CORNET
Final Report / Schlussbericht

IN2EuroBuild
Consistent European Guidelines for Internal Insulation of Building Stock and Heritage
Einheitlicher europäischer Leitfaden für die Innendämmung von Bestandsbauten und Baudenkmälern

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Content

Executive Summary

Energetic refurbishment of exterior walls is one of the most important steps to reduce the energy demand of the existing building stock under Central European climatic conditions. In some old buildings, interior insulation is the only option for insulating the exterior walls. This is particularly the case when facades characteristic of the appearance of the city, valuable in terms of architectural culture or otherwise worthy of preservation are the subject of energy retrofitting, as well as in the case of exposed masonry or boundary buildings. In the case of buildings used only temporarily, however, interior insulation can also offer significant energy benefits, as it enables significantly faster and more cost-effective conditioning.

Interior insulation must be executed with care, as it can increase the risk of moisture problems such as condensation, mould growth, or frost damage. However, when well designed and executed, they are a reliable and proven insulation measure suitable for most applications.

Despite many research projects on the subject, now many established system solutions for interior insulation, and decades of positive experience, the technique is still too rarely used compared to its great potential. Some planners are still uncertain about its application due to the large number of available systems and different modes of action. Clear, simple and comprehensive guidelines for building practitioners are needed on the way to a reliable and large-scale application of interior insulation. Closing this gap was therefore the main objective of the IN2EuroBuild project "Consistent European Guidelines for Internal Insulation of Existing and Heritage Buildings".

For this purpose, a comprehensive guideline for the planning of interior insulation measures was developed in the project as support in the planning process and for decision-making. It guides the user from the inventory analysis of the building to the renovation planning of the facade, selection of suitable insulation systems, verification, and detail consideration.

This comprehensive guideline is divided into two parts.

In order to achieve optimum renovation success, the concept must be based on the existing condition of the building. In the first part of this set of guidelines, therefore, the evaluation and condition analysis of exterior walls on existing buildings was addressed in order to be able to reliably assess the hygrothermal behaviour.

In the second part of the set of guidelines, the user is guided through the renovation planning of the façade, the selection of suitable insulation systems, verification, and detail consideration. It describes the aspects that must be taken into account throughout the entire process of planning and executing an interior insulation measure.

Both parts of the guideline are aimed at people who have no or little experience in the field of energy renovation and interior insulation, but who want to be informed and at least have a say in the whole process. This group of people can include, for example, building owners, investors or public authority employees, but also architects or engineers who rare-ly deal with internal insulation and therefore do not know the different planning principles and dependencies in detail. Readers should be enabled to assess a factual situation and select a suitable

interior insulation system in the numerous, unproblematic cases where specialists do not need to be consulted.

In addition to the practical guidelines, other important topics related to interior insulation measures were examined.

As the hygrothermal characteristic values for historic mortars and plasters are often not known, but relevant for the design of measures, various historic recipes of mortars and plasters were manufactured during the project work and their complete hygrothermal material characterization was carried out.

In addition, a compilation of representative exterior wall types in Germany and their regional distribution was made in order to provide assistance for the classification of existing building materials.

In recent years, insulating materials made from renewable organic materials have gained in importance. They improve the CO2 balance and are considered to be environmentally friendly and particularly good for indoor climate comfort. However, the limiting moisture contents specified in standards and guidelines for such materials have up to now generally been quite low, which considerably restricts their range of application. Manufacturers, however, have good practical experience beyond the previously permissible areas of application. For this reason, extensive investigations were carried out on various insulation materials as part of the project, so that realistic limit criteria could be established for the more moisture-resistant natural fibre insulation materials used as interior insulation.

A further issue was the extension of the previous simplified design procedure for the so-called capillary-active insulation materials. According to the current regulations, a hygrothermal simulation is required for their verification. Since moisture accumulation and the incipient capillarity depend on many factors, there were no simplified design rules so far. In order to reduce the effort for simulations, a classification of the performance of capillary-active insulation materials was made on the basis of many investigations. Thus, for defined boundary and usage conditions, a simplified verification for certain classes of such insulations is now possible. The investigations and results as well as the simplified design rules are presented here.

1 Evaluation of the existing buildings

Clear, simple and comprehensive guidelines at the level of building practitioners are the missing link on the way to a reliable and large-scale application of internal insulation, which is the main objective of this IN2EuroBuild project (Consistent European Guidelines for Internal Insulation of Building Stock and Heritage). This previously existing gap has been closed with the availability of the complete and comprehensible guide.

