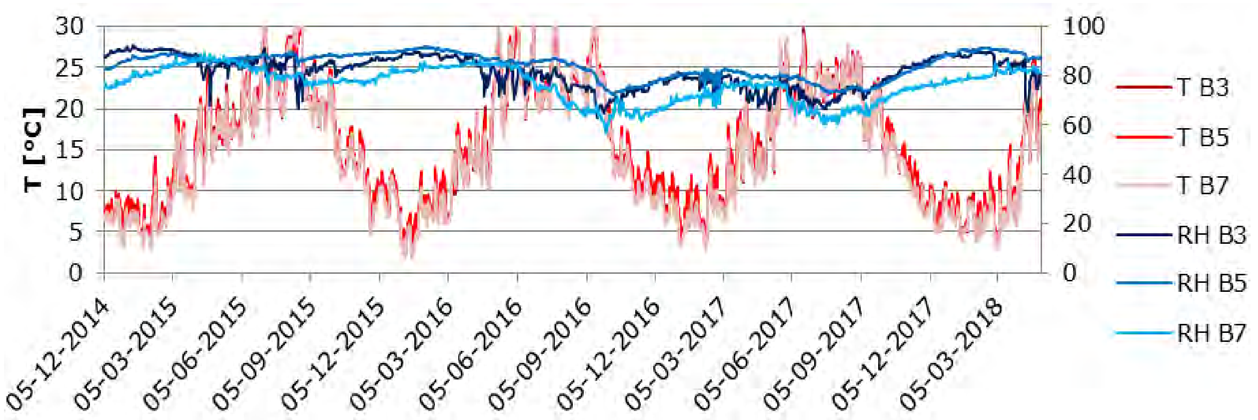


Figure 38: Joist end temperature (T) and relative humidity (RH) in the case study building in Meinungsgade, Copenhagen. Despite an initial drying process, the moisture content exceeds the 80% level in the third measurement year (2018).

Ueno suggests two solutions to remove the joist end from the masonry by cutting off the beam end and carrying the static loads with a supporting construction. In both versions, capillary contact between masonry and joist ends is eliminated with a capillary break between masonry and wood at the face of the beam end. The first solution of supporting the floor joists is a steel angle bolted to the masonry below the joist ends. Another solution is an additional stud frame wall, which assumes constructive preconditions of the storeys below. (Ueno & Lstiburek, 2015)

3.5.2.2 Window reveals

Window reveals combine several potential risks. One of these aspects is the reduced possible insulation thickness due to the restricted window geometry. Usually, preservation orders protect the external building appearance and prohibit a change of window dimensions. Therefore, an extension of reveal space for the installation of adequate insulation around the window is often not possible. Alternative measures might be a removal of the historic plaster at the window reveal to gain space or the application of high-performance insulation materials in this area.

Another window issue is the interrupted vapour retarding/blocking foil through the opening in case of condensate-limiting insulation systems. These types of connections are always risky and depend on a proper workmanship. Furthermore, the jointing between window and wall represents a weak point for wind driven rain. These problematic aspects are often combined with adverse material junctions as the lintel or reveal elements are often made of natural stone or roofing stone elements (Oswald, Zöllner, Liebert, & Sous, 2011)

Generally, the location of the window should be as close as possible at the insulation layer of the surrounding wall and there should be a continuously insulated area around the problematic joints to reduce the thermal bridge effects. The impact of the window placement level within the window reveal is shown in Figure 39. The detail at left shows a placement in the middle of the window reveal with very low surface temperatures close to condensation level (about 12.6°C), while the detail at right shows a placement close to the insulation layer with resulting balanced temperature conditions (minimum surface temperature is about 14.4°C).

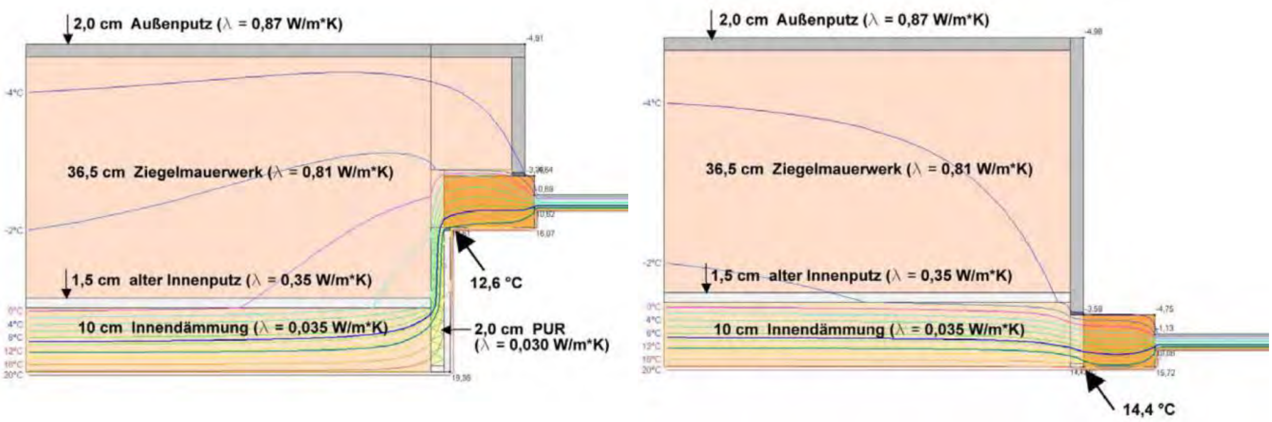


Figure 39: Comparison of the window placement impact on resulting interior surface temperatures. Left detail shows very low surface temperatures (about 12.6°C) for the middle-placement, right detail shows more balanced conditions for the inner placement of the window level (about 14.4°C) (Oswald, Zöllner, Liebert, & Sous, 2011).

Problematic thermal points around the window could be diminished with a placement of the window close to the insulation layer (see Figure 39), a continuation of the insulation layer behind the window reveal, punctual heating, highly insulating materials or a second fenestration layer. These measures are also applicable for floor-to-ceiling windows. In this case, the absence of a radiator (local heating) could be compensated with a floor heating system.

Among the case study buildings, two cases, the building in Weimar, Germany and the building in Klitgaarden included measurements around the window. Outcomes for one of these measurement points are illustrated in Figure 40. The condition in the window reveal area showed only a marginally increased relative humidity level compared to the undisturbed wall area.

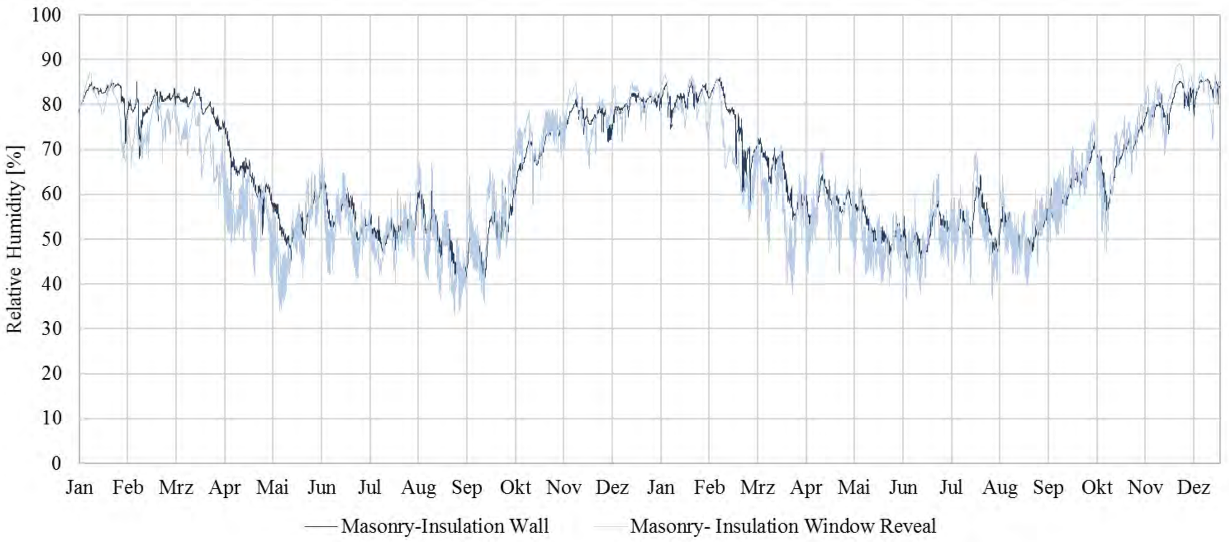


Figure 40: Conditions in the wall between insulation layer and 240 mm masonry (dark blue) compared to the condition in the window reveal area (light blue). The fluctuations of the relative humidity are higher and the moisture level is slightly higher at the window reveal area.

3.5.2.3 Partitions

Partitions are interrupting the internal insulation layer and thus causing reduced surface temperatures. The higher the thermal resistance of the interrupted layer in comparison to the existing wall, the higher the bridge effect and thus the damage risk. A beneficial solution for this detail is a decoupling of the partition from the original wall combined with an added insulation strip in the connection area. This is often possible in case of lightweight-partitions and less convenient for solid partitions. Measures for the second case are continued insulation layers along the partition flanks or a placement of conducting elements. A continuation of the insulation layer could be realized in form of insulation sections of a constant thickness or in form of insulation wedges. Conducting elements are for example metal l-shaped battens, which conduct the heat from the warmer part of the partition into the corner. This measure does not decrease the heat loss at the bridge area but it improves the surface conditions. A measure with the same principle but higher heat losses would be the placement of heating pipes at the corner or similar targeted local heating.

3.5.3 Face brickwork

Face brick walls suffer remarkably from driving rain events with a relatively long lasting impact on the overall moisture load of the exterior wall. Risky walls show an immediate response of brick moisture content on rain events. Supporting factors for the driving rain sensitivity are, among others, high precipitation amounts, weather exposed façade orientations, reduced solar incidence, not-existing or incomplete hydrophobization, inappropriate brick types and improper, cracked or weathered joints. The irregularities of these brickworks, including irregularities in the stones and joints, cracks etc. are illustrated in the following picture Figure 41 for the example of the case study on Meinungsgade in Copenhagen.

Figure 41: Face brickwork from RIBuild case study building Meinungsgade, Denmark.

Hydrophobization demands a particular attention for face brickwork. Firstly, hydrophobic treatment must be conducted several times to ensure the desired water-repellent effect and the effect is supposed to be weakened over time. Secondly, two material aspects are changed in the construction if hydrophobization is added, the liquid water conductivity and marginally the vapour diffusion resistance. The first aspect is desired concerning the ingress of wind-driven rain into the construction. However, it is undesired in the opposite direction as it hinders the transport of liquid water out of the construction through the outermost hydrophobized layers. This aspect is, especially in combination with a slightly reduced vapour permeability, counterproductive. It could lead to frost spalling of the water-repellent layer if noticeable amounts of liquid water reach the inner wall, e.g. through surface defects of the hydrophobized layer or jointing ruptures. (Peper, Kaufmann, & Hasper, 2010) (Scheffler, 2016)

Against this background, the quality of bricks and joints is decisive for the effect of hydrophobization as the wind driven rain could reach behind the face brickwork layer through cracks. This could be avoided with additional moisture-buffering layers (e.g. non moisture-sensitive plaster of larger thickness) at the inside of the masonry. (Bosch-Laaks, 2006) (Lamers, 1997)

4 Case Study Realization

4.1 Planning the monitoring concept

Depending on the monitoring concept in the case study building, e.g. hygrothermal evaluation of selected details or different wall directions, different sensor types are installed at different positions in the building. In most cases, temperature and relative humidity sensors are placed to record the indoor and outdoor conditions, the situation at critical points like wall edges or other thermal bridges and at reference points, which are supposed to show a typical hygrothermal behaviour. A measurement of heat flux is often supplemented at the inner surface, a measurement of wood moisture content often performed in joist ends or other wooden construction elements. The development of a hygrothermal measurement concept is shown below for the case study building no. 1 in Weimar, Germany. First, the floor plan was analysed in order to define critical points for the measurement track locations in the building. Four points were identified, all of them included critical areas, some also undisturbed reference points (Figure 42). The selection of critical points was done under consideration of the building geometry (thermal bridges), the wall orientation and the usage of the rooms (e.g. bathrooms, sleeping rooms with higher moisture levels).

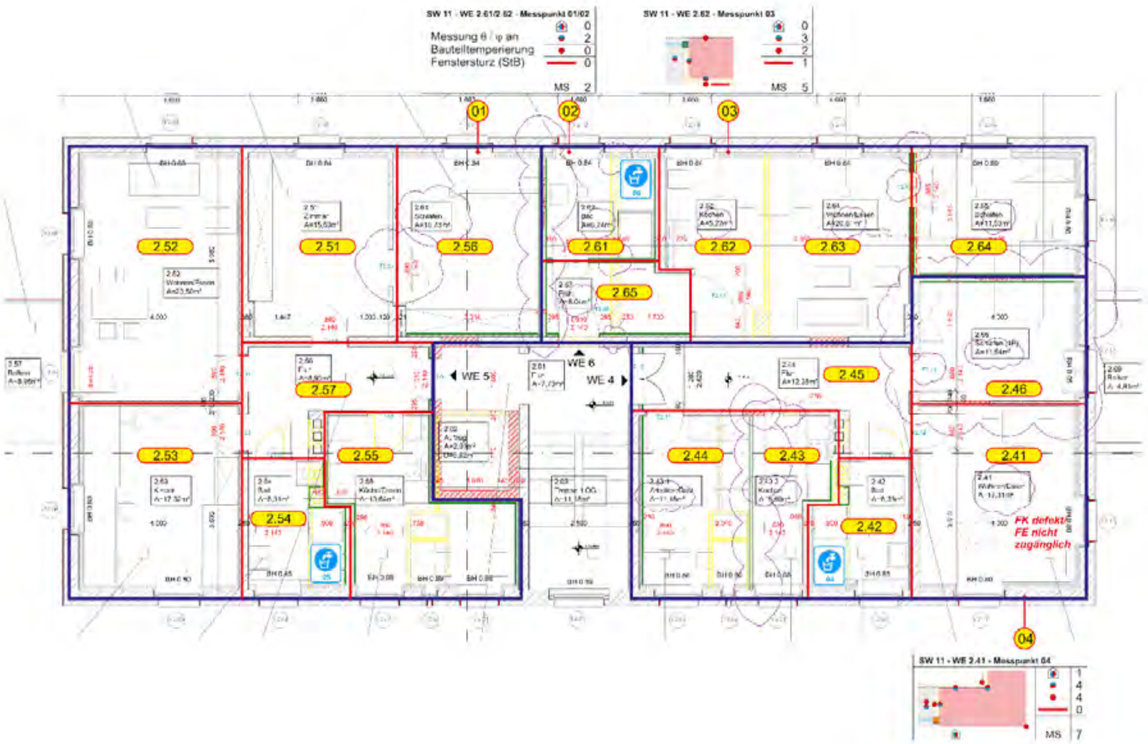


Figure 42: Selection of measurement track position in the floor plan of the building in Weimar, Germany. Each track is defined with an ID and with the type and locations of sensors.

The second step in the definition of the measurement concept is the design of each measurement track itself. Each zone or room requires at least the measurement of indoor air condition. Furthermore, combined temperature and humidity sensors are applied at critical, condensation-relevant points (Figure 43). Additional sensors are placed for special cases, e.g. the calculation of the transient U-value.

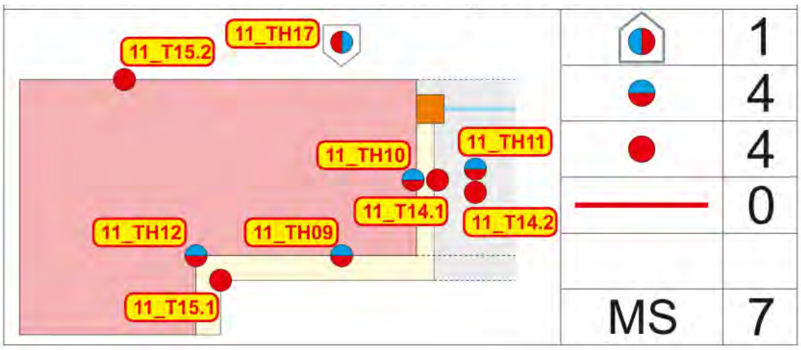


Figure 43: Selection of measurement track position in the floor plan of the building in Weimar, Germany. Each track is defined with an ID and with the type and locations of sensors.

Prior to installation of monitoring sensors, sensor quality should be calibrated. This is done with high-precision reference sensors. Calibration ensures the producer-defined precision of chosen sensors and thus the value range that defines the limits of results interpretation. Each sensor is exposed to the same condition as the reference sensor. The deviations of each sensor to the reference sensor are then analysed over different value ranges. This procedure is shown in Figure 44 for the case study building in Weimar.