In the past, there have been several projects and publications that are intended to support the renovation of old buildings by means of interior insulation. However, this has not been able to decisively increase the acceptance of and knowledge about interior insulation among the general public. Previous projects were often aimed at people with the appropriate prior technical knowledge ([1], [1]), as engineers, architects or specialists, or focused on specific sub-areas [3]. Other publications that are too extensive ([1] und [5]) have a deterrent effect and unfocused publications provide too little information [4]. In contrast, there is a lack of low-threshold, condensed and nevertheless intelligible information.

As already mentioned, it is important to keep the size of the publication within reasonable limits in order to achieve greater acceptance by the target audience. That is why it was divided: The first part deals with the building analysis, the second part is about the planning of interior insulation measures.

The many years of experience of the participating institutes in the planning and monitoring of interior insulation measures in a large number of buildings, many of which are listed, were taken into account in the development of the guidelines ([1], [6], [7], [8], [9], [10])

1.1 Guideline Building analysis

A thorough investigation of the existing building is a necessary condition for the successful refurbishment. Therefore, the first part of the two guides concentrates on the condition analysis and assessment of buildings. In many buildings, unproblematic conditions are found, so that this analysis can be brief.

The explanations start from a simple level of knowledge and they only teach the necessary basics in order to understand and evaluate the general condition of a building. Readers should not be overwhelmed by the complexity or amount of information provided. However, there are also conditions that are more complex and cannot be assessed easily. In such cases, it is then explicitly recommended to consult experts.

The guideline first conveys the principles of how a building analysis is to be planned in advance. At the beginning, this means gathering and evaluating all possible information about the (construction) history of the building. These are often written sources such as plans, archive documents, expert opinions or invoices, but also oral sources such as users and housekeepers, both current and especially former.

The building assessment focuses on moisture damage, as this is the main cause of damage to buildings. Moreover, these are often easy to assess. Damage that affects the statics, for example, is more difficult to assess and may be life-threatening, which is why it is not dealt with in these guidelines

A two-stage procedure is proposed, in which the structural situation is fundamentally recorded in the first stage. If damage is found, it is recorded and provisionally assessed. In the case of damage, a second stage has usually proved useful and is therefore recommended. This involves a more detailed examination of the damage with the help of various measuring methods and, if necessary, with the assistance of experts.

The research methods presented were part of a separate work package, which is discussed in more detail in the following chapter.

Case 15 Degradation of protection materials near the wall base

Powdering, flaking, cracking, detaching of materials. Usually, the degradation might become very intense, because of the high moisture and salt-exposure.

EXAMINATION
Analysis of the protective material, analysis of salt content, humidity diagnostics

CAUSE
Mostly through the action of frost or salts, combined with an underlying humidity problem, for instance rising damp or splash water (ground inclined towards wall).

SOLUTION
- Any underlying humidity problem should be resolved (e.g. rising damp)
- Restore the building materials. It might be necessary to use materials with a lower water uptake and higher frost resistance.
- Rainwater drainage at the wall base (e.g. through a gravel bed) may be necessary.
- Apply drying measures at the inside if necessary.

REMARKS
- The wall base requires special attention, as it is highly exposed to moisture and salts. Proper protection from splash water is necessary, as this prevents moisture from penetrating deep into the wall.
- When applying internal insulation, an efficient protection against splash water in good condition is required. The minimal height of a splash protection is 30 cm.

Figure 1: Example of a damage pattern that is explained in the appendix

To provide the necessary basic knowledge, one chapter explains the basic types of possible moisture sources. It is followed by more exact descriptions of their manifold manifestations:

- how do they appear,

- what conditions are necessary (materials, wall constructions),
- what mechanisms lead to the destruction of building fabric?

The analysis part closes with a larger appendix that contains many pictures of damage examples or structural conditions that can favour damage (Figure 1). It is necessary to show and explain these as readers might have low knowledge of damage patterns or are insecure. In this way, readers can see how the individual types of damage actually look in practice. Possible causes, reasonable examinations methods and solutions are briefly discussed for each example.

1.2 Development of simplified on-site tests

This work package aims to present simple measuring methods that do not require many years of experience or expensive equipment. However, such methods are also explained, which are usually only carried out by experts. Finally, the aforementioned target group of the guides should be enabled to assess the necessity of such advanced methods in principle.

The examination possibilities in the first phase of the building analysis extend primarily to the five senses, supported by very simple aids. In principle, lay people are therefore also able to carry them out. The "expert eye", which lay people normally lack, and the corresponding procedure are explained by many examples: how to use one's own five senses, what exactly to look out for, which parts of buildings are particularly susceptible to what damage, etc. There are enough sources of damage that can be easily detected by lay persons, such as defective downpipes. Especially the simple examination methods are given a lot of space so that they can be safely applied and interpreted. These are e.g. the wetting-test or the Karsten-tube test [11].

The second phase of investigations may be necessary to confirm a damage, to better assess the extent or to refute the damage hypothesis. Various tests of different quality are described for this purpose. The simpler tests can be performed by lay people, the others normally by experts. The latter are also described in order to give readers an overview and show about what test might provide the necessary information in case simple tests are not sufficient.

1.3 Characterisation of wall types and external layers

1.3.1 Material analysis

In order to guarantee an optimal moisture management with interior insulation of the exterior walls by hygrothermal component simulation, hygrothermal material parameters are required.

Due to the development of various capillary-active interior insulation systems, many hygrothermal material parameters of modern building materials are available. In the case of interior insulation of the exterior wall, the existing construction has a significant influence on the hygrothermal behaviour of the overall system. Nevertheless, there is a clear lack of historic plasters, renders and masonry mortars in material databases. Additionally, the composition and practical application of historic renders and masonry mortars is poorly understood in the building physics community.

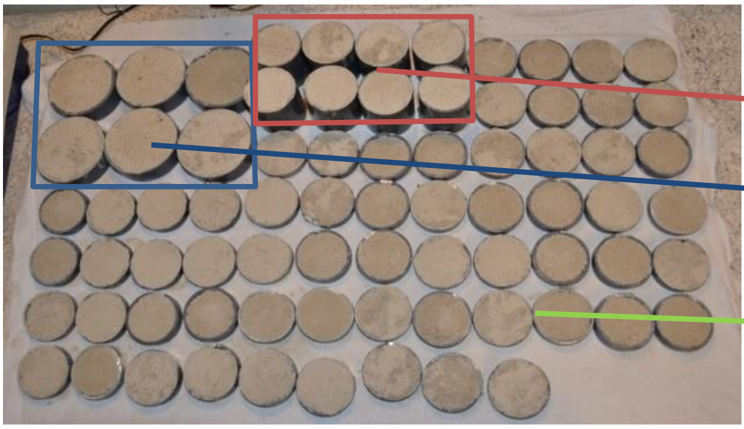
With the help of an experienced master bricklayer with a long family tradition in this field, historical plasters and masonry mortars were recreated and their mortar and plaster formulations were documented. A systematic material investigation for subsequent mortars and plasters was carried out.

Table 1 Composition of historical plasters and masonry mortar

Nr.	Application	Room parts	Aggregate grain size, sand	Room parts	Lime	Room parts	Cement
1	Masonry mortar/undercoat plaster (interior/ exterior)	4	0 - 4 mm (Gravel pit Kuhn)	1	Hydraulic lime 5	1/4	CEM II 32,5R
2	Finish plaster (interior)	2,5	0 - 1 mm U (Uhsmansdorf)	1	White lime 90*		
3	Fine and finishing plaster (exterior)	4	0 - 2 mm (Gravel pit Kuhn)	1	Hydraulic lime 5		
4	Jointing mortar for clinker (exterior)	3	0 - 1 mm U (Uhsmansdorf)			1	CEM II 32,5R

*slaked lime at least a few days better but weeks to soak

The **masonry mortar and undercoat plaster** (Table 1,1) consists of sand, hydraulic lime and little cement. It was used as a base plaster of masonry on the inside and outside and for. On the inside of higher quality interiors a neat lime slurry (Table 1,2) was used as a **finishing plaster**. For this purpose, the white lime was soaked for at least 1 day. The plaster was applied with a felt rubbing board, with a very fine sponge board or with a small wooden board. The **finishing plaster** (Table 1, 3) for exterior surfaces contains only sifted sand and hydraulic lime. No cement was added. The **jointing mortar** (Table 1, 4) for clinker masonry consists of sand with a grain size up to 1 mm, cement and extremely little water. The jointing material was so dry during processing that no water or cement film was prominent during processing. The water-cement ratio is very low. The grouting is very open-pored.



Specimens for measurement

A_w/w- value

Bulk density, thermal conductivity, specific heat capacity, µ-value

Moisture storage function (adsorption and desorption)

Figure 2: Specimens for the determination of hygrothermal material properties

Figure 2 shows the necessary number of specimens for the determination of the hygrothermal material values. In order to produce a material as it would be manufactured on a construction site, the specimen preparation was made analogous to the setting behaviour on the masonry. Therefore, the specimens were prepared on a dried Fermacell board with a separating layer.

The condensation test was carried out for the masonry mortar and undercoat (Table 1,1, see chapter 4.1).