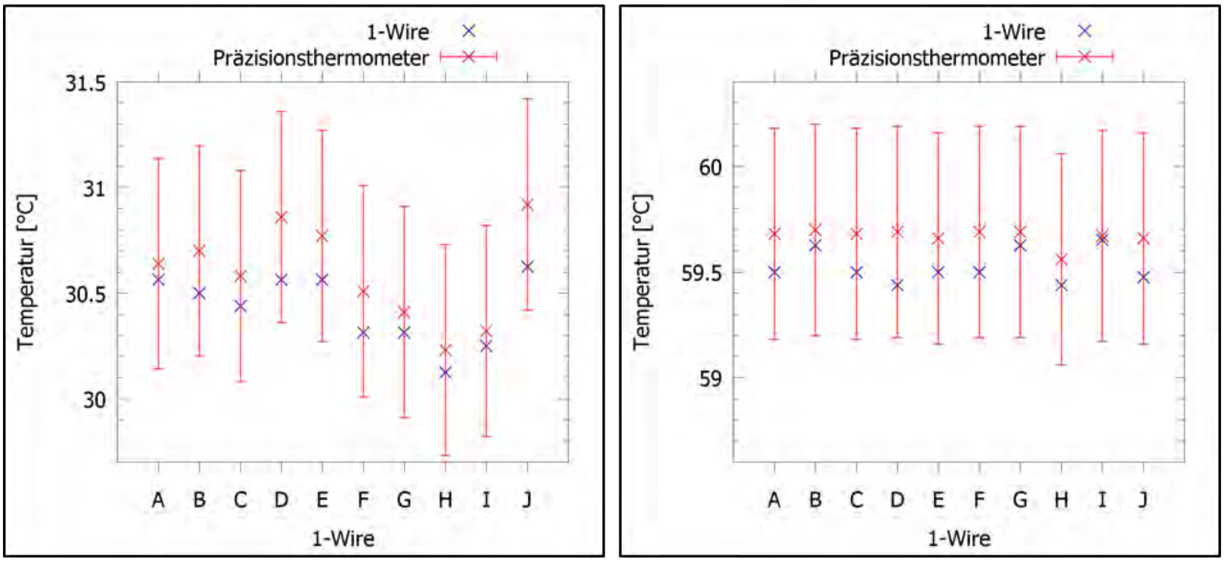


Figure 44: Calibration of temperature sensors with a producer-given accuracy of 0.5 K for the building in Weimar. Sensors to be calibrated are listed on the x-axis (characters A to J, blue crosses), temperature scale is given on the y-axis. Sensors show an average deviation of 0.3 K from the reference sensor (red crosses) and are within the allowed value range (red whiskers) for a low (left graph) and a high (right graph) temperature range.

4.2 Setting up the monitoring system

A knowledge of boundary conditions during the measurement phase is essential for the evaluation of measured states resp. fluxes as well as for the comparison of sensors with other projects. The measurement of indoor air conditions requires only air temperature and relative humidity values. More complex is the weather data characteristic. The ideal case would be a local weather data measurement. This is rarely possible as the effort is very high. A full station would require solar short wave radiation (global and diffuse), air temperature and relative humidity, wind velocity and direction, and precipitation. Especially the short wave radiation equipment requires a supporting construction, expensive sensors, a shading device etc. The acquisition of data sets from a nearby weather station is a common alternative.

Within the building, representative measurement track locations are chosen. In order to evaluate a retrofitted construction with the non-retrofitted construction, two approaches could be realized. The first option is to install measurement equipment prior to refurbishment and record one case after the other. Unfortunately, this limits the comparability as the weather and usage conditions might be completely different in this serial approach. The second option is to install measurement equipment in a refurbished and a non-refurbished reference room or wall section in the same building respectively room. This aspect requires a comparability of the two rooms concerning geometry, materials, usage etc. The advantage of this approach is the simultaneous measurement of both construction variants and thus a good comparability.

After choosing representative locations of measurement tracks, the extent of measurements in form of sensor location within the construction, sensor type (precision, robustness, etc.) and number of sensors are to be defined. A set of additional sensors for the most important points is recommended, as some of the sensors could fall out in the course of the measurement period. A dense grid of sensors is also recommended, as this allows more options for the interpretation of results. One example for such a high-resolution measurement track is given below for the published case study building in Slovakia. The focus of this project was a thermal analysis of the construction. The wall track comprised one temperature sensor at each material interface as well as at the interior and exterior surface. Measurement results for one day are illustrated in Figure 45.

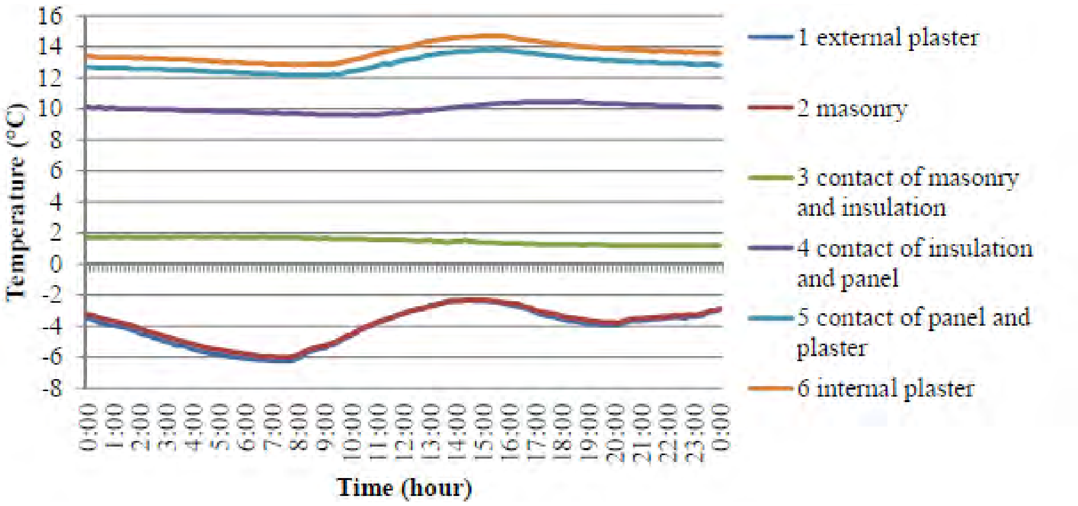


Figure 45: Temperature measurement in different depths of the wall construction: shows fluctuations close to surfaces and stable conditions inside, allows identification of risky positions (Bad'urová, Jošt, Bahleda, & Ďuďák, 2016)

The spatial distribution of sensors is decided for the construction section and for the construction dimension. Besides the measurement of different depths, a measurement in different heights or distances from critical details might be reasonable, e.g. if different initial states are given over the room height because of rising damp prior retrofit. Another reason might be the placement of heaters and their impact on the spatial distribution of wall temperatures. An example for such a track over several heights is given below for the published case study building in Dublin, Ireland. Sensors are placed in the window breast area (reduced wall dimension) and over several heights around the window.

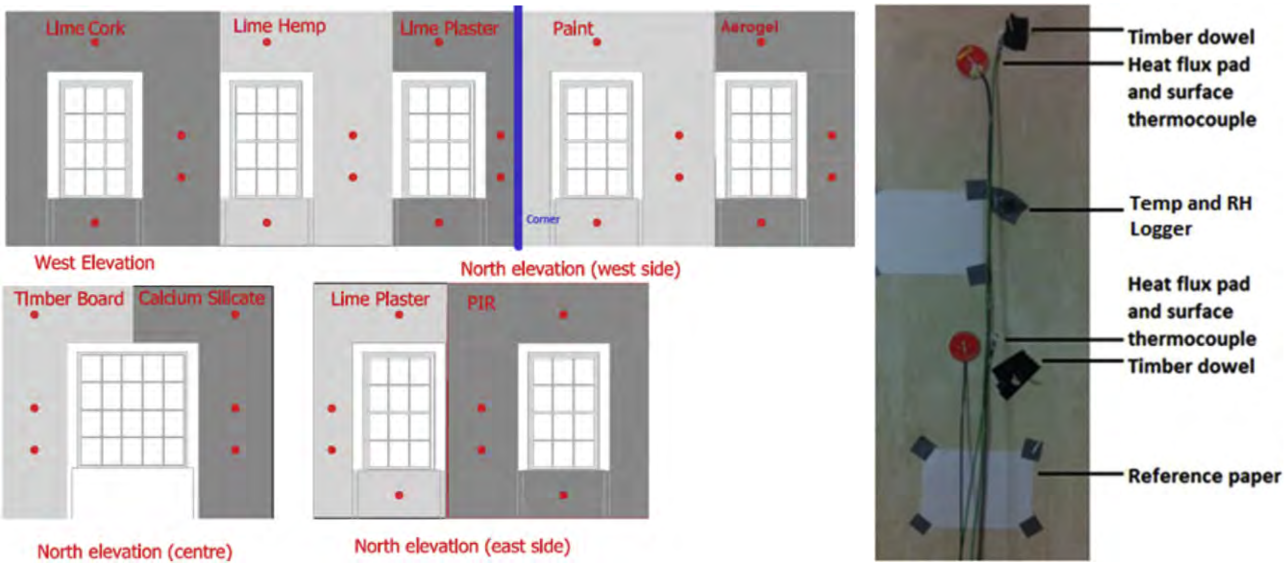


Figure 46: Temperature measurement in different heights and positions of the wall. Left graph shows the distribution of measurement tracks, right graph shows a single measurement track. (Walker & Pavia, 2015)

The placement of sensors is done in different ways in the monitored buildings. Some sensors are inserted through drilled holes from inside. The holes had to be refilled after the insertion. In a project in Canada, these fillings were made with a sealing of the sensor backside via epoxy and a filling of the drilled hole itself via spray foam insulation (temperature sensors) resp. bentonite clay (humidity sensors) (Wilkinson, DeRose, Sullivan, & Straube, 2009).

Another example is illustrated below for the RIBuild case study building in Meinungsgade, Copenhagen. Sensors are all placed in the same height but in two different directions (corner living room) and at the bridge area (exterior wall edge). Furthermore, sensors are placed in the joist ends. In this case, drilled and sensor-filled holes are filled with foam.

Figure 47: Placements of sensors behind beam-ends (left), drilled and sealed with foam, and in notches in the interior render (right), notches for the wire sealed with foam

4.3 Building inspection

An important basis for the creation of a sustainable renovation concept is an on-site inspection. This includes collecting data on local conditions, the state of the building and its usage characteristics. All these aspects are important for the definition of the retrofit concept, e.g. maximum thickness of the insulation, type of the insulation and treatment of bridge areas. For the assessment and detailed design of retrofit variants, additional material parameters are required to allow a realistic prediction of the hygrothermal behaviour via simulation models. An important prerequisite for taking the "correct" remedial measures is the knowledge of bulk density, thermal conductivity, vapour diffusion resistance and liquid water conductivity of the materials in the external wall. Knowing these parameters makes later selection of a suitable internal insulation system easier. It might also show the necessity of accompanying measures like hydrophobizing.

4.3.1 Non-destructive condition assessment

4.3.1.1 Visual inspection

Each building inspection is initiated with a visual assessment of the building. A previous collection of documents, drawings etc., describing the building is helpful. Ideally, the visit takes place directly after a rain event, in order to capture a visual impression of the capillary water absorption of the façade and thus its protective state and, above all, to clearly recognize damage in the splash water area and the roof drainage and its consequences.

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

As part of the visual inspection, a comprehensive, clear photo documentation of the building should be created. It is generally used to document the condition of the building, including the damages, in addition to the plans and other documents relating to the building. It should be used to illustrate which materials, layer thicknesses (photographies with a scale), details, etc. have been implemented in detail. Often the existing plans represent an ideal case, which was not implemented in this way. In practice, deviating wall constructions, materials, dimensions, etc. usually show up.

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

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

4.3.1.2 Temperature and heat flux measurement

Temperature or heat flux measurement is an appropriate non-destructive on-site method to estimate the U-value of the existing masonry as well as the refurbished constructions. A two-step investigation of pre- and post-intervention state is recommended, as the U-value of the existing construction is required for deciding the insulation concept. An overestimation of the U-value for the existing construction should be avoided to cover the critical case (Walker & Pavia, 2015). Masonry U-value is dependent on density and moisture content of bricks and mortar, volume fractions of brick resp. mortar and material combinations (e.g. filling material of low quality in thick walls). An infrared imaging prior selection of U-value measurement points is often helpful to ensure a selection of representative points. Temperature and heat flow measurements are subject to the fluctuations of local conditions, i.e. the results can only be used as a guideline.

4.3.1.3 U-Value estimation via temperature measurement

In this method, temperature sensors are applied to measure the surface temperature of the construction (θ_{si}) and to record indoor and outdoor air temperatures (θ_i, θ_e). Several measurements should be made at different positions to account for variations in masonry heterogeneity and joint fractions before an average U-value is determined. The measured values must be recorded over a sufficiently long period in order to determine a stable mean value. Average condition during these periods should be stable. Otherwise, the heat-up or cool-down process would cause a higher resp. lower U-value than given as heat is stored or released from the building masses. The heat transfer coefficient is calculated according to ISO 9869.

4.3.1.4 U-Value estimation via heat flux measurement

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

An example for this procedure was conducted for the RIBuild case study building in Riga (Catholic Seminar). U-value measurements were done for North and West facades over period of two weeks. Two heat flow measurements on the inside and three temperature measurements (indoor air, indoor surface and outdoor air) were logged. Measurements were carried out in the non-heated parts of the building. Therefore, a temperature difference was provided by a heating box at the inside of the wall.

Figure 48: Heat flux sensor and heated box setup used on the west facade of the RIBuild case study building Catholic Seminar in Riga.

4.3.1.5 Infrared-imaging

Infrared imaging is mainly a valuable method to identify qualitative thermal properties of the constructions. This addresses material discontinuities, thermal bridges, etc. Standard DIN 16714 distinguishes between passive and active IR-imaging. Passive approach employs the existing temperature conditions in the test environment (building) while active IR-imaging approach is based on an initiated temperature condition resp. heat flow, e.g. via controlled heat source or sink. Active IR-imaging is less feasible in buildings and primarily used in mechanical engineering inspections, due to the scale. (ISO 6781:1983, 1983), (DIN EN 16714-1, 2016).

Thermography can be used in a qualitative investigation as well as for a comparative investigation. Detection of material irregularities, thermal bridges, leakages, liquid water accumulation in the building envelope attribute to the quantitative approach. The detection of thermal bridges is subject of a separate standard (DIN EN 13187, 1999). Evaluation of the post- and pre-intervention surface temperatures or comparison of different test fields, e.g. reference wall and insulated wall, attribute to the second approach.

Examples of IR-images are given in Figure 49. In both cases, IR-imaging was used to identify the spatial distribution of the materials and identify typical wall areas for the sensor placement (qualitative thermography). In the Irish project (Walker & Pavia, 2015), it was furthermore used to evaluate the difference between pre and post intervention situation (comparative thermography). The requirements for this comparison are the selection of equal views and similar days with nearly identical temperature conditions in the hours before the measurement for the shots to be compared. The impact of solar radiation and rain should be excluded for this comparison by an appropriate selection of the measurement period, e.g. in a dry phase (rain) and in the morning hours or at overcast sky days (solar radiation). Naturally, the best days for an IR-imaging campaign are during the coldest time of the year, when the highest heat fluxes resp. temperature differences between indoor and outdoor conditions are given.

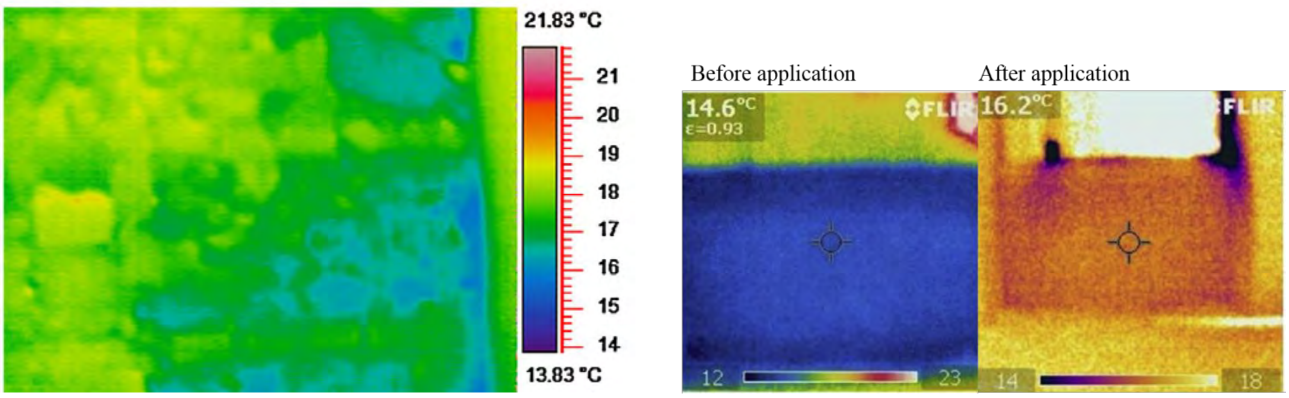


Figure 49: IR-image of a historic irregular wall made of brick and natural stone located in Turin, Italy (left figure) (Bianco, Serra, Fantucci, Dutto, & Massolino, 2015, S. 90, Fig. 6) and IR-imaging of the window sill before and after the application of hemp lime plaster for a building located in Dublin, Ireland (right figure) (Walker & Pavia, 2015, S. 163, Fig. 9).

Accepting a relative high range of uncertainty, a further quantitative study is also possible with passive thermography. As IR-images provide information about the surface temperatures, an estimation of the U-value might be made based on the IR-image boundary conditions (temperature course of the previous day for indoor and outdoor air) and the image results itself. For this application, a selection of days at stable boundary conditions (diffuse solar radiation, reduced daily temperature amplitude) is essential. The disadvantage of this method is the rising inaccuracy for heavy walls. The higher the storage capacity, the more influential is the course of the previous days or hours on the result. An example of this challenge is explained in (Bianco, Serra, Fantucci, Dutto, & Massolino, 2015).

4.3.1.6 In-situ moisture content measurement

An increased moisture load of the construction is not always visible. If, for example, after a summer solar radiation phase, the outer surface of the outer wall has dried, a moisture penetration within the wall core is difficult to determine. On the other hand, surface condensation may be discernible in unused, cold cave spaces in summer, which does not necessarily indicate moisture penetration from the outside, but may be summer condensation. With on-site measurements (if possible in combination with a sampling), sufficiently accurate statements can be made.

Non-destructive moisture measurements provide mainly a qualitative conclusion about the moisture content in the existing building in form of a “wet” – “humid” – “dry” distinction. There are several measurement techniques enabling the identification of water content in existing walls in different depths. (Hola, 2017) (Sandrolini & Franzoni, 2006) (Voutilainen, 2005)

Dielectric moisture indicators were used in a project in Latvia (Biseniece, Zogla, Kamenders, Purvins, & Kass, 2017). The outcomes were compared with a destructive measurement technique and yielded both, quantitative and qualitative differences as shown in Figure 50. Quantitative differences were attributed to the measurement accuracy itself, e.g. the evaporation of moisture due to the drilling of samples. Quantitative differences for the deeper measurements were unexpected and not directly justifiable. It demonstrates that an interpretation of such measurements should be taken with caution. The authors suggest the removal of whole bricks resp. masonry parts for the identification of moisture contents. This is done in other projects, e.g. (Söhnchen & Schoch, 2017).

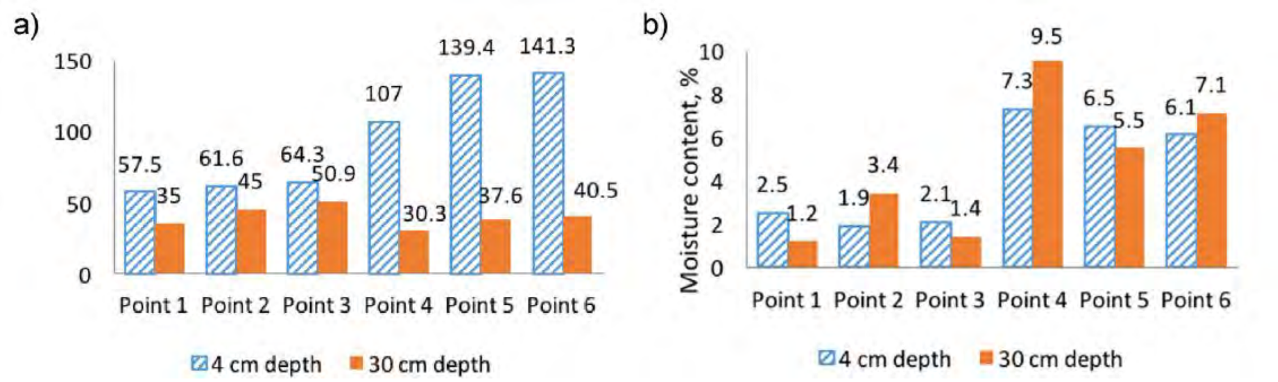


Figure 50: Comparison between a) non-destructive moisture content measurements via dielectric moisture indicators and b) destructive measurements via drill-cores and drying. Blue bars give the results for a depth of 30 cm, orange bars for a depth of 4 cm. Both measurements were done at identical positions (points 1-6) in the wall. (Biseniece, Zogla, Kamenders, Purvins, & Kass, 2017, S. 579, Fig. 2)

4.3.1.7 Capacitive moisture measurement

The capacitive measuring method allows non-destructive moisture measurements in near-surface areas (up to approx. 2-4 cm depth of material depending on the building material density). It is suitable for mineral building materials, but also for wood. The capacitive humidity measurement is based on the functional principle of a capacitor. The procedure exploits the different dielectric constants of dry, non-conductive substances (about 2-10) and water (about 80). Depending on the dielectric, the capacitance of the capacitor changes. The higher the humidity, the higher the electrical conductivity and at the same time the increase in the dielectric constant of the substance to be measured. The complex relative dielectric constant is a material-specific quantity. One factor to be considered is the raw density of the test product. With increasing density, the display value increases with dry and moist material.

The measuring field is formed between the active probe on the upper side of the device and the material to be evaluated. The change in the electric field due to material and moisture is recorded in the meter, converted to digital (output, for example, as a digit unit or also as a conversion in % by weight). The measurement is a relative measurement. The difference between the dry and the wet building material is displayed. Dissolved salts can turn the building material into an electrolytic conductor, resulting in higher capacitance values. This method is well suited for comparative measurement to detect differences between wet and dry areas, but is considered unsuitable for qualified humidity measurements. It is suitable as a pre-tester for the following destructive measuring methods.

4.3.1.8 Resistance moisture measurement

In the resistance measurement, current is passed through the material to be measured by means of two electrodes that are hit, rammed or drilled into the material. The electrical resistance is measured as a function of the electrical conductivity. In dry building materials, the resistance is very high, as dry building materials conduct the power poorly. Thus, a low reading is displayed on the meter. As the moisture content of the material increases, so does the conductivity, as the water contained in the material conducts the stream well. This displays a higher reading. With the measuring method, the moisture content at the material surface, but also in deeper component layers can be measured. However, drilling is required to allow longer electrodes to be inserted. The displayed measurement results can be converted into moisture percentages taking into account different building materials. Falsifications of the measurement results are possible due to unequal moisture distribution and inhomogeneity in the material, due to other conductive materials in the wall, e.g. Cables, lines or cleaning rails, salts in the building material, surface treatment or poor contact of the electrodes to the material. By several measurements, however, such incorrect measurements can be corrected somewhat.

Figure 51: Examples of a resistance humidity measuring device (Source: left: testo.com, right: www.gann.de)

This type of moisture measurement was conducted in the case study building in Brüttelen, Switzerland. The chosen equipment is shown below in Figure 52.

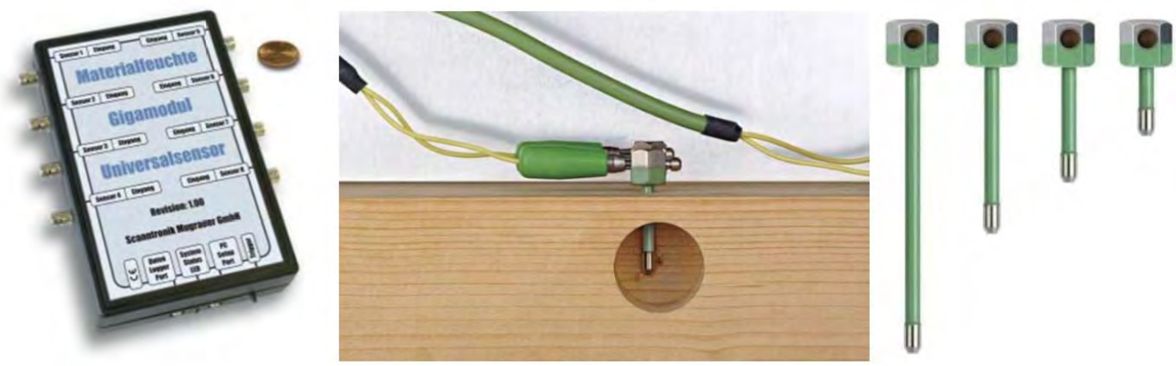


Figure 52: 8-fold extension module, measuring cables and electrodes to measure moisture content in masonry and rendering.

4.3.1.9 Microwave moisture measurement

This measurement method is also a non-destructive method. The measuring principle is the radar reflection method, which allows a one-sided application of the applicators to the material to be measured. The waves are reflected as they pass through the material and detected by a meter. The method belongs to the dielectric measuring methods, i.e. the measurement is based on the determination of the permittivity of a medium to be examined. Since the dielectric constant of water is significantly higher than the usual building materials, the moisture penetration of the examined building materials causes a significantly increased measured value.

Using different applicators, various measuring depths can be realized with the penetrating method with high sensitivity, from near the surface to a penetration depth of 800 mm. Non-destructive systematic multi-layer raster moisture measurements can be carried out and graphically displayed as both areal and depth-resolved moisture distributions. Thus, a distinction in near-surface moisture and moisture in the core of components is possible. Moisture damage can be clearly classified and multi-dimensionally characterized with the area-based grid moisture measurements, since different patterns of moisture distribution are produced depending on the type of moisture damage. In particular, damage from rising damp and leaks can be easily identified with volume measurements (at various depths). In the sensors, material-specific calibration curves of various building materials are integrated.

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

Figure 53: Example of a microwave moisture analyser with different measuring heads (Source: hf-sensor.de)

This type of measurement was used in the RIBuild case study building in Latvia (Catholic Seminar). Walls of the building were scanned with non-invasive microwave moisture meter to qualitatively assess moisture in the wall at 30 mm depth. The North facade was scanned on all three floors. West facade was scanned on the ground and first floor, since second floor on this facade is heated. Measurements were done at a 0 – 2 m above the floor by dragging the sensor in line patterns. Boundaries of readings were registered for each floor and facade.

4.3.1.10 Further measurements

For the case study building in Dankepi, Latvia, Time domain reflectometry (TDR) measurements were used. The measurement shows an accuracy of ±2.5% for the volumetric water content (VWC). An operational temperature from 0 to 70 °C was used in external walls of living room and bathroom. Prior to installation, the sensor rods have been shortened to 100 mm length (due to restriction in drilling depth) and calibrated in laboratory by using sample dolomite stone from the case study building. Water content graph was obtained for sample dolomite stone. Full saturation of the stone was at 22.5%.

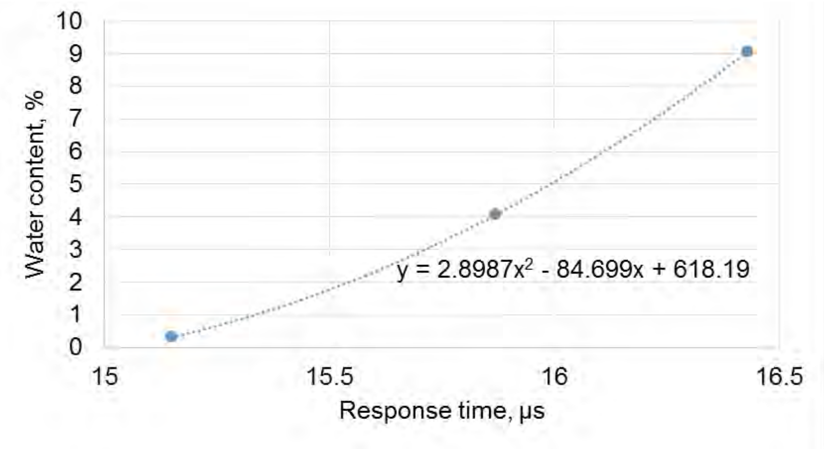


Figure 54: Calibration graph for TDR sensors in Dankepi, Latvia.

Water content measurements are shown in Figure 55. The building's dolomite stones showed a density from 2060 to 2340 kg/m³ and an average water content per volume of 11% (7-14%), determined by immersion in water. Monitoring results showed that water content mostly stayed below 8% in both measurement points.

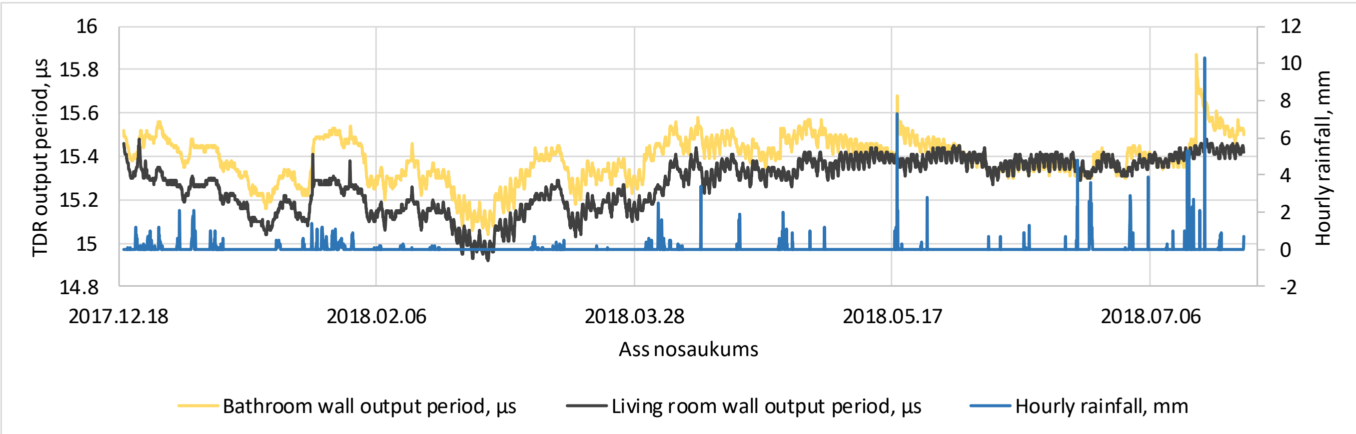


Figure 55: Output period of TDR probes.

Another measurement principle was conducted in the case study building in Klitgaarden, Denmark, The Troxler measurement. Troxler equipment measure an equivalent to moisture content and do this with the uses of a radioactive source. A neutron source within the Troxler emit neutrons and with a selective measuring of the returning neutrons the moisture content can be assessed. This method requires reference measurements for each material to calibrate the Troxler results. Measurements with the Troxler were carried out at two separate building visits. Once before application of the interior insulation, with access to the walls' interior side and another visit after application with access from only the outside. The researchers completed measurements in two or three heights and at many positions.

All measurements are condensed in the following diagram. It differs whether one position have:

- External measurements from first visit, light blue.
- In addition external measurements from second visit, sand yellow.
- In addition interior measurements from first visit, dark blue.

Height increases away from the thick line, e.g. the nearer the thick line the lower height a value is measured. The thick line is an offset of the wall i the plan, numbers between the two are from interior measurements (possible before insulating). Yellow boxes are frequent exception from this.

Figure 56: Troxler measurements before insulating and again after insulating. The first values in a double column (shown with faded and thick dashed line) contain 2016 and 2017 measurements (e.g. upper left:12, 13, 15 & 12, 14) measured in the middle of the covered wall length while the following single column include 2016 and 2017 measurements (e.g. upper left: 14, 13 & 15, 13) below the window. The third column only include measurements from 2016. Heights stated are measured from the foundation. Yellow boxes are placed where possible due to space limitations. Values from 17 to 25 are assessed as in transition between non-critical and critical moisture content for bricks while above 25 is critical.

Figure 57: Troxler measurement tool standby while other measurements are carried out (left). Troxler equipment in use (right) (Brandt & et al., 2013).

4.3.1.11 Measurement of capillary water absorption

An on-site inspection provides a first impression of the capillary water absorption of the façade. Helpful information is especially expected at a visit just after a rainfall event. However, different weather conditions are required for the measurements of the capillary water absorption of the façade. The temperature should exceed 5 °C for several days and the wall should be relatively dry. This means, a rainfall event should be dated back several days. Ideally, the measurement should take place in late afternoon, since then a falsification of measured values can also be excluded by possibly existing nocturnal surface condensate on the facade. Different simple in-situ tests exists for the estimation of water absorption: wetting test (besprinkling, visual inspection), Karsten tube test, and Franke panel test.

A disadvantage of in-situ test methods is the multi-dimensional transport of liquid water. This represents not the same situation as for the one-dimensional transport initiated in lab tests. This particularity is less relevant for less absorptive materials. The same is true for the measurement error. This is especially high for highly absorbing materials. Enhanced methods with additional water chambers aside the test water tube reduce side transport effects (e.g. Pleyers test tube).

An advanced in-situ test method with a better accuracy but also a higher measurement effort is the test apparatus developed by Stelzmann ((Stelzmann, Berg, Möller, & Grunewald, 2016) , (Stelzmann, 2013). This creates a water film instead of the hydrostatic pressure in Karsten and Franke devices and shows a good accordance with laboratory measurements. In general, in-situ test methods for the water absorption result in remarkably higher values than laboratory procedures, e.g. gravity promotes water uptake.

4.3.1.12 Wetting the facade

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

4.3.1.13 Karsten test tube

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

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

Karsten tube measurements were conducted in several RIBuild case study buildings, for example in Spikeri building in Riga, Latvia. Water uptake tests were carried out with the Karsten tube on the external surface covered with water repellent hydrophobic paint Lotusan. Three measurement points of undisturbed wall were selected. At the first point the paint has peeled off due to humidity influence (rain water pipes are not cleaned and water was falling on the wall). The second point was a plain layer of paint, one meter above the point with peeled paint. The last point was a plain layer of paint.

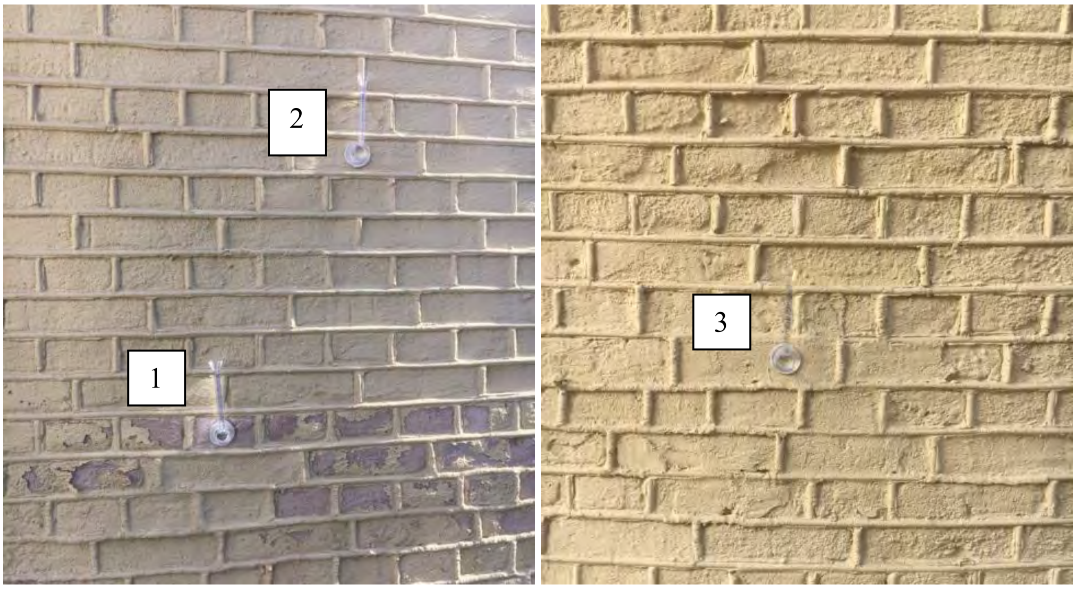


Figure 58: Three measurement points of undisturbed wall in Dankepi, Riga (Latvia): (1) the paint has peeled off due to humidity influence, (2) plain layer of paint 1 m above the point with peeled paint and (3) plain layer of paint.