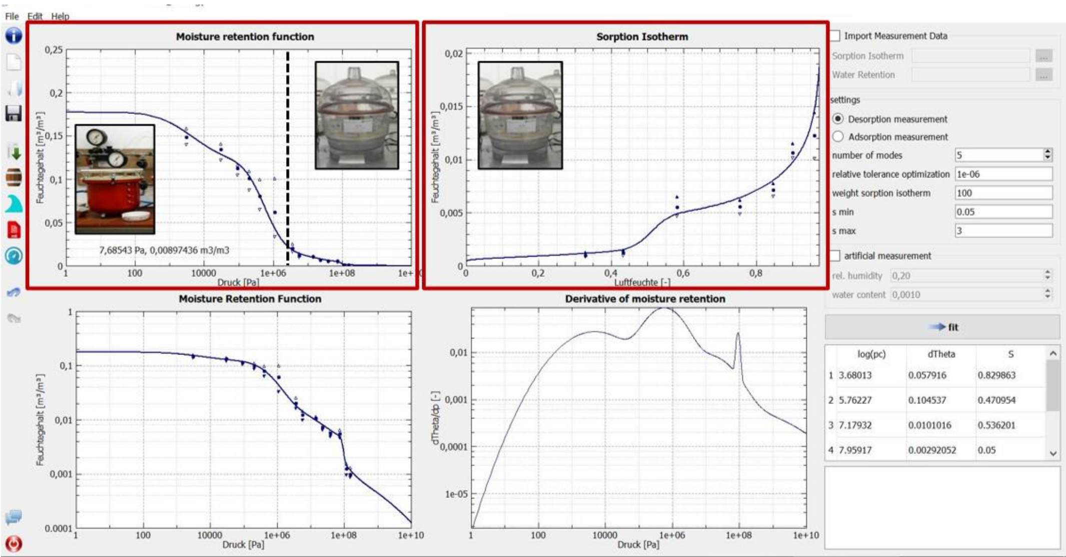


Figure 3: Screenshot of the MaterialGenerator: Fitting of the moisture retention curve with the help of desorption values and values of overhygroscopic water content

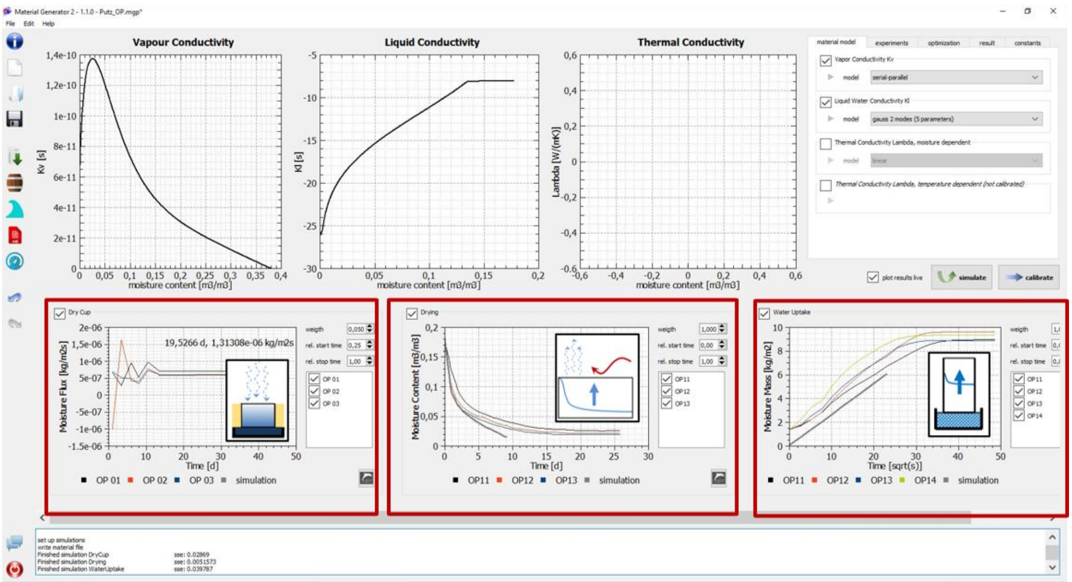


Figure 4: Screenshot of the MaterialGenerator: Calibration of moisture transport function (vapour and liquid water) with the help of results from drying experiment, water uptake experiment and dry cup experiment

For the generation of hygrothermal material functions new software “MaterialGenerator”, developed at the IBK, was used (see Figure 3 und Figure 4, [12]). From all measured hygrothermal material values and with the help of algorithms material files are formed that serve as basis for hygrothermal simulations. After termination of the generation process, material files of all materials are transferred to the databases of different component or building software, such as COND, THERAKLES, DELPHIN and NANDRAD.

1.3.2 Representative wall types in Germany

The following section describes the procedure for identifying representative building structures for the building stock in Germany. In a first step, the relevant building stock is identified. This is followed by an analysis of the construction structures mainly used in this building stock. At the end, a selection of representative construction structures is made, including the used materials.