Results of the Karsten tube measurement are presented in Figure 59. The grey curve represents the painted area of the masonry. The water column height did not drop within the 20 minutes of measurements. The water absorption of the stone with slightly peeled-off paint (orange line) showed only a small reduction during this measurement time. In contrast, the stone with completely peeled-off paint shows a very high absorption (blue curve). The water column of 5 cm was sucked by the stone during less than seven minutes. The second water column was even absorbed within five minutes by the wetted and uncoated stone.

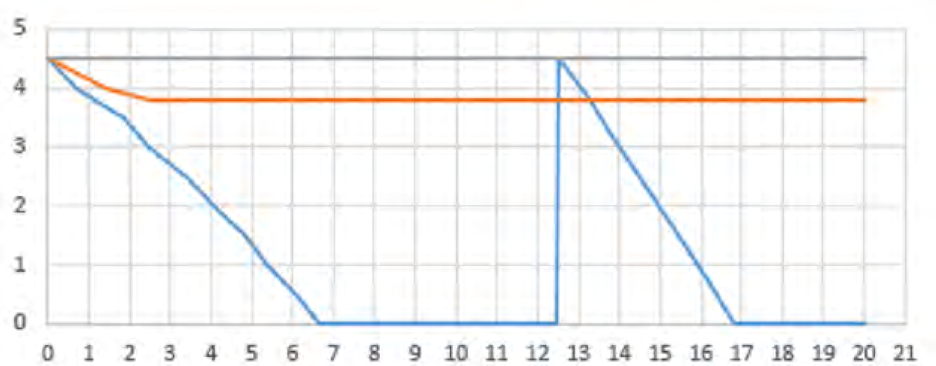


Figure 59: Water uptake test results (Karsten tube) from RIBuild case study building Spikeri, Riga (Latvia): the paint has peeled off due to humidity influence (blue line), plain layer of paint 1 m above the point with peeled paint (orange line) and plain layer of paint (grey line). Y-scale gives the scale of the Karsten tube water column, X-scale gives the time in minutes.

Similar measurements were performed in the case study building in Haderslev (Denmark) (Figure 60). In this case, a comparison between different measurement points within the brick-joint pattern was made. It illustrates how influential a representative measurement position is. Visual inspection of the façade revealed no major cracks or damage. Karsten tube experiments have been carried out on brick and mortar joints. Results are shown as average and standard deviation of three tests on both brick and mortar (Table 11).

Table 11: Water uptake test results (Karsten tube) in RIBuild case study building Klitgaarden (Denmark)

	Absorbed in 5 minutes [ml]	Estimated sorptivity, by Hendrickx' method [kg/m^{2}s^{½}] based on (Hendrickx, 2012)
Brick	1.8±0.3	0.00677±0.00084
Mortar joint	12.5±5.4	0.0168±0.00038

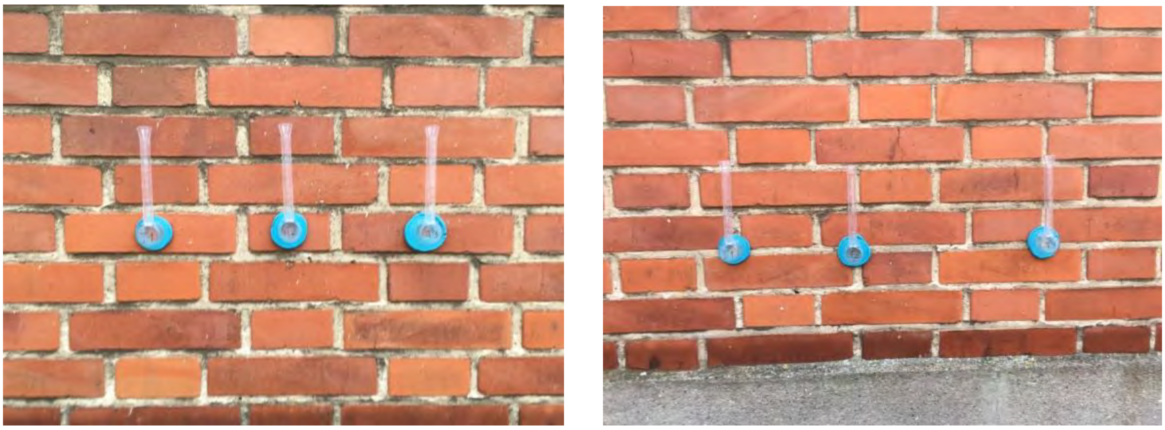


Figure 60: Karsten tube measurements on Bricks (left) and joints (right) for RIBuild case study building in Haderslev (Denmark).

The comparison shows that the mortar joints have a much larger sorptivity than the bricks.

4.3.1.14 Franke test panel

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

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

4.3.1.15 Water absorption measurement device by Stelzmann

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

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

4.3.2 Destructive tests

Destructive tests are also required for the proper evaluation of material characteristics and thus especially for the hygrothermal characterization that is required for hygrothermal simulations. These tests are not explained in this report, as they are subject of WP2. The following extracts should only give an impression of some basic properties, which are determined in the frame of the case study buildings.

The first example is the measurement of hygrothermal properties for the case study building in Brüttelen, Switzerland (Figure 61, Table 12). As the shell limestone material in this residential building was not known, basic characteristics were measured in order to find a matching material in the database of the software tool that was used for the prediction of retrofitted construction's hygrothermal behaviour.

Figure 61: Samples from Brüttelen quarry of shell limestone probably used for the construction of the monitored building. Picture taken by IBP.

Table 12: Properties of Brüttelen shell limestone measured on samples by IBP.

Property	Symbol	Unit	Value
Density	ρ_{Roh}	$kg.m^{-3}$	2366
Particle density	ρ_{Rein}	$kg.m^{-3}$	2708
Porosity	ϕ	$m^3.m^{-3}$	0.11
Thermal conductivity	λ	$W. m^{-1}.K^{-1}$	2.25
Thermal capacity	C_p	$J.kg^{-1}.K^{-1}$	850.0
Water vapour resistance factor	μ	-	203 if ϕ_i [0 – 50]% 67 if ϕ_i [50–100]%

In the frame of the tests performed in Catholic Seminar building in Riga, Latvia, frost resistance of the bricks was measured. Eleven brick samples were subjected to fifteen freezing-thawing cycles. Six brick samples were tested at full water saturation. Five were tested with the maximum predicted winter saturation level determined in a hygrothermal simulation. This was achieved by soaking samples to maximum, then drying to the desired moisture content and covering with evaporation-proof film before starting the cycles. Test results are presented in Figure 62. Fully saturated samples split or formed critical cracks between 2 to 6 cycles. Samples saturated to 20% of total volume have no visible damage after 15 cycles.

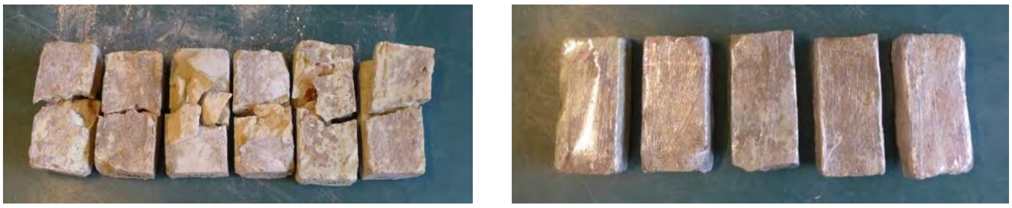


Figure 62: Bricks after 15 frost-thaw test cycles. Left: Fully saturated samples (~36%). Right: Samples saturated to 20%.

5 Conclusions

The majority of analysed case study buildings had external walls made of plastered brickwork. In some cases, the basement resp. first floor walls were made of natural stone and only the upper floors consisted of solid brick masonry. In this case, applied natural stones were sandstone and rubble stone. The masonry thickness varied between 250 and 790 mm with an average of about 450 mm. The average U-value was about 1.6 W/m²K for the historic walls before insulation. The average achieved insulation level (U-value) of the retrofitted constructions was 0.46 W/m²K for the published cases and 0.33 W/m²K for the RIBuild cases. The chosen thermal resistance of the insulation system (R-value) seemed not to be defined in the context of existing wall thermal resistance, although the relationship between these two values are decisive for the change of thermal conditions in the wall and thus the potential damage risk.

A possible dependency of the chosen thermal insulation resistance on the level of driving rain protection of the existing wall (e.g. provided via exterior rendering, hydrophobizing, or clinker brick cover) cannot be evaluated for all cases, especially for the published ones, as this information is mostly not provided. This should be improved in future case studies. Driving rain protection is an essential factor for the performance of internally insulated buildings.

In the majority of the published case studies and the RIBuild case studies, undisturbed walls have been equipped with measurement tracks. 35 projects combined these wall measurements mainly with tracks in the joist ends, partially with tracks in the external wall edge or around the window. In most cases, the extent of measurement should have been greater to evaluate the risky points of interest and compare different constellations in a single building (e.g. different façade directions).

In the majority of cases with critical conditions, there is only an initial exceedance of the threshold values for relative humidity resp. wood moisture content in the drying period (first years) of the monitoring phase. Most of the evaluated constructions showed uncritical conditions, several showed only initially critical conditions and five cases were problematic. A closer look to the insulation materials of critical projects show a huge variety with VIP, mineral wool, Aerogel, PU and EPS. Neither of these materials are belonging to the group of condensate-tolerating resp. capillary active materials. In general, a sufficiently long monitoring phase is needed to detect whether critical conditions are still present. The more vapour-open and capillary active the construction is and the smaller the built-in moisture, the shorter is the drying period. It spans at least two or three years. In many of the analysed cases, this is longer than the measurement period.

The analysis of weather conditions and reported damage or damage indicators yielded a link between location, especially the closeness to the sea (high average wind velocity) and the annual precipitation sum, with reported risks indicators for the published case studies. Four of the five northernmost locations in the published case studies were rated as risky due to high measured moisture levels in the walls. Some of them did not feature an adequate driving rain protection. In general, information about the driving rain protection, e.g. the quality of the external rendering were not given in the published cases.

Four of the RIBuild case study buildings were reported with damage risk indicators. Two of them were lacking of a proper driving rain protection (no exterior rendering, no roof overhang), three of them were exposed to high precipitation levels during the measurement period, and all of them showed additional moisture load as built-in moisture of the insulation system. The drying behaviour of these constructions is therefore of higher interest. Especially the usage of the building in the first month after retrofit should be suitable to promote the drying process.

Interior boundary conditions were another analysed aspect of boundary conditions. They were unfortunately only documented in form of usage types for the majority of published case studies. Most of the buildings were used for residential purposes, some as educational buildings and office buildings. A relevant number of them was not permanently used or discontinuously used.

An important basis for creating a sustainable renovation concept is an on-site inspection. This includes collecting data on local conditions, the state of the building and its usage characteristics. All these aspects are important for the definition of the retrofit concept, e.g. maximum thickness of the insulation, type of the insulation and treatment of thermal bridge areas.

For the assessment and detailed design of retrofit variants, additional material parameters are required to allow a realistic prediction of the hygrothermal behaviour via simulation models. On-site measurements allow only coarse characterization of the constructions and should be supplemented with laboratory tests. An important prerequisite for taking the "correct" remedial measures is the knowledge of bulk density, thermal conductivity, vapour diffusion resistance and liquid water conductivity of the materials in the external wall. Knowing these parameters allows a realistic hygrothermal simulation of the future performance of these retrofitted buildings.

Appendix I: Table of RIBuild Case Studies

	**Dankepi** **Sece Parish, Jaunjelgava Country** **Latvia** **(RTU)**
Insulation:	Version A: mineral wool (λ=0.035 W/mK, ρ=60 kg/m³), 150 mm Version B in bathroom: mineral wool (same properties), 200 mm insulation in timber frame, supplemented with vapour retarder, covered with double plasterboard
Type of insulation:	vapor permeable and capillary inactive insulation
Year of construction:	The case study building was built in 1893 as farmer's house.
Retrofit periods:	Energy efficiency was improved by applying internal insulation in 2006 and additional improvements were carried out in 2015. The main goal was to increase indoor temperature in cold periods and reduce wood fuel consumption.
Description:	The building has two floors. In 1992, the building was denationalized and the ownership of the building was retrieved by the original owner's family. During the Soviet period, the building was poorly maintained and worn out, and the building owner has decided to invest in the renovation of the building in 2006 and improved in 2015.
Building usage:	Originally used as one family house for one farmer family, during the Soviet period it was nationalized and inhabited with more than five families. Although the building is residential, during the Soviet times the basement was used as cattle shed which had led to severe damages of wooden beams and ground floor floors. After renovation, only one part of the building is used all year around. The rest of the building is used during weekends, holidays and summer.
Building location:	Sece Parish, Jaunjelgava Country, Latvia
Construction:	Historic dolomite wall with varying thickness of 450 to 600 mm, original plaster (20 mm), mineral wool insulation with vapor barrier, plaster board
Measurements:	Temperature, relative humidity, volumetric water content (TDR) and heat flux sensors were installed in non-disturbed walls in Northeast façade.
Points of interest:	Indoor climate was measured. Wall integrated temperature and relative humidity sensors measure temperature between the dolomite wall and insulation layer and between insulation layer and plasterboard.
Outcomes:	Hydrothermal behaviour of the external wall indicates that regarding mould growth construction is in the safe area considering that in the normal conditions (excluding water leakage accident) the relative humidity between insulation layer and plasterboard and in the room stays relatively low (below 60%). al .(2010) mould growth can occur at 80% high relative humidity if temperature is at least 20˚C for porous materials. Temperature measurements shows that external part of the dolomite wall undergoes repeated freeze thaw cycles, but risk of frost decay is low, as dolomite does not reach its saturation.

	**Spikeri** **Maskavas Str 8., Riga** **Latvia** **(RTU)**
Insulation:	Version A: 50 mm aerogel mat (λ=0.018 W/mK) Version B: 50 mm and 100 mm polyisocyanurate (PIR) (λ=0.023 W/mK) Version C: 50 mm vacuum insulation panels (VIP) (λ=0.008 W/mK)
Type of insulation:	Version A: vapor permeable (vapor retarder) , capillary inactive Version B: vapor permeable (vapor retarder) , capillary inactive Version C: vapor tight
Year of construction:	The case study building was built in 1930.
Retrofit periods:	Renovation of the building was carried out in 2012 – 2013 within the project “Co2ol Bricks - Climate Change, Cultural Heritage & Energy Efficient Monuments“ (Baltic Sea Region Program 2007-2013).
Description:	The buildings has one floor, a cylindrical shape and a small floor area of less than 60 m².
Building usage:	Before renovation, this naturally ventilated building was used as public restroom while during last years it was utilised as storage facility without heating. Until now, the building is still used as public rest room.
Building location:	Spīķeri quarter is located in Riga, Latvia. This is a historic red brick warehouse district built between 1864 and 1886.
Construction:	External walls of the building are built from externally painted silicate bricks in a thickness of 510 mm.
Measurements:	During renovation of the building temperature and heat flux sensors were installed within internal insulation materials (aerogel and VIP) at the North and North-West facing facades. Furthermore, temperature sensors were installed between the insulation layers (aerogel: in 10 mm distance steps for 6 positions and VIP: in 25 mm steps for 3 positions) of external walls and additionally between masonry-insulation and between insulation-plasterboard (at both positions also in PIR field with additional relative humidity). Outdoor and indoor temperature and relative humidity measurements were performed as well. Measurement periods are between January and November 2014 (phase I) and since October 2017 (phase II).
Points of interest:	The main goal of monitoring activities is to study hygrothermal performance of silicate bricks wall retrofitted with different internal insulation in cold climate. The pre-renovation analysis includes an assessment of the energy balance, moisture content, salt presence, and damages and construction details.
Outcomes:	It can be concluded that VIP ensures the best insulation, but relative humidity between masonry and insulation layer is high: 7% of measurement time above 90% and 51% of time above 80% (in PIR: only 3%, in aerogel: 55%). Water content measurements are mostly below 4%. There is no risk of mould growth as between wall construction layers where suitable relative humidity (above 80%) is, temperature stays below 10˚C. Risk of frost decay due to temperatures drop below 0˚C in the masonry is low as bricks do not reach their saturation.

	**Catholic Seminar** **O. Vaciesa Str. 6, Riga** **Latvia** **(RTU)**
Insulation:	Mineral wool 50 mm (λ=0.035 W/mK, ρ=60 kg/m³) in timber frame supplemented with vapour retarder, covered by double plasterboard
Type of insulation:	Vapor permeable (vapor retarder), capillary inactive
Year of construction:	The case study building was designed by famous architects Heinrich Sheel and Freidrich Scheffel and was built in 1910.
Retrofit periods:	Renovation of the building was carried out in 2017. The main goal was to reduce GHG emissions in historic buildings.
Description:	The case study building is L shaped and has three floors on the W-E wing, two floors on the N-S wing and the basement.
Building usage:	The case study building was built in 1910 as psychiatric clinic known as Sokolovskis' clinic. Since 1923, it is owned by Catholic church and used as Catholic seminar. During Soviet period the building was used as hospital and elderly house. The Catholic Church retrieved it back in 1992. Most premises (except for few rooms on the last floor on Western and Eastern facades) in the building have not been used for several years. The building was not heated during winter 2017/2018 (monitoring phase).
Building location:	O. Vaciesa Str. 6, Riga, Latvia
Construction:	Historic masonry in the ground floor shows a thickness of 660 mm, consisting of a brick shell outside, a cavity of 100 mm and a load-bearing bricklayer. It is covered with 20 mm exterior rendering and 20 mm interior plaster. The wall thickness in the basement is wider (700 mm), in the first and second floor smaller (550 to 660 mm).
Measurements:	During renovation of the building temperature and heat flux sensors are installed within internal insulation material of external walls in non-disturbed walls in North and West facades. Temperatures and relative humidity were measured between brick wall and insulation, between insulation and plasterboard and furthermore for indoor and outdoor conditions. Heat flux and temperature sensors were installed at the inner surface. Weather condition measurement was installed on the roof.
Points of interest:	The main goal of RiBuild monitoring activities is to study hygrothermal performance of masonry wall retrofitted with internal insulation in cold climate.
Outcomes:	Temperature in the room is steady and even in the colder winter days stays above 10ºC. As rooms are not used, there are no any moisture sources. Relative humidity stays below 60% during winter and increases during summer reaching 80%. Relative humidity between masonry and insulation stays below 80% and between insulation and plasterboard below 60%, the same as in the room. The same situation is in the wall on the 2nd floor.

	**Thomas Laubs Gade** **Copenhagen** **Denmark** **(DTU)**
Insulation:	iQ-Therm 30 mm (λ=0.031 W/mK, ρ=70 kg/m³), completed with glue mortar (iQ-Fix), and iQ-Top and iQ-Fill on the surface.
Type of insulation:	Vapor permeable (retarding) and slightly capillary active. iQ-Therm is marketed as a capillary active insulation system. It consists of a PUR foam, with channels of calcium silicate in a 40x40mm grid.
Year of construction:	The building is a multi-storey residential building from 1899.
Retrofit periods:	During renovation in 2015, internal insulation was applied to eastern facade.
Description:	The building itself consists of 1300 m² spread over four floors. The building is built in traditional Danish style, with solid masonry and embedded wooden beams and lath for floor separations.
Building usage:	The occupancy of this apartment is unknown, however normal occupancy and usage (living) is assumed. The heating for the building is provided by district heating through radiators. It is assumed there is neither cooling nor ventilation system in the apartment.
Building location:	The case building is located in Copenhagen. The city is located on the eastern coast of Zealand. This building is located in the borough called Østerbro.
Construction:	The external walls consist of 1½ brick (350mm), and the surface of the masonry is blank and untreated. The walls are rendered on the inside. , the floor separations consist of wooden beams embedded in the external walls. These beams are supported by a wooden lath. The wooden parts of the wall construction can be considered critical points.
Measurements:	Four combined temperature and relative humidity (T and RH) sensors are installed in the test room. Three sensors are located at the wall-insulation interface (wall – eastern façade) and one sensor is monitoring the indoor climate.
Points of interest:	By means of the hygrothermal measurements, damage models (mould index, wood decay) can be introduced in order to assess potential risks associated with the altered hygrothermal conditions following internal insulation
Outcomes:	The measured indoor climate appears rather normal with the highest relative humidity in winter times, and lowest in summer. It can be seen that in the first winter season (2015) the relative humidity exceeds 65%, which can be attributed drying of construction mortar. Unfortunately, the data was found insufficient for application of the mould model, due to the fact that data from the first year can be disregarded due to the alkaline conditions in the cementitious glue mortar and a fall out of measurements for four months. The initial moisture content is (naturally) very high (100%), but after a year it appears to fall below the 85% mark. Further reduction is expected

	**Residential building** **Haderslev** **Denmark** **(DTU)**
Insulation:	iQ-Therm 80 mm (λ=0.031 W/mK, ρ=70 kg/m³), completed with glue mortar (iQ-Fix), and iQ-Top and iQ-Fill on the surface.
Type of insulation:	Vapor permeable (retarding) and slightly capillary active. iQ-Therm is marketed as a capillary active insulation system. It consists of a PUR foam, with channels of calcium silicate in a 40x40mm grid.
Year of construction:	The building was built in 1932.
Retrofit periods:	During renovation in 2015, internal insulation was applied to a room on the upper floor.
Description:	The building is a two-floor residential building with 130 m² living area. It is built in typical Danish style with gable roof with eaves, masonry and wooden beams as floor separations. The insulated room is on the 2nd floor.
Building usage:	The building is occupied by a family of two adults and one child. The occupants are expected to have a normal work/school schedule. The heating system in the building is supplied by district heating through radiators, there are no cooling and the ventilation system.
Building location:	The building is located in Haderslev, in the southern part of Jutland, the peninsula of Denmark. The building is located in a residential area with primarily one family houses.
Construction:	The external walls consist of 1½ brick (350 mm), and a blank external surface. The walls are rendered with approximately 10 mm on the inside. As traditional Danish building style, the floor separations consist of wooden beams embedded in the external walls. These beams are supported by a wooden lath. The wooden parts of the wall construction can be considered critical points
Measurements:	Seven combined temperature and relative humidity sensors are installed in the test room. Three sensors are located at the wall-insulation interface (western and southern façade) and three sensors behind the wooden beams (western façade). A seventh sensor is monitoring the indoor climate. The sensors at wall-insulation interfaces are placed in a height of about 1.5 m.
Points of interest:	The focus is monitoring the hygrothermal conditions (temperature and relative humidity) at wall-insulation interfaces, and behind wooden beam-ends, as these are areas of risk and interest. Furthermore, the interior climate is monitored. Damage models (mould index, wood decay) are introduced in order to assess potential risks associated with the altered hygrothermal conditions following internal insulation.
Outcomes:	The indoor temperature and indoor relative humidity are not out of the ordinary. The latter mainly fluctuates between 35-65%. Relative humidities in the wall are above 98% for the duration of the measuring period that is more than two years. The measured data has been applied to the VTT mould and decay models, which led to a prediction of high, and unacceptable mould indexes and furthermore extremely high wood decay risk.

	**Meinungsgade Copenhagen Denmark (DTU)**
Insulation:	Kingspan K17 60 mm (λ>0.020 W/mK, ρ>35 kg/m³), fastened with glue mortar and covered with gypsum boards.
Type of insulation:	Vapor permeable (retarding) and capillary inactive
Year of construction:	The building is a multi-storey residential building from 1877.
Retrofit periods:	During renovation in 2014, internal insulation was applied to south and southwestern facade.
Description:	The building itself consists of 790 m² spread over five floors. The building is built in traditional Danish style, with solid masonry and embedded wooden beams and lath for floor separations.
Building usage:	The occupancy of this apartment is unknown, however normal occupancy and usage (living) is assumed.
Building location:	The case building is located in Copenhagen, in the borough called Nørrebro. Nørrebro started to form in the 1850's, as the previous city boundaries were removed.
Construction:	The external walls consist of 1½ brick (350mm), and a blank surface. The walls are also rendered on the inside. The floor separations consist of wooden beams embedded in the external walls. These beams are supported by a wooden lath.
Measurements:	Seven combined temperature and relative humidity sensors are installed in the room. Three sensors are located at the wall-insulation interface (two in southwestern façade and one in southern façade) and three sensors behind the wooden beams (at southwestern façade). A seventh sensor is monitoring the indoor climate.
Points of interest:	The focus is monitoring the hygrothermal conditions (T and RH) at wall-insulation interfaces, and behind wooden beam-ends as these are areas of risk and interest. Furthermore, the interior climate is monitored. By means of the hygrothermal measurements, damage models (mould index, wood decay) can be introduced in order to assess potential risks associated with the altered hygrothermal conditions following internal insulation.
Outcomes:	Relative humidity in the walls after second measurement year stays mainly below 80% with some short-time exceptions. The conditions in the beam-ends fluctuate harmonically without drying tendency and show values of up to 90%. The results from in situ measurements generate mould indexes (VTT mould model) above 1 in most cases, with the exception of sensors 2 and 4, both at the wall interfaces. All beam-ends reach a maximum mould index of 3-4.

	**Kildeværdsgade** **Copenhagen** **Denmark** **(DTU)**
Insulation:	Kingspan K17 25 mm (λ>0.020 W/mK, ρ>35 kg/m³), fastened with glue mortar and covered with gypsum boards.
Type of insulation:	Vapor permeable (retarding) and capillary inactive
Year of construction:	The building was built in 1905.
Retrofit periods:	During renovation in 2015, internal insulation was applied to northern facade.
Description:	The building is a multi-storey residential building from 1905. The building itself consists of 700 m² spread over four floors. The building is built in traditional Danish style, with solid masonry and embedded wooden beams and lath for floor separations.
Building usage:	The occupancy of this apartment is unknown, however normal occupancy and usage (living) is assumed.
Building location:	The case building is located in Copenhagen, in the borough called Østerbro. Østerbro was created in the 1800s as Copenhagen expanded, and by the 1880s, the multi-story buildings were blooming in Østerbro.
Construction:	The external walls consist of 1½ brick (350 mm), and a rendered and painted external surface. The walls are rendered with approximately 10 mm on the inside. As traditional Danish building style, the floor separations consist of wooden beams embedded in the external walls. These beams are supported by a wooden lath.
Measurements:	Seven combined temperature and relative humidity sensors are installed in the room. Three sensors are located at the wall-insulation interface (northern façade) and three sensors behind the wooden beams (northern façade). A seventh sensor is monitoring the indoor climate.
Points of interest:	The focus is monitoring the hygrothermal conditions (temperature and relative humidity) at wall-insulation interfaces, and behind wooden beam-ends, as these are areas of risk and interest. Furthermore, the interior climate is monitored. Damage models (mould index, wood decay) are introduced in order to assess potential risks associated with the altered hygrothermal conditions following internal insulation.
Outcomes:	Relative humidity in the wall is below 75% in the third year of measurements. The values measured behind the beam-ends are slightly higher but still uncritical with values below 80%. The measured data has been applied to the VTT mould and decay models, which led to a prediction of no mould growth risk (mould indexes permanently 0).

	**Graziosi's house** **Cattolica** **Italy** **(UNIVPM)**
Insulation:	EPS insulation (60 mm) mounted with adhesive mortar (10 mm) and covered with interior plaster (6 mm), final U-Value ranges between 0,48 W/m²K (290 mm wall) to 0,53 W/m²K (160 mm wall)
Type of insulation:	Vapor permeable, capillary inactive
Year of construction:	The villa was built around 1935.
Retrofit periods:	A general retrofitting of Graziosi's House was performed in 2003, to improve the energy efficiency and the indoor comfort. Since the house is a locally listed building, an interior insulation system was implemented and supplemented with further measures, e.g. replacement of windows, insulation of roof and renewal of the heating and DHW equipment.
Description:	Graziosi's House is a three-storey, semi-detached house. At the ground floor, there are living room, kitchen, services and a veranda. At the first floor, there are two bedrooms, a study room and services.
Building usage:	A single family of three people lives in the house. It is occupied throughout the year. The heating seasons spans from October until April.
Building location:	The case study is a private house located in Cattolica, a town in the centre of Italy. It is a coastal town next to the Adriatic Sea.
Construction:	The external original walls are built in plastered brick masonry with variable thicknesses, from 290 mm (U=1.76 W/m²K) to 160 mm (U= 2.58 W/m²K). The material layers of the original walls are 20 mm of external plaster (lime and cement based plaster), 250 to 120 mm brick masonry and 10 mm interior plaster (lime and gypsum based plaster).
Measurements:	A temperature and relative humidity probe was installed inside a small cavity in the intrados near the connection of the wooden beam and the insulated external wall. Two sensors measured the surface conditions of the wall (northeast oriented), both in the internal and the external sides. An additional sensor was used to monitor the indoor climate of the room (temperature and relative humidity). The outdoor climate was monitored by a weather station. The installation of the monitoring system was performed in December 2016 and it was tested for a month to check the system affordability. Data collection started in January 2017.
Points of interest:	The on-site experimental activity focuses on the impact of internal insulation on the building envelope, especially near the connection between the wooden beam and the insulated masonry, in order to evaluate the failure risk and the possible mould growth.
Outcomes:	Recorded relative humidity values were always below the LIM II. In conclusion, with the Sedlbauer's Isopleth Method it can be assessed that on the internal surface of the Graziosi's House case study there are unfavourable conditions for mould growth.

	**Recorate Palace** **Ancona** **Italy** **(UNIVPM)**
Insulation:	Version A: 130 mm calcium silicate (λ=0.053 W/mK), internal plaster Version B: 80 mm XPS (λ=0.035W/mK), gypsum plasterboard both mounted with adhesive mortar
Type of insulation:	Version A: vapor permeable, capillary active Version B: vapor permeable (retarder) and capillary inactive
Year of construction:	Rectorate Palace is a Nineteenth-century palace built in 1866 in a Renaissance revival style.
Retrofit periods:	A representative room was internally insulated and instrumentally equipped. However, after the seismic events in 2016 and 2017 in the central area of Italy, the energy retrofit intervention was stopped.
Description:	The building has a rectangular shape and it is structured around a central courtyard. The front of the building has a three-storey high façade, composed by a five arches arcade on the ground floor. The rest of the structure is five-storey high.
Building usage:	Rectorate Palace is an office building. The building was evacuated for safety reasons after the earthquake in 2016. Hence, heating and moisture plants were locally introduced in order to simulate occupancy.
Building location:	The building is located in Ancona, a medium sized town and capital of the Marche Region. The town is located on the Adriatic Sea.
Construction:	Different typologies of external walls can be found in the building: the bearing wall is made by bricks and stones in a mix texture, finished by facing-bricks, plaster or stone cladding. The wall thickness ranges from 50 to 90 cm.
Measurements:	The monitoring activity concerned two insulation solutions installed in a North-West oriented room of 14 m2 at the first floor. Temperature and relative humidity sensors were positioned inside small cavities in the interface of the different layers between the old masonry and the insulation panels as well as between the XPS-insulation panel and the gypsum plasterboard. For both insulation systems, sensors were also installed on the internal and external side of the wall surface. An additional sensor was used to measure the indoor climate.
Points of interest:	The aim of the experimental activity was to analyse the hygrothermal conditions of the wall surfaces and at the interface between the masonry and the insulation materials, to evaluate the risk of mould growth.
Outcomes:	In general, the recorded values of temperature and relative humidity show a similar situation for both the CaSi and the XPS systems. The non-capillary active insulation seems to perform slightly better than the capillary active. The mould assessment shows that all values are below the LIM II curve. For the interior surface of the two insulation systems installed in Rectorate Palace case study there are consequently unfavourable conditions for mould growth.

	**Building 1** **Schwabestraße, Weimar** **Germany** **(TUD)**
Insulation:	TecTem 70 mm (XPS board with calcium silicate) (λ=0.045 W/mK, ρ=100 kg/m³)
Type of insulation:	Vapor permeable (retarding) and slightly capillary active (through calcium silicate areas)
Year of construction:	The building was erected in 1925 in the South-West of Weimar. Weimar is located in Middle-Germany.
Retrofit periods:	Refurbishment of all three buildings was carried out from 2013 to 2014.
Description:	All case study buildings in Weimar show two stories proper and an attic floor under the mansard roof. The buildings are occupied on three levels (1st, 2nd and attic floor). Each of the occupied floors is separated into three living units. It has been equipped with mechanical ventilation (controlled supply and exhaust air).
Building usage:	Living quarter on Schwabestraße in Weimar consists mainly of residential buildings. Building 1 was originally used as residential building on two levels and is then occupied on three levels (including attic floor) since the retrofit was finished (2015).
Building location:	The building is located in the South- Western part of Weimar in a low-density area.
Construction:	External walls in the basement are built with 380 mm Travertine; external walls in the upper floors are made of 365 mm brick masonry. The walls are covered with lime cement plaster outside.
Measurements:	Measurements include three measurement tracks in external walls (two in the 2nd floor, one in the 3rd floor) towards North and South-West. Furthermore, outdoor climate (temperature and relative humidity) and indoor climate were recorded. The wall tracks consist of one heat flux board, several combined sensors measuring the temperature and relative humidity at the surface inside and outside as well as in the interstitial condensation plane. They are placed in the edges and window reveals.
Points of interest:	The underlying project aimed to assess the energetic efficiency of different insulation systems in combination with different heating and ventilation strategies. This point addressed also the damage risk of the construction (moisture conditions at critical thermal bridge points).
Outcomes:	Indoor conditions ranged between 16 and 26°C. Depending on the temperature level, relative humidity averaged between 45- 50% during winter season. Measurements within the wall showed an uncritical condition for undisturbed walls (relative humidity within first and second year below 80%). For critical details (window lintel and reveal, wall edge), moisture conditions are uncritical with a small exceedance of 80% level during cold periods (outdoor temperature below 5°C).