Survey of historic building stock

The refurbishment report of BMWK published at the end of 2014 shows the distribution of residential buildings in Germany according to their construction age. According to this report, almost 40 % of German residential buildings were erected between 1949-1978. A study [13] came to an almost identical conclusion. Accordingly, there have been no significantly more recent results or updates to the data in this period. More recent studies are not available. For further analysis, it is therefore assumed that the more detailed evaluations of the IWU study [16] have lost none of their relevance.

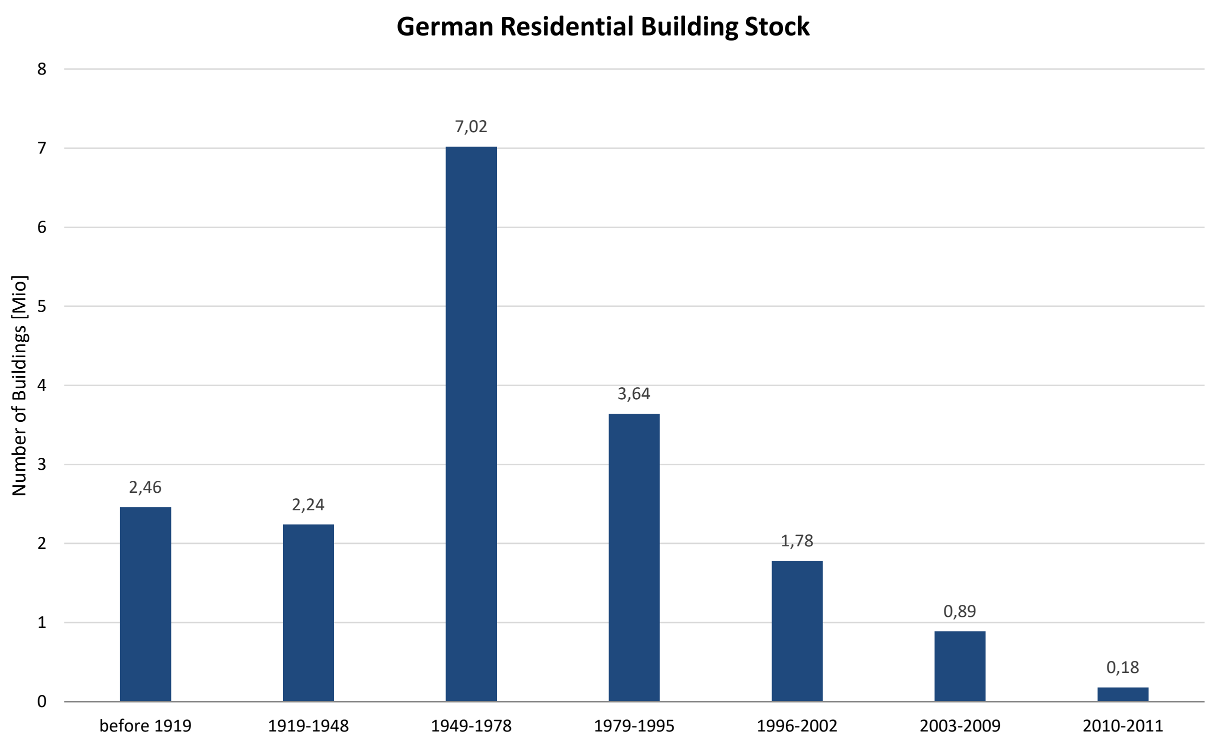


Figure 5: Distribution of the residential building stock in Germany by Building Age Classes

The IWU study [16] comprises about 7500 data sets and covers about 50 % of all German cities and counties. It can thus be easily applied to the entire territory of Germany.

The authors come to the conclusion that there are two dominant exterior wall constructions in Germany, which are consistently represented across all building age classes: 61 % are single-shell masonry constructions and 30 % are double-shell masonry constructions. The remaining 9 % are made up of different types of construction, such as timber frame construction or precast concrete elements [13]. The distribution of the construction types depend on the region. In northern Germany, for example, the double-shell masonry tend to dominate, whereas in middle and southern Germany the single-shell masonry predominates.