	**Building 2** **Schwabestraße, Weimar** **Germany** **(TUD)**
Insulation:	Multipor 70 mm (λ=0.045 W/mK, ρ=90 kg/m³)
Type of insulation:	Vapor permeable (retarding) and capillary inactive
Year of construction:	The building was erected in 1925 in the South-West of Weimar. Weimar is located in Middle-Germany.
Retrofit periods:	Refurbishment of all three buildings was carried out from 2013 to 2014.
Description:	All case study buildings in Weimar show two stories proper and an attic floor under the mansard roof. The buildings are occupied on three levels (1st, 2nd and attic floor) with three living units on each story. It has been equipped with exhaust air units in the moist rooms.
Building usage:	Living quarter on Schwabestraße in Weimar consists mainly of residential buildings. Building 2 was originally used as residential building on two levels and is then occupied on three levels (including attic floor) since the retrofit was finished (2015).
Building location:	The building is located in the South- Western part of Weimar in a low-density area.
Construction:	External walls in the basement are built with 380 mm Travertine; external walls in the upper floors are made of 365 mm brick masonry. The walls are covered with lime cement plaster outside.
Measurements:	Measurements include three measurement tracks in external walls (two in the 2nd floor, one in the 3rd floor) towards North and South-West. Furthermore, outdoor climate (temperature and relative humidity) and indoor climate were recorded. The wall tracks consist of one heat flux board, several combined sensors measuring the temperature and relative humidity at the surface inside and outside as well as interstitial condensation plane. They are placed in the edges and window reveals.
Points of interest:	The underlying project aimed to assess the energetic efficiency of different insulation systems in combination with different heating and ventilation strategies. This point addressed also the damage risk of the construction (moisture conditions at critical thermal bridge points).
Outcomes:	Indoor conditions ranged between 16 and 30°C throughout the year. Relative humidity averaged between 30-45% during winter season. Measurements within the wall showed an uncritical condition for undisturbed walls (relative humidity within first and second year below 75%) and critical details (window lintel and reveal, wall edge) with less than 75% for the window reveal and edge, less than 80% for the window lintel during cold periods (outdoor temperature below 5°C).

	**Building 3** **Schwabestraße, Weimar** **Germany** **(TUD)**
Insulation:	Multipor 50 mm (λ=0.045 W/mK, ρ=90 kg/m³)
Type of insulation:	Vapor permeable (retarding) and capillary in active
Year of construction:	The building was erected in 1925 in the South-West of Weimar. Weimar is located in Middle-Germany.
Retrofit periods:	Refurbishment of all three buildings was carried out from 2013 to 2014.
Description:	All case study buildings in Weimar show two stories proper and an attic floor under the mansard roof. The buildings are occupied on three levels (1st, 2nd and attic floor) with three living units on each story. The building was equipped with a hybrid ventilation system (supply air via window-integrated slots, exhaust air through bath and kitchen vents for whole unit).
Building usage:	Living quarter on Schwabestraße in Weimar consists mainly of residential buildings. Building 3 was originally used as residential building on two levels and is then occupied on three levels (including attic floor) since the retrofit was finished (2015). Some units remained unused until spring 2017.
Building location:	The building is located in the South- Western part of Weimar in a low-density area.
Construction:	External walls in the basement are built with 380 mm Travertine; external walls in the upper floors are made of 365 mm brick masonry. The walls are covered with lime cement plaster outside.
Measurements:	Measurements include three measurement tracks in external walls (all on the 1st floor) towards Northeast, North-West and South. Furthermore, outdoor climate (temperature and relative humidity) and indoor climate were recorded. The wall tracks consist of one heat flux board, several combined sensors measuring the temperature and relative humidity at the surface inside and outside as well as in the interstitial condensation plane. They are placed in the edges and window reveals/lintel.
Points of interest:	The underlying project aimed to assess the energetic efficiency of different insulation systems in combination with different heating and ventilation strategies. This point addressed also the damage risk of the construction (moisture conditions at critical thermal bridge points).
Outcomes:	Indoor conditions ranged between 12 (unoccupied phase) and 27°C throughout the year. Relative humidity averaged between 45-50% during winter season. Measurements within the wall showed temporarily critical conditions of more than 90% for the North-directed wall (including lintel, reveal and edge) and mostly uncritical conditions of less than 80% for all other walls.

	**Old Farm Building** **Brüttelen** **Switzerland** **(HES-SO)**
Insulation:	Isover glass wool PM M 035 (three layers) 170 mm (λ=0.035 W/mK, ρ=60 kg/m³), vapor retarder Isover Vario Xtra (0.3 m $\leq$ sd $\leq$ 20 m)
Type of insulation:	Vapor permeable (retarding) and capillary inactive
Year of construction:	The building complex, located in the countryside around Brüttelen town at 449 meters above the see level, was built around 1900 as a farm.
Retrofit periods:	In 2014, one of the two main buildings of the old farm was refurbished to become a family house. Before the retrofits done in 2014, the building had already been lightly refurbished. In particular, the windows and the heating system were already renewed from the original ones.
Description:	The building is a heritage building, which implied an internal insulation of the external walls.
Building usage:	This house was refurbished between the October 2013 and March 2015. During this period, the house was vacant. From the 01.04.2015, a four-people-family settled in the house: two parents with their two young children. Since that date, this is their main residence.
Building location:	The building is located in the countryside around the commune of Brüttelen, in Canton Bern, in Swiss Midlands. It is part of a farm complex, as the main building.
Construction:	There are three different types of external walls in this house. The main one is the solid masonry in shell sandstone (500 mm), on almost all of the facades. An extension in wood was made on the northwest façade of the first floor. The brick cavity wall in the attic constitutes the third typology.
Measurements:	The building monitoring was realized in the framework of the MOFEINN research project between 2014 and 2017. In this project, two refurbished walls were equipped with humidity and temperature sensors in different layers of the construction. . The aim is to measure the moisture content and the temperature of the construction for two extreme boundary cases: one wall being the most exposed to the weather conditions, and one wall being the least exposed to the weather conditions.
Points of interest:	Monitoring data are used to confront the transient simulation results calculated with WUFI Pro in order to evaluate the impact of the inputs uncertainty on the results, to calibrate the input parameters to fit to the measurements and to analyse the simulation relevance for moisture and condensation problems anticipation and solution in planning phase.
Outcomes:	Highest relative humidity was measured behind the insulation in north-west wall. The level started at 95% maximum in the first year and decreased below 90% in forth year. Second wall with south-west direction started at 95% in first year and dropped down below 80% in forth year. All other positions are less critical with values below 80% in last year. Calibration of simulation model (WUFI) is still running and not finished.

	**Klitgaarden Hundested Denmark (IFLEX, AAU)**
Insulation:	iQ-Therm 80 mm (λ=0.031 W/mK, ρ=49 kg/m³), a PUR plate with an array of capillary active calcium silicate channels
Type of insulation:	vapor permeable and (slightly) capillary active
Year of construction:	Klitgaarden is a freestanding single-family house from 1875 in two stories with a total area of 221 m^2.
Retrofit periods:	The renovation project of the building aimed for a minimum heating requirement and a preservation of original outdoor facade details. Everything down to the buildings shell and first floor have been taken apart. The comprehensive renovation was finished in 2016 (early 2017)
Description:	The building has a thatched roof and the floor area distribute in the following way: 77 m2 in the first floor and 144 m2 in the ground level.
Building usage:	The house had not been used in twenty years. As holiday home with four rooms it is expected to accommodate two persons per room equivalent to eight occupants in holiday periods. As full time occupancy, as many as five occupants would normally be expected in four room houses.
Building location:	The building is located in Hundested, close to the sea in the northern end of Zealand about seventy kilometres northwest of Copenhagen, Denmark.
Construction:	The building is erected with solid masonry walls and a foundation of granite boulders on top of a stone foundation. The gables are one brick thick while the facades are one and a half brick. Thickness of the façade wall (about 350 mm brick) and gable wall (about 230 mm brick) differ, but both are originally solid masonry walls.
Measurements:	Sensors are installed in all external walls. In addition to the build-in sensors, some reference sensors are placed inside and outside. The sensors are somewhat focused in the northwest and southeast end of the building. Roof and first floor is not monitored. The build-in sensors measure relative air humidity and temperature in the interface between masonry and insulation to assess the moisture condition in the interface. Additionally, some more practical measurements are carried out with Karsten Tube, Troxler and HF.
Points of interest:	The project investigates a building's physical condition prior to a renovation with interior insulation and monitor the external walls' condition after the completed renovation. Measurements before renovation are singular no time series. Parallel to application of insulation to the walls interior two minor areas (one square meter each) are hydrophobized on the western and southern wall. The impact should be evaluated.
Outcomes:	Four of the seven sensors measure 100 % relative humidity. Although some sporadic decreased seem to occur it appear not to change the conclusion that the walls are very moist. Only the east orientated wall appear to be drying and additional monitoring is required to determine a steady level.

Appendix II: Table of Published Case Studies

The following overview of monitoring projects includes articles since 2003. Only projects with a longer monitoring period and full measurement tracks were included.

Authors/ Reference Report Title	Focus/ Research Questions
(Loga, Feldmann, Diefenbach, Großklos, & Born, 2003) **Wiesbaden - Lehrstraße 2, Energetische Modernisierung eines Gründerzeithauses**	Insulation: composite boards made of 55 mm polystyrene and 5 mm Heraklith (wood wool insulation layer) as plastering bearer , thermal conductivity 0.035 W/mK Type of insulation system: air tight (plastering), vapour-open, not capillary active Building: typical Gründerzeit building, erected between 1880 and 1890, renovation from 2001-2002 Building usage: residential (supposed to be unoccupied during measurements) Building location: Wiesbaden, Germany Construction: solid brick, appr. 380 mm thickness, plastering with ca. 20 mm internal and external plaster layer Measurements: in second and third storey six measurement tracks including moisture content and temperature of joist end, indoor relative humidity and temperature Points of interest: joist ends in south- and east-directed facades Outcomes: continuously reducing moisture content (related to long-time measurements), slightly increased level (1-2% mass related) at beams with internal insulation compared to uninsulated junction, annual average is about 15% (mass related)
(Häupl, Jurk, & Petzold) **(Inside thermal insulation for historical facades, 2003)**	Insulation: several different insulation systems, e.g. calcium silicate 50 mm Type of insulation system: different types Building: ca. 1900 Building usage: no usage during measurement period (orig. office building) Building location: Bahnmeistergasse, Senftenberg, Germany Construction: masonry with face brickwork, 365 mm , internal plaster Measurements: relative humidity, temperature above and within the joist ends, moisture content measurements in wood, measurement in ceiling between ground floor and first floor in north-west façade of the building Points of interest: masonry (interstitial condensation plane) and joist end, drying effect of forward stroke close to the joist ends on the performance Outcomes: Joist end moisture content just after refurbishment about 20% (mass-related), then continuous drying process, additional heat loss due to forward stroke placement within the masonry (at joist end) estimated with 10%
(Ruisinger, Petzold, Grunewald, & Häupl, 2004) **(Häupl, Grunewald, & Petzold, 2004)** **Energetische Sanierung des Herrenschießhauses in Nürnberg mit kapillaraktiver Innendämmung**	Insulation: calcium silicate boards, 50 mm Type of insulation system: capillary active and vapour open Building: Renaissance building, built in 1583 Building usage: intermittent usage for training courses and events Building location: Nürnberg, Germany Construction: combination of wooden framework and sandstone (400 mm sandstone and internal brick leaf) Measurements: indoor and outdoor air relative humidity and temperature, humidity and temperature at boundary between insulation and masonry, interior and exterior surface temperatures and relative humidity, interior heat flux Points of interest: exterior wall edge, wall sections (east and north-directed external walls) Outcomes: relative humidity in condensate layer at the edge about 85% in the first and 65% in the second winter period, no critical conditions recorded after first measurement year, differences in temperatures between wall and edge up to

	5K and 20 % rel. humidity, good accordance between simulated (DELPHIN) and measured temperatures, lower for relative humidity (up to 8%)
(Häupl, Fechner, & Petzold, 2004) **Internal Retrofit of Masonry Wall to Reduce Energy and Eliminate Moisture Damage: Comparison of Modeling and Field Performance**	Insulation: calcium silicate, 28 mm Type of insulation system: vapour open, capillary-active Building: not mentioned, estimated: 1850 Building usage: large, rural residential building Building location: Edemissen Eickenrode (near Hannover), Germany Construction: framework construction with wooden stud (oak) and brick infill which is covered with cement plaster outside, retrofitted inside with 28 mm calcium silicate on 5 mm casi-plaster and 25 mm loam plaster Measurements: three measurement points in first floor with sensors in infill field and around the collar beam (surface temperatures, temperature and relative humidity behind insulation and wood moisture content in collar beam, heat flux plate in the field), indoor and outdoor climate (temperature and relative humidity, outside also global radiation and driving rain) Points of interest: Evaluate moisture performance of overall construction, impact of indoor conditions on performance, energetic effect of refurbishment (energy consumption) Outcomes: uncritical conditions: temperature behind insulation above frost limit, relative humidity at interior surface not above 80%, wood moisture content persistently below 18% (mass related), accumulated condensate in construction below 0.5 kg per m² building envelope, transmission heat flux reduced by 50%, simulation with Delphin (V4, 2D) shows good accordance with measurement results
(Kautsch, Häupl, Hengsberger, & Streicher, 2005) **Zellulose-Innendämmung ohne Dampfsperre – Versuchsgebäude in Liebenau**	Insulation: cellulose plastering, 50 mm (sputtered) (0.052 W/mK) Type of insulation system: vapour open and capillary active Building: erected in 19th century, three levels, west-directed and south-directed external walls were set up as test walls Building usage: - Building location: Liebenau resp. Graz, Austria Construction: solid brick wall appr. 500 mm thickness, Measurements: added with reference measurements in non-renovated rooms, global radiation, rel. humidity and temperature outside, combined temperature and relative humidity, heat flux in wall (surfaces, in masonry, interface masonry-insulation, in insulation layer), indoor conditions (temperature, rel. humidity), lab measurements for material properties (insulation and plastering) Points of interest: sensors placed in undisturbed external wall and in the edge Outcomes: due to workmanship process high initial moisture level but continuous drying-out process, afterwards moisture level uncritical (5% volume-related in winter), critical surface conditions (>80% rel. hum.), cracks in insulation caused locally increased moisture level, comparison with simulation results (Delphin) with sufficient accordance
(Wagner, et al., 2008) **EnSan - Hamburg, Kleine Freiheit 46-52**	Insulation: one building with 50 mm calcium silicate (0.065 W/mK) with internal cavity and gypsum fibreboard, second as reference building without insulation Type of insulation system: vapour open and capillary active Building: two parts of the Gründerzeit- building with different renovation standards, both built in 1907 and renovated in 2006, five levels with 14 appartments Building usage: residential building Building location: Hamburg, Germany Construction: Solid brick masonry with 360-560 mm thickness and external and internal plastering, new construction was invented for joist ends to prevent direct contact between masonry and wood (original joist ends were damaged (decay))

	Measurements: material measurements, construction: heat flux density, surface temperature (also at joist ends) indoor: air temperature and rel. humidity, outdoor: air temperature and rel. humidity, HVAC- system performance values, global radiation Points of interest: wall in breast area, joist ends Outcomes: measurements supplemented with HAMT- simulations (Delphin) for all relevant thermal bridges (balconies, windows etc.) to reduce their impact on energy demand, joist ends performance optimized, no risky conditions
(Wilkinson, DeRose, Sullivan, & Straube, 2009) **(Measureing the Impact of Interior Insulation on Solid Masonry Walls in a Cold Climate)**	Insulation: closed-cell spray foam insulation Type of insulation system:no further information, no material characteristics given Building: Three-storey public school building, erected in the 1950th Building usage: Public school Building location: Toronto, Southern Ontario, Canada Construction: Basic construction made of bricks (3 layers), two tested wall composites: one unmodified with 50 mm hollow clay tiles, 20 mm plaster and two coats of painting, the second construction with 50 mm insulation, 25 mm air space, 12 mm dry wall with latex painting Measurements: one of each wall type (insulated and non-insulated) was measured in each direction (South and West) in the uppermost floor in the building, each wall segment was equipped with 8 sensors measuring the situation in the middle of the outermost (1,2) and innermost (3,4) brick layer (one sensor: T, RH, second sensor T, MC), the middle of the masonry (MC, T) (5), the interstitial condensation layer (6), furthermore measurement of indoor (7) and outdoor climate (8), furthermore driving rain measurement, evaluated period 09-2007 – 07-2008 Points of interest: Estimation of the freeze-thaw-cycles (criteria according to ISO 1992) and corrosion risk in comparison between the insulated and non-insulated case, comparison between simulations with WUFI (Pro Vers. 4.1) and measurements Outcomes: Low freeze-thaw risk due to uncritical weather conditions in the measurement period, increased but still low risk for embedded steel corrosion for the insulated wall, sufficient accordance between simulation and measurement (simulation within the 10% range of the measurements)
(Conrad, Häupl, Petzold, & Löber, 2007) **(Häupl, et al., 2010)** **Energetisch und bauphysikalisch optimierte Sanierung eines Baudenkmals in Görlitz**	Insulation: calcium silicate boards, 50 mm (combined with insulating plastering at outside, 30 mm), thermal conductivity 0.069 W/mK Type of insulation system:vapour open and capillary active Building: Renaissance building, built in 1728, parts before 1600, renovation finished in 2010 Building usage: residential building Building location: Görlitz, Germany Construction: Solid masonry (mixture of brick and rubblestone), ca. 300 mm Measurements: (measurement track internal insulation) outside weather conditions (surface global radiation, temperature, relative humidity), heat flux density, surface temperature and relative humidity inside, relative humidity and temperature at boundary between insulation layer and existing construction, indoor climate Points of interest: wall area at breast (below window) Outcomes: Strong damping effect through plastering, insulation and solid masonry construction, no condensate behind insulation layer detected / to be expected
(Hasper, Kaufmann, Pfluger, Feist, & Aust, 2010)	Insulation: cellulose flocks, 80 mm (thermal conductivity 0.052 W/mK) Type of insulation system:capillary active and vapour open Building: Historic magazine, built in 1911

Energetische Sanierung eines denkmalgeschützten Speichergebäudes mit aufgesprühter Zellulose-Innendämmung	Building usage: intermittent usage as hostel (residential building) Building location: Wartin (Casekow), Germany Construction: single-leaf brick masonry, wooden joist floor Measurements: heat flux, temperature, humidity, balance humidity, global radiation, air temperature & humidity and driving rain, measurements 2008-2010 Points of interest: wall profile, window reveals, wooden construction parts (joist ends) Outcomes: no long-time moisture accumulation, balance moisture at boundary masonry/insulation over long periods > 80%, qualitative differences for measured wood moisture contents (4 of 6 sensors show uncritical conditions, 2 critical conditions)
(Peper, Kaufmann, & Hasper, 2010) **(Innendämmung und Wandfeuchte (Neues aus Forschung und Entwicklung, Arbeitsgruppe 5))**	Insulation: polystyrene 80 mm Type of insulation system:different systems Building: year of construction ca. 1872-1912, renovation 2005-2009 Building usage: residential building Building location: Ludwigshafen, Germany Construction: cavity brick wall with thickness of 240 mm (load bearing layer) mortar layer of 12 mm, 120 mm (facing wall), insulation system as composite boards with gypsum plasterboards, sealed vapour barrier resp. moisture-adaptive vapour retarder inside and additional gypsum plasterboard, twofold hydrophobic treatment of exterior surface Measurements: outdoor: driving rain (gauge), rel. humidity and temperature, construction: interior surface temperature and temperature and rel. humidity between insulation and existing construction, four years of measurements Points of interest: moisture performance of internal insulation, comparison between vapour tight and vapour retarding system, efficiency of hydrophobic treatment (checked with lab measurements) Outcomes: hydrophobic effect insufficient although renewed several times, strong impact of driving rain events, long drying period of the overall construction (>2 years), performance of construction with vapour retarder was slightly better but no significant difference to vapour barrier construction, construction performance acceptable (relative humidity below 80%) with fourth hydrophobic treatment of exterior surface
(Stopp, Strangfeld, Toepel, & Anlauft, 2010) **(Messergebnisse und bauphysikalische Lösungsansätze zur Problematik der Holzbalkenköpfe in Außenwänden mit Innendämmung)**	Insulation: calcium silicate, 60 mm Type of insulation system:vapour open Building: built 1582/1583, solid basic storey, Building usage: office rooms, assembly rooms etc. Building location: Nürnberg, Germany Construction: Solid sandstone wall of varying thickness Measurements: Temperature, relative humidity, moisture content wood, driving rain and local ambient air temperature and relative humidity Points of interest: south side, joist ends surrounded by insulation material, two reference cases with lime cement plaster instead of internal insulation, one joist end with artificial cracks and thus convective inlet from room air, one joist end beside heat pipe, one joist end externally insulated with XPS, measurements during autumn/winter 2009 Outcomes: relative humidity not critical in the joist ends, best performance (lowest moisture content and relative humidity) for the joist end with local heating (pipe), more stable conditions in the un-insulated wall segments during the measured winter period compared to the insulated wall segments.
(Wegener, 2010) **(Beurteilung von Innendämmsystemen**	Insulation: reed insulation boards 50 mm, clay rendering inside Type of insulation system:not capillary active, not moisture resistant, vapour-open, air tight reed mats, high natural silicate content, no swelling

- Langzeitmessungen und hygrothermische Simulation am Beispiel einer Innendämmung aus Schilfrohrplatten)	Building: Cottage-Villa, erected between 1870-1880, refurbishment of the first floor, façade with decorative elements (e.g. window bandage), moderate roof overhang Building usage: residential building (living room and sleeping room chosen for exemplary insulation) Building location: Wien- Währing, Austria Construction: solid brick masonry of about 500 mm, "Rieselputz" (coase rendering material) at the outside, interior rendering (likely not a historical one) Measurements: installation completed in August 2007: temperature and relative humidity sensors, measurement results for more than 3 years, sensors recording indoor and outdoor air condition (T, RH), three wall measurement tracks in different heights (heights of 0.75 m, 1.75 m, 3,15 m), one track in the wall edge, each track with at least one sensor at the interior surface and behind the insulation, type of room: sleeping room Points of interest: Hygrothermal performance of the insulation system itself and of the insulation in combination with the clay rendering inside, Outcomes: Mould growth at the clay plaster surface during drying period (first weeks after installation), after drying period uncritical moisture conditions.
(Morelli, et al., 2012) **(Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment)**	Insulation: Aerowolle (mixture of aerogel and stone wool fibres) 20mm at window reveals and 40 mm at wall, Vacupor (vacuum insulation panels), 20 mm at window reveals and wall both with thermal conductivity of 0.019 W/mK Type of insulation system:vapour tight Building: multi-family building, six storeys (30 apartments), built in 1896 Building usage: residential building, supposed to be unoccupied during measurements (not mentioned in article) but normal indoor conditions with 40-55% rel. humidity Building location: Copenhagen, Denmark Construction: solid-brick masonry (thickness 36-72 cm) with vapour barrier and insulation products covered by Measurements: temperature and relative humidity at interface between masonry and insulation at plane wall and temperature at window reveals, relative humidity in joist ends, indoor temperature and relative humidity Points of interest: evaluation of two different insulation systems in test apartment in advance of the entire refurbishment of the building, placement of Aerowolle at east- and north-directed façade and Vacupor at west-directed façade, investigation of joist ends and spandrels with internal insulation (Aerowolle, reveals also with Vacupor) Outcomes: joist end relative humidity at the beginning around 75%, later reduction to 60%, state at interface between masonry and insulation around 85% at beginning of measurements, later reduction to 80%, high moisture levels at beginning could result from sensor-mounting built it moisture, after removal of insulation no mould growth detected (visible inspection and Mycrometer surface test for mould growth) in 6th floor but in ground floor (street level, insulation mounted on wallpaper) behind Aerowolle
(Strangfeld, Staar, & Stopp, 2012) **Das hygrothermische Verhalten von Holzbalkenköpfen im innengedämmten Mauerwerk: Drebkau**	Insulation: perlite boards, 80 mm Type of insulation system:vapour open and capillary active Building: built in 1794, renovation finished in 2010 Building usage: School building (educational usage) Building location: Drebkau, Germany Construction: brick masonry ca. 300 mm Measurements: indoor: temperature and relative humidity in different rooms, construction: joist moisture content (two different sensor types: relative humidity and conductivity), air velocity in cavities behind joist ends (anemometers)

	Points of interest: ca. 30 joist ends with different constructive solutions (cavity with perlite filling, floor heating system, local radiant heating systems, artificial thermal bridge via surrounding made of lime sand bricks , untreated joist ends) , hygrothermal evaluation of north-east and south-west- directed facades Outcomes: difference of 2-3 % (mass related moisture content) between directly measured (conductivity method, higher level) value and through relative humidity (sorption isotherms) calculated values, good effect of local heating for reduction of wood moisture content at joist ends, uncritical conditions
(Ueno, Straube, & Van Straaten, 2013) **(Field Monitoring and Simulation of a Historic Mass Masonry Building Retrofitted with Interior Insulation)**	Insulation: polyurethane spray foam insulation, 75-90 mm Type of insulation system: Building: 1917, three storey building, site-cast reinforced concrete for structural elements, renovation in 2010-11with removal of internal plastering and application of internal insulation Building usage: office building, occupied since late 2011 Building location: Boston, USA Construction: face brick, fill brick, hollow clay block, asphalt-based dampproofing coating, cementitious internal plaster rendering Measurements: thin walls: temperature and moisture content in face brick, temperature and relative humidity in collar joint behind face brick layer, outside surface temperature , thick wall: as thin wall but without outside surface temperature and with temperature and moisture content at interface between insulation and clay block, weather station on roof (temperature, relative humidity, wind speed and direction, horizontal rain, horizontal solar radiation), radiation sensors at façade, interior conditions (temperature and relative humidity) in all zones adjacent to measured walls, collection from Oct 2011 to Jun 2013 Points of interest: comparison of north- and south-directed facades, two insulated wall types (thick and thin) with single resp. double fill brick layer, one reference wall without insulation and one area with high driving rain exposure, comparison with simulation results gained from WUFI Outcomes: Lower temperature level and higher moisture content (fluctuating around 80-90%) of insulated wall, good accordance between simulated and measured temperature but not for moisture response (reason not clear)
(Klõšeiko, Arumägi, & Kalamees, 2013) **(Hygrothermal performance of internally insulated brick wall in cold climate: field measurement and model calibration)**	Insulation: calcium silicate 50 mm, aerated concrete 60 mm, polyurethane board with capillary-active channels 50 mm, polyisocyanurate boards (PIR) 30 mm Type of insulation system:capillary-active and vapour-open, vapour tight Building: Reproduction of a historical construction Building usage: originally school building, unoccupied during measurement period Building location: Estonia Construction: brick wall 730-750 mm (three layers of brick, two cavities), insulated fields with 100 – 120 cm width with four insulation systems above (5-15 mm adhesive mortar was used for mounting and covering, except for PIR), one reference wall without insulation with 160 cm width Measurements: temperature & relative humidity at interface between original masonry and insulation, temperatures at inner and outer surface, heat flow on inner surface of insulation, measurement results of one year, Points of interest: Performance of four different insulation materials (side by side at the same wall, separated with joints) under living space conditions (humidified at different humidification levels with additional vapour loads of up to 4 g/kg, resulting indoor relative humidity up to 90%), check of accordance with simulation results (Delphin) Outcomes: No critical temperatures in terms of frost damage risk (never below 0°C for interface between masonry and insulation), permanently critical moisture content in composite board, lower level in PIR field, both with stable conditions

	and delayed response on indoor climate changes, more quickly response for CaSi and AAC field, good accordance between simulated and measured relative humidity at insulation-masonry interface
(Kautsch, Ruisinger, Hengsberger, & al., 2013) **(OEKO-ID - Innendämmung zur thermischen Gebäudeertüchtigung - Untersuchung der Möglichkeiten und Grenzen ökologischer, diffusionsoffener Dämmsysteme)**	Insulation: sprayed on cellulose, 80 mm ; perlite boards, 80 mm; thermo silit plastering 120 mm; wood soft fibre boards, 60 mm; reed, 100 mm Type of insulation system:vapour open and capillary active Building: Sanatorium "Mariagrün", three storeys, located on hill in city of Graz, former psychotherapy and rehab centre, founded in 1885 Building usage: building planned to be renovated and later used as day-care facility for children, installation of five test fields and one reference field over two storeys (each material spanning two storeys and including one joist end) in one external wall, measured indoor humidity to low, humidification added and construction tightness improved step-wise Building location: Graz, Austria Construction: all insulation materials covered with either lime or clay final rendering, six joist ends sealed (filled cracks, sealing tape etc.), two joist ends with gaps of 2-3 cm between joist and insulation Measurements: combined temperature/ relative humidity sensors at interface between insulation and masonry, at side and at the outside face of joist end cavity, indoor (both storeys separately) and outdoor air; surface temperature sensors inside and outside, wood moisture content sensors at exterior face of joist end, Points of interest: Evaluation of ecologically uncritical building materials for internal insulation, thicknesses were chosen in order to match the goal U-value of 0,4 W/m²K, comparison of sealed and unsealed joist ends, Outcomes: perlite boards, wood fibre boards and reed dried out faster and remained on lower moisture content level than other systems, uncritical (mass-related) moisture content of wooden joist ends (<20%), strongly delayed response of joist end moisture content on driving rain events, thermo silit showed longest drying period of appr. 1 year, unsealed joist ends showed significantly higher moisture content
(Plagge R. e., 2014) **Co2ol Bricks Report - Holstenkamp, Hamburg**	Insulation: Insulation plastering Klimasan, 55 mm Type of insulation system:vapour open and capillary active Building: two detached houses with ground floor and occupied attic storey, Building usage: residential building Building location: Hamburg, Germany Construction: Solid masonry, 360 mm consisting of external brick layer (110 mm) and interior lime-sandstone layer (240 mm) Measurements: Outdoor and indoor air temperature and relative humidity, in four different apartments exterior and interior surface conditions (heat flux inside, temperature), masonry conditions and insulation-masonry interface conditions (relative humidity and temperature), weather data from DWD weather station (Hamburg Fuhlsbüttel), measurements in east-directed external wall Points of interest: dew point temperature in construction, interior surface conditions (relative humidity, temperature), transient heat transmission coefficient, evaluation of heating system performance (convective and radiant, wall-integrated) Outcomes: critical conditions at thermal bridges, esp. during low-temperature (minimized heating with low set-point temperatures) winter periods, HAMT-simulation with Delphin (V4) used for design and adaption of constructive joints (e.g.insulation layer thickness) in advance
(Sanders, Baker, & Hermann, 2014)	Insulation: 125 mm polystyrene insulation with (gypsum) plasterboard covering Type of insulation system: vapour open /tight Building: Measurements in top floor corner flat at south and west facing walls of traditional sandstone building

(Hygrothermal assessment of wind-driven rain as a risk for internal insulation retrofit of traditional buildings)	Building usage: usage type of building not mentioned Building location: Glasgow, suburb Govan, Scotland Construction: 600 mm sandstone Measurements: global and diffuse radiation, wind speed, wind-driven rain (rain gauge), temperature, rel. humidity (in radiation shield), indoor temperature, rel. humidity, construction: humidity, temperature and moisture (wood block moisture content) sensors at five locations in west-facing wall, time domain reflectonometry (TDR) internally and externally Points of interest: evaluation of hygrothermal performance of a traditional sandstone construction (undisturbed wall, no bridged area) retrofitted with internal insulation, comparison with HAMT simulations (WUFI 2D version 3.3) based on material properties from WUFI database Outcomes: Measured relative humidity between insulation and masonry temporarily higher than 80% , sufficient accordance for boundary temperature between different sandstones of simulation and measurements, stronger drift between measured and simulated relative humidity
(Bishara, Meissner, & Plagge, 2014) **(3EnCult (Efficient Energy for EU Cultural Heritage) - Documentation of each study case)**	Insulation: iQ-Therm system (board system including advesive mortar and plastering) 50 mm Type of insulation system: vapour open and capillary active Building: building originally erected in 1870, reconstructed in 1912, renovation finished in 2010 Building usage: residential building, temporarily not occupied Building location: Dresden, Germany Construction: brick masonry (cavity walls, one double brick layer of ca. 250 mm and one single-brick layer of ca. 110 mm, cavity ca. 40 mm) in upper floors, mixture of sandstone and brick (ca. 550 mm) in basement Measurements: Indoor climate: temperature and rel. humidity in two rooms, surface temperatures at different positions, outdoor climate: surface temperatures, weather dataset (temperature and relative humidity, short- and longwave radiation, precipitation, wind direction and velocity), positions in construction explained below Points of interest: performance of insulation system iQ-Therm: joist ends, boundary between insulation and existing construction, radiant heating system, thermal bridges Outcomes: Supplemented with HAMT-simulation (Delphin) to investigate surface conditions (mould growth risk, condensation), results show risky conditions for one bridge, uncritical conditions for joist ends and other points
(Plagge & Scheffler, 2013) **(Bauphysikalische Begleitung, Analyse und Berichterstellung zur Öffnung der vor 15 Jahre ausgeführten Innendämmung mit Mineraldämmplatten)**	Insulation: Multipor mineral boards, 50 mm Type of insulation system: vapour open, capillary-active Building: residential area built in 1920th, four multi-family houses, refurbishment in 1998 Building usage: residential usage Building location: Finsterwalde, Germany Construction: brick masonry 380 mm, partially with exterior plastering, partially with face brick (with hydrophobizing, opened and measured wall sections in face brick area) outside, lime plastering 20 mm, insulation boards 50 mm fixed with adhesive mortar of 5 mm, internally covered with gypsum plasterboards (fixed with gypseous mortar), openings filled with PU foam Measurements: measurements for three years after refurbishment including outdoor and indoor temperature and relative humidity, outside and inside surface temperatures, heat flux, temperature and r. humidity between insulation and masonry, temperature and relative humidity in middle of the insulation layer and masonry layer