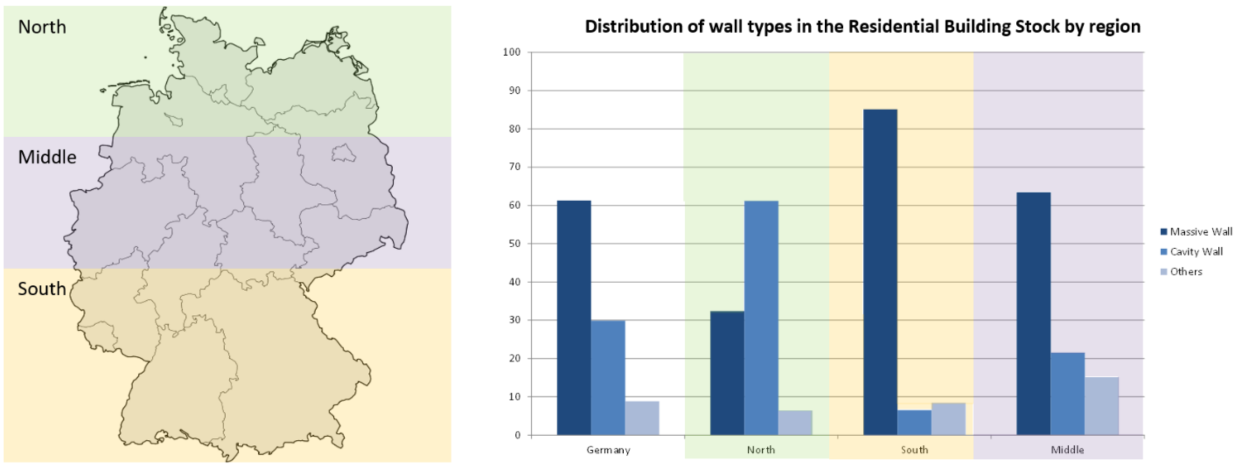


Figure 6: Distribution of wall types in the residential building stock by region in Germany

Based on this pre-selection, the ZUB ("Centre for Environmentally Conscious Building") catalog of regionally typical construction methods and materials ([14]) was compiled in tabular form. The result can be found in the appendix to the report. The two dominant construction types are described in more detail below.

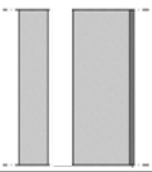
No.	Konstruktion	Baualtersklasse	Verbreitung	Schichtenaufbau	Materialeigenschaften				
				(von innen nach außen)	Stärke [cm]	d [kg/m³]	λ [W/(mK)]	µ-Wert [-]	Aw [kg/m²h^0.5]
1	Ziegelmauerwerk einschalig Sicht oder verputzt 	1919 - 1948	Nord Mitte Süd	Kalkputz	1,5	1500	0,40	9	1,1
				Vollziegel	25	1750	0,5	35	3
					30	1750	0,5	35	3
					38	1750	0,5	35	3
				Hochlochziegel	30	1400			
				Kalkzementputz	1,5	1500	0,6	25	0,5
				(von innen nach außen)	Stärke [cm]	d [kg/m³]	λ [W/(mK)]	µ-Wert [-]	Aw [kg/m²h^0.5]
4	Kalksandstein zweischalig Sicht oder verputzt 	1949 - 1957	Nord	Kalkgipsputz	1	1250	0,30	12	8
				Kalksand-Vollsteine	24	1800	0,80	40	0,7
				(Tragschale)	30	1800	0,80	40	0,7
				Luftschicht (ruhend)	6				
				Vormauerziegel	11,5	1750	0,5	35	3
				Klinker	11,5	2000	1	40	1
				Kalkzementputz	1,5	1500	0,6	25	0,5

Figure 7: Description of typical wall types predominantly erected in different time periods

The tables show a classification of the individual constructions according to Building Age Classes together with the corresponding distribution within Germany. A further column contains typical layer thicknesses and material properties. The material properties are limited to data on bulk density and thermal conductivity. The specification of hygric material parameters is not given. An explanation of this can be found under “Conclusions”.

Massive Wall

Until the end of 19th century most wall construction were designed based on experiences and common rules of thumb. One example for external (load-bearing) walls is given by (Heine 1842) who suggests wall thickness of 1/6 of the bench height for rubble stone walls and of 1/8 for brick masonry. Another rule is provided by (Lämmerhirt 1869) who supposes wall thicknesses of 1.5 brick length for load bearing external walls. These rules were replaced with local construction regulations which were published from the 1870 on. These local regulations remained valid in parallel to the enactment of diverse national standards (e.g. DIN 1053 from 1937: first common masonry standard, DIN 4106, see also [15]).

In 1872 the metric system was adopted in Germany. This led to a common brick format, called ”Reichsformat” with dimensions of 25 cm (length), 12 cm (thickness), 6.5 cm (height). The usual head joint thickness was 1.2 cm, bed joints 1 cm.

Faced brickwork made of premium frost-resistant brick shows beneficial moisture buffering effects. Due to cost reduction, this premium layer was often combined with low-budget brick backing. The hygrothermal behavior of masonry made of clinker is slightly different. These bricks are less moisture permeable and provide moisture buffering mainly through the joints. For cost reasons, clinker was also used as facing layer and sometimes even in a reduced form (perforated clinker, [15]).