	Points of interest: control of insulation system at critical positions after 15 years of usage, analysis of post-erection measurements, check of masonry and jointing with regard to water absorptivity (Karsten's test tube) Outcomes: measurements show drying process of built-in moisture, impact of driving rain events, temperature conditions and occupancy patterns: north-directed room and wall construction at higher relative humidity level (lower temperature level) than west-directed room/wall construction | inspection check of walls and joist ends: refurbished wall (upper part of the wall) constructions show much lower driving rain sensitivity and moisture content than older masonry (plint part of the wall with cracked, sanding jointings and without hydrophobizing), joist ends without visual or measured critical conditions, no damage at window reveal although thin insulation layer of 3 cm
(Bishara, Meissner, & Plagge, 2014) **(3EnCult (Efficient Energy for EU Cultural Heritage) - Documentation of each study case)**	Insulation: mineral wool (ca. 100 mm) in conjunction with vapour retarder (sd=50m) Type of insulation system: vapour open /tight Building: complex, single buildings built from 1688 (Persiusspeicher) until 1836 (Schinkelspeicher) Building usage: originally warehouse (until 1904), after renovation apartment buildings Building location: Potsdam, Germany Construction: solid brick masonry in investigated floor (4th floor), thickness ca. 300 mm Measurements: indoor: air temperature and rel. humidity, surface temperature at critical points, outdoor climate: taken from local weather station, exterior surface temperature via Thermography Points of interest: Surface conditions in undisturbed and bridged wall areas (mould growth risk, condensation), salt load influence on hygrothermal performance, adjustment of details due to risky conditions (mould growth, high wood moisture content etc.) Outcomes: design of junctions and measurement outcomes combined with HAMT- simulation (Delphin), critical points were analysed and improved, for some details (timber stud, window reveal) critical moisture content or surface condition was predicted and details were adjusted (e.g. adding of vapour retarder)
(Marincioni & Altamirano-Medina, 2014) **(Effect of orientation on the hygrothermal behaviour of a capillary active internal wall insulation system)**	Insulation: dense woodfibre board with mineral layer (Pavadentro), 100 mm Type of insulation system: vapour-open, capillary-active Building: 16th century building, refurbishment in 2011 Building usage: education centre (teaching rooms, open-plan offices, exhibition zone), measurement in educational room (interval usage: short time with high loads) Building location: Maidenhead (near London), England Construction: solid brick walls 330 mm, levelling layer with lime-based coat (<6mm), bonding coat (5 mm) as adhesive mortar between insulation and masonry, interior surface covered with lime plaster, exterior surface without treatment (face brick wall) Measurements: measuring tracks in teaching room on South facing and on north-facing wall (opposite walls) in two different heights including: temperature and relative humidity at interface between masonry and insulation, indoor temperature and relative humidity and outdoor climate, period appr. 1,5 years Points of interest: Examine impact of wall orientation on performance of internal insulation systems Outcomes: initial moisture level (built-in) varied between 82 and 95% relative humidity, drying-out process after two month on south-directed façade, four month on north side, stronger drying process on south façade, final relative

	humidity in interstitial area below 80% at north façade, around 60% at south-façade
(Klõšeiko, Kalameesa, Arumägia, & Kallavusb, 2015) **(Hygrothermal Performance of a Massive Stone Wall with Interior Insulation: an In-Situ Study for Developing a Retrofit Measure)**	Insulation: mineral wool 100 mm with vapour barrier Type of insulation system: vapour tight Building: replication of an old cow barn, erected in 2014 Building usage: visitor centre of a museum (likely unoccupied during monitoring), dehumidification installed after July 2014 Building location: Setu region, Estonia Construction: double leaf rubble stone wall (550 mm masonry, 32 mm cavity, 100 mm mineral wool in wooden framework,), wooden boarding, PE foil,150 mm inner leaf cavity with ventilation holes and openings to outdoor air Measurements: relative humidity and temperature in upper wall and lower wall (each within air gap, between wooden boarding and vapour barrier, between vapour barrier and inner leaf, heat flux in middle part of wall, relative humidity and moisture content at joist end Points of interest: performance of north-directed façade with two different ventilation concepts for the cavity (closed and opened cavity to outdoor air), evaluation of mould growth risk based on Viitanen approach Outcomes: high relative humidity, severe mould growth risk, high (mass-related) moisture content of joist ends of >25% (decay risk)
(Wegerer, Nackler, & Bednar, 2015) **(Measuring the Hygrothermal Performance of an Interior Insulation made of Woodfibre Boards)**	Insulation: woodfibre boards (ca. 0.04 W/mK) 60 mm with 1mm diffusion-resistant mineral layer with vapour retarder layer at the very inside, e.g. on glued-on gypsum fibre boards Type of insulation system: vapour open and capillary-active system Building: Two buildings, Makartvilla (in souterain room with appr. 1m wall height below terrain with westwards-oriented façade and damp in masonry) and worker's residential home of Sedlak Building usage: Markartvilla: office, worker's home: residential usage (both unoccupied during weekends) Building location: both in Vienna, Austria Construction: solid masonry (thickness 30-45 cm), two insulation variants: insulation contact layer made of soft fibre boards and layer of clay plaster, four different room side materials: clay mortar, clay dry-panel, gypsum fibre panel, wood wool panel Measurements: temperature and relative humidity sensors between insulation layer and existing wall (within clay plaster layer and other positions) Points of interest: Evaluate drying-up process of clay, functionality of insulation at earth-adjacent walls , moisture content of existing masonry Outcomes: Long drying process of clay plaster with more than half a year associated with temporary mould growth risk, afterwards balanced conditions at low relative humidity level in clay layer also due to low moisture emissions in evaluated rooms
(Ueno & Lstiburek, 2015) **(Field Monitoring of Embedded Wood Members in Insulated Masonry Walls in a Cold Climate)**	Insulation: Extruded Polystyrene, 50 mm Type of insulation system: vapour tight, sealed construction Building: appr. 1910-1930 Building usage: no occupied situation, only intermittent heating Building location: Lawrence (MA), United States Construction: solid brick wall and hollow clay block backup wall with insulation on polyurethane adhesive and internal uninsulated cavity (wood framing inboard), three investigated types of (1) spray foam insulation, (2) fibre glass insulation and (3) no insulation around joist ends Measurements (period, sensors, sensor locations): two years, temperature (+-0.2K), relative humidity (+-3%) and wood moisture content (+-?) at 11 joist

	locations, indoor air temperature and relative humidity in two zones, outdoor conditions from airport weather station next to building location Points of interest: impact of joist treatment, orientation (solar loads and wind-driven rain loads) Outcomes: permanently high relative humidity and moisture content (mass related?) at joist ends with values close to 100% rel. hum. and around 20-30% m.c., impact of different joist end treatments low, impact of orientation high, response to wind-driven rain events strongly delayed (either seasonal)
(Bianco, Serra, Fantucci, Dutto, & Massolino, 2015) **(Thermal insulating plaster as a solution for refurbishing historic building envelopes: First experimental results)**	Insulation: Insulation plaster (vegetal aggregate materials derived from corncob added to natural hydraulic lime plaster and expanded silica - perlite), 60 mm Type of insulation system: λ = 0.09-0.12 W/mK, vapour-open (μ = 5-10), capillary active Building: Historic building from about 1580 Building usage: Hotel Building location: Torino, Italy (Address: Piazza Carlo Emanuele) Construction: 50 cm heterogeneous brick and stone wall Measurements: Non-destructive thermal measurements in two similar rooms (one refurbished, one as reference room), sensors recorded surface temperature inside and outside, air temperature indoor and outdoor, heat flux at inner surface Points of interest: Effect of insulation plaster of transmission heat losses, Applicability of plaster, IR-imaging Outcomes: Insulation plaster reduced heat flux by 30% compared to non-refurbished wall, U-value of refurbished construction was about 0.58 W/mK, U-value of existing wall was estimated with 0.8 W/m²K, uncritical conditions.
(Walker & Pavia, 2015) **(Thermal performance o fa selection of insulation materials suitable for historic buildings)**	Insulation: Six insulation types and thermal painting: aerogel 20 mm, cork lime plaster 40 mm, hemp lime plaster 40 mm, calcium silicate boards 35 mm, timber fibre boards 45 mm, PIR boards 38 mm, thermal paint Type of insulation system: vapour retarding, non-capillary active and vapour-open capillary active Building: erected in 1805, Royal Hospital Kilmainham building Building usage: former hospital building, current usage not mentioned Building location: Dublin, Ireland Construction: 770 mm thick brick wall (likely brick masonry outside, infill with other material), some parts of reduced thickness, e.g. beneath windows only 400 mm, roughcast lime render plaster outside (renewed in 2005) Measurements: Building measurement: surface measurement of temperature and heat flux inside in each wall section in three different rooms directed to North and West-side, sensors installed above window, in window sill and beside window, internal wall temperature in depth of 130 mm via drill holes covered by tape, thermographic survey for the pre- and post-insulation state, moisture measurements with timber dowels Material measurement: thermal conductivity, density, specific heat capacity of the insulation materials Points of interest: Comparison of measured and producer-given thermal conductivities with the corresponding impact on the difference between measured (heat flux measurements) and calculated U-value, evaluation of pre and post insulation via thermographic survey, moisture content in the walls for different insulation systems Outcomes: Measured U-value of the existing wall 1.32 W/m²K, producer values for thermal conductivity lower than measured, error in U-value calculation according to this 4-11%, one reason might be moisture content sensitivity of thermal conductivity, moisture content in the walls about 10-12%, no effect of thermal painting measured

(Harrestrup & Svendsen, 2016) **(Internal insulation applied in heritage multi-storey buildings with wooden beams embedded in solid masonry brick façades)**	Insulation: mixture of aerogel and mineral wool with integrated vapour barrier, 40 mm Type of insulation system: vapour tight Building: old heritage building, built at beginning of 20th century Building usage: residential (apartments) Building location: Copenhagen, Denmark Construction: solid masonry (appr 300-400 mm), joints with lime mortar, 40 mm insulation boards, 10 mm gypsum board Measurements: temperature and relative humidity sensors in joist ends in two apartments (4th and 5th floor) on south-west facing façade, indoor air temperature and relative humidity sensors in both apartments Points of interest: comparison with simulation in Delphin (5.8), simulation: impact of masonry thickness, insulation technique around joist end, wind-driven rain loads and indoor conditions on damage risk at joist end Outcomes: uncritical conditions at joist end with maximum relative humidity below 65% (two bricks masonry thickness) and 65-70% (one brick masonry thickness), good accordance between simulation and measurement, simulation: reduced mould growth with insulation gap in socket area, north-oriented façade most vulnerable due to missing solar radiation (drying potential)
(Baďurová, Jošt, Bahleda, & Ďuďák, 2016) **(Analysis of the Internal Insulation of Renovated Building)**	Insulation: 5 different types, each 130mm thickness: 1= sheep wool (λ=0.04 W/mK), 2: hemp (λ=0.04 W/mK), 3: Recycled textiles (λ=0.047 W/mK), Crushed cork (λ=0.04 W/mK), blown cellulose (λ=0.04 W/mK) Type of insulation system: different types, see above Building: School building, erected in 1906 Building usage: local centre of a civil association (Arthur) Building location: village Hruby Sur, Slovakia Construction: Basic construction from outside to inside: lime plaster (λ=0.87 W/mK, d=40mm), brick wall (λ=0.86 W/mK, d=440 mm), insulation layer (d=130 mm), fibre board (λ=0.04 W/mK, d=60mm), clay plaster (λ=0.57 W/mK, d=30 mm), U-value = 1,37 W/m²K, insulation in window breasting area with Multipor (thickness not mentioned) Measurements: Temperature measurements in different depths of the wall in each insulation field: exterior surface (plaster), masonry, condensation plane (insulation –masonry), interface insulation- board, internal plaster, Points of interest: demonstration of the thermal performance of ecological valuable materials, investigation of the environmental impact of the applied materials Outcomes: thermal performance worse than predicted and expected, graphs for three different insulation materials on the coldest day of the measurement period (outdoor conditions not explained, no direct comparison with computed values)
(Söhnchen & Schoch, 2017) **(Complex building element monitoring - interior insulation in practical test)**	Insulation: Multipor (Xella) 50 mm Type of insulation system: vapour-open, not capillary active Building: From beginning of 19th century, former castle (Schloss Güterfelde bzw Gütergotz) Building usage: Originally used as castle, later sanatorium for lung patients and training centre for SA, since 1945 used as retirement home, since 2013/2014 apartment building with 36 units Building location: Güterfelde, 10 km in the South of Potsdam, Germany Construction: likely brick (not explained), masonry in lower floors with thickness of 80 cm, reduced thickness in upper floors, external render with water-repellent property Measurements: Material testing for creation of material functions needed for the hygrothermal simulation of the construction (assessment and dimensioning of insulation layers), different measurement tracks in four different apartments

	located at three different floors, altogether 37 sensors including outdoor and indoor air conditions (T,RH), surface temperatures on both sides of the wall, heat flux inside, combined T,RH at different positions within glue mortar layer, furthermore local weather measurements to gain climate boundary conditions for the simulations, measurement period from June 2013 until June 2016 (with interruption 2014) Points of interest: Risk of mould growth in condensation layer, comparison of pre-intervention simulation with measurement results, comparison between simplified dew-point temperature value and real values from measurement, development of efficient monitoring system Outcomes: measurement analysis for measurement track in lower floor at window reveal with 10 sensors yielded temporarily critical relative humidity (90-100%) in the glue mortar layer at certain points (e.g. exterior wall edge, window reveal), comparison of measurement results with simulation results showed good accordance but slightly higher temperature level in the simulation than expected and more speedy reaction of humidity state in simulation compared to measurements, previously simulated U-value matches very well the measured one (0,7-0,8 W/m²K)
(Biseniece, Zogla, Kamenders, Purvins, & Kass, 2017) **(Thermal performance of internally insulated historic brick building in cold climate: A long term case study)**	Insulation: three different insulation types: aerogel mat 50 mm, VIP 50 mm and PIR 10 cm Type of insulation system: all not capillary active materials, vapour diffusion resistance medium (PIR, likely with aluminium lamination) till infinitively high (VIP), not mentioned explicitly Building: Small building with circle-shaped floor plan in city centre of Riga, Latvia (located in Spikeri-quarter, UNESCO World Heritage area) Building usage: currently used as public restroom and municipal tourist information centre Building location: Spikeri-quarter in Riga, Latvia Construction: Basic construction: silicate brick masonry with 510 mm, outside treated with hydrophobic agent (water-repellent coating) Measurements: Air and inner-construction temperature measurements at different positions in each of the three test fields and in different depths covering the interfaces between masonry and insulation (1), insulation – insulation (VIP, Aerogel, 2) and insulation – plasterboard (3), each in 5 min interval, furthermore indoor and outdoor temperature and heat flux at inner surface in 10 min interval, measurement period from January till November 2014 (about one year after refurbishment) Points of interest: Risk of frost damage in existing masonry (evaluation of freezing-thawing cycles), energetic performance of wall sections during usage and real weather bearings compared to computed values, evaluation of moisture situation via hygrothermal simulations (DELPHIN) Outcomes: measured U-values of Aerogel as expected from calculation, measured U-values of VIP better than expected (calculated: 0.09, measured: 0.06), could be attributed to spatial inhomogeneity (frame-field) or temperature dependency of thermal conductivity, conclusions from the DELPHIN simulations: slightly different temperature conditions than measured, critical relative humidity in interstitial condensation layer for both test fields (more than 90 resp. 95% relative humidity)
(Hamid & Wallenten, 2017) **(Hygrothermal assessment of**	Insulation: building in Örebro: 70+45 mm mineral wool with vapour retarder in between, cavity towards masonry (15 mm) and OSB (12 mm) plus gypsum board (13 mm) coverage towards room Type of insulation system: Mineral wool: vapour-open, not capillary active

internally added thermal insulation on external brick walls in Swedish multifamily buildings)	Building: Three tower block buildings (one of them used for measurements) hosting entirely 29 apartments, renovation from 2013 to 2016, Installation of sensors 2015 Building usage: used as apartment house Building location: Örebro, Sweden Construction: brick-faced masonry 250 mm thickness Measurements: Measurement of temperature and relative humidity in different depths in the building with 26 sensors, measured states in 10 min resolution and for a period of 6 months, sensors placed in North and South-directed walls, placement far away from thermal bridges in undisturbed area of the wall, depths: 90, 150, 200 mm from inner surface Points of interest: Validate hygrothermal project of construction, modelled with WUFI Pro (Version not mentioned), Evaluate damage risk in regard to mould growth resp. microbiological growth in general, Problematic: no material data available for particular project (selection of similar materials from different data bases), no indoor climate measurements, no local weather data set (e.g. solar radiation computed, not measured) Outcomes: Measurements: high impact of cardinal direction on wall performance, variation of moisture content over wall height Simulation: Validation not possible as there are big deviations between measured and simulated values (peaks), further variant studies performed with hygrothermal model, yielded better performance of capillary active materials for corrosion risk
(Hansen, Bjarlov, Peuhkuri, & Harrestrup, 2018) **(Long term in situ measurements of hygrothermal conditions at critical points in four cases of internally insulated historic solid masonry walls)**	Insulation: Two different insulation systems: (1) phenolic foam boards (λ=0.02 W/mK, μ=) and (2) PUR-boards with calcium silicate cores (λ=0.037 W/mK, μ=) applied in thicknesses of 80 mm (A), 60 mm (B), 25 mm (C) and 30 mm (D) Type of insulation system: vapour open, none (1) resp. low (2) capillary activity Building: A: Ny Allegade 10 (system 2) erected in 1932, two storeys, B: Meinungsgade 1 (system 1), erected in 1877, C: Kildevaeldsgade 69 (system 1), erected in 1905 and D: Thomas Laubs Gade 5 (system 2), built in 1899 Building usage: residential buildings (selected apartments were measured) Building location: Haderslev (case A) and Copenhagen (case B to D), Denmark (building names are street names) Construction: solid brick walls of 360 mm thickness with internal render and in case (C) also exterior render and painting Measurements: T, RH sensors at the interface between insulation and existing wall combined with measurements at the joist ends (except case study D), cardinal directions of the walls with measurement tracks are (A): south and west, (B) south and south-west wall in 5^{th} floor, (C) north, 5^{th} floor, (D) east direction, 3^{rd} floor, indoor conditions and local weather conditions were measured Points of interest: Evaluation of mould growth risk in the buildings based on an adapted VTT-model version, validation of a hygrothermal project (Delphin) and prediction of long-time behaviour (10 years of future-scenario weather data) and parameter variation (varied insulation thickness and type, render) based on this model, simplifications for the model: 1D with wall material of mortar (showed best accordance with measurements) Outcomes: Mould growth risk evaluated for all four buildings, remarkable risk given in the case with the highest insulation resistance and the thinnest wall, negligible risk for the other two cases (one case not evaluated due to data quality), measurements likely not representative due to convective inlet enabled through leakage of vapour barrier (around joist end)

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