Massive walls made of natural stone differ strongly due to local availability and experiences. Cobble, rubble, quarry stone and erratic were widely used, especially in rural areas. They were mostly combined with brick masonry for structural stability reasons. Sandstone, granite, limestone, syenite and tuff were used where they were naturally occurring, e.g. Saxon sandstone mountains near Dresden. A further distribution of natural stone was forwarded with the railway network expansion after formation of the German national state in 1871.

From 1919 on, several special forms of masonry were developed to improve the thermal insulation of these walls. Approaches ranged from density reduction (e.g. increased porosity by adding organic substances which were burned out), format and hole enlargement, optimization of hole shape to reduction of joint dimensions. Also, alternative materials were developed, e.g. hollow concrete blocks and concrete blocks.

Cavity Wall

The objectives for placing cavities in external walls were an improvement of insulation standard, reduction of moisture in the masonry and material saving. Constructions range from small wall cavities up to cavity networks. These constructions show cavities passing through the entire external wall, spanning several storeys. Often they are connected to ceilings ventilating from the basement or roof. Connections between both wall layers (load-bearing layer and facing) were realized with perpenders (often treated with tar or bitumen), wire tie or flat steel. From 1919 on, several cost-efficient construction and material types were developed, especially for small single family dwellings. This led also to very thin masonry walls with load-bearing layers of only 12 cm thickness for these cavity walls ([15]).

Problems were thermal and moisture bridges through the connections between both layers or at the edges of the construction (corner, reveals etc.) and increased convective heat transfer due to strongly circulating air in the cavity. Therefore, cavities were often divided or filled, e.g. with cork or saw dust. Radiative heat exchange was sometimes reduced by the help of a foil at the internal side of the external masonry layer ([15]).

Conclusions

The graphical evaluation of the thermal and hygric parameters of more than 200 masonry bricks measured in the laboratory did not reveal any direct correlation between the building age and the specific material properties. No parameter ranges characteristic for a Building Age Class could be identified. In particular, there is a wide range of values for water vapor diffusion and liquid water conductivity. The value of thermal conductivity can be better delimited. For mainly brick masonry, thermal conductivity lies between 0.6-0.9 W/(m·K). Walls made of solid natural stone, as rubble stone or sandstone, with a considerably higher thermal conductivity of about 2 W/(m·K) are an exception.

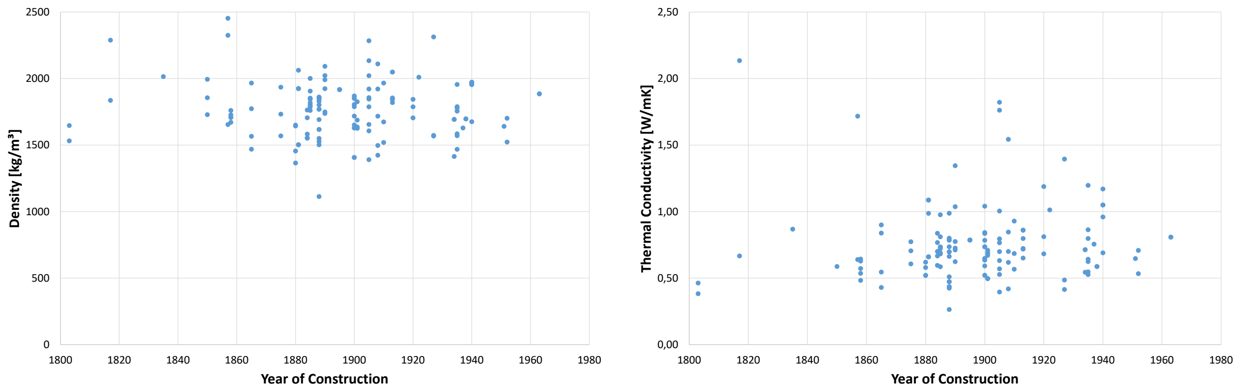


Figure 8: Density and thermal conductivity of 200 test specimens measured in the laboratory of the IBK

1.3.3 Representative wall types in Belgium

The Belgian building stock is a rather old one. About a third (36%) is constructed before 1945, a period where most buildings in Belgium were constructed with massive masonry walls, typically with thicknesses around 30 cm. About another third (36%) is constructed between 1946 and 1981. By then, most buildings had cavity walls, although they were generally not insulated as their main purpose was to reduce rainwater penetration towards the inside. It was only after the energy crisis in the 1970s, insulation was added in walls, however at first with only a limited thickness. After the implementation of the Energy Performance of Buildings

Directive (EPBD) in Belgium in 2006, all new Buildings have to respond to minimal requirements for wall insulation (U_{max} = 0.6 W/m²K in 2006 to 0.24 W/m²K from 2014 onwards).

This means that 72% of the Belgian buildings were constructed during a period were generally no wall insulation was added. Only 10% of the buildings date from a period of time were most walls were well insulated. Even though the distribution by construction date is only a rough estimate for the wall typology and older buildings might have been energetically renovated in the meantime, it is safe to say that most Belgian buildings are poorly insulated and that there is a huge need for post-insulation of these walls (including interior insulation).

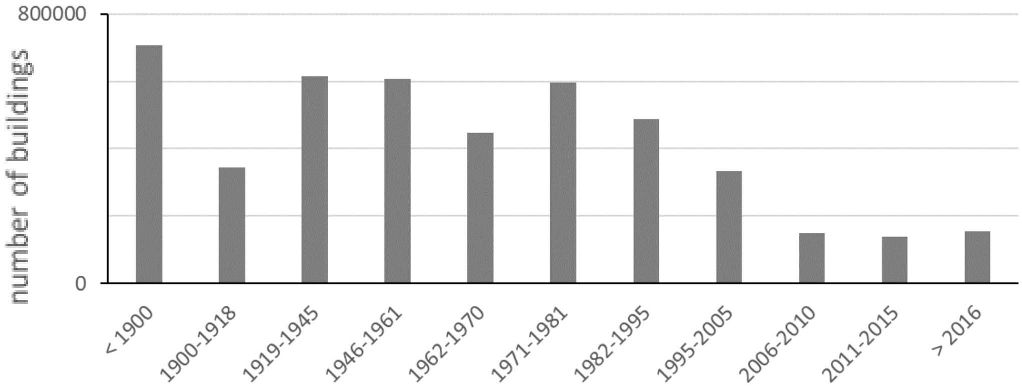


Figure 9: Distribution of Belgian building stock by date of construction [17]

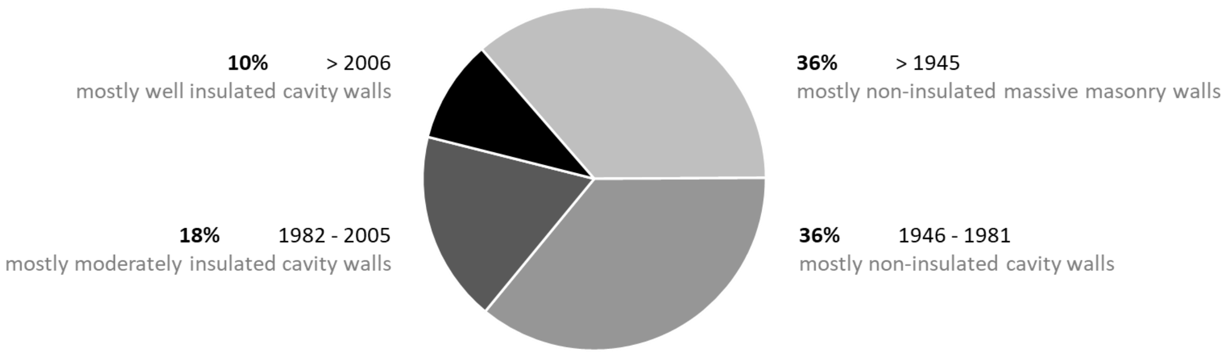


Figure 10: Distribution of Belgian building stock by date of construction and typology

2 Design and Execution of the interior insulation

The aim of producing the second part of the guideline (façade renovation and interior insulation) was to develop clear, simple and reliable design rules for dealing with interior insulation that are applicable to a variety of situations with different wall constructions, different insulation systems and in different climatic regions. Here, all concerns related to the topic of "planning the interior insulation measure" are treated in an all-encompassing manner.

This improves the user's skills and control in both design and execution; uncertainties associated with interior wall insulation are reduced. Thus, large-scale application readiness of this methodology for building practitioners is enabled. The speed of energy renovation of the existing building stock as well as the proportion of interior insulation used can thus be increased.

The user of the guide is directed step by step through the individual phases of processing by working through all the complexes of topics relevant to him. Thus, there is no danger that individual circumstances and requirements will be forgotten or insufficiently considered. Planning concepts can thus be created more quickly and easily, and any additional services that may be necessary can be scheduled in at an early stage and included in the cost planning. Simple procedures are described for the design of insulation systems in order to limit the number of cases in which complex numerical simulations are required.

This second guide is divided into the following sections

- Façade renovation concept
- Insulation concept and
- Design of structural connection details

Since the guide itself can seem quite extensive to the user due to its variety of possible scenarios, the supplementary creation of a clear flowchart created a convenient way to get all the necessary information and instructions that apply to the specific building in a very time-saving and clear way, without having to read the entire guide, but also not leaving out any important aspects. By linking the individual steps in the flow chart to the corresponding chapters in the guide, the relevant information and recommendations are always called up when they are needed. Clicking back will take readers back to the flowchart.

The flow chart is designed in such a way that there is a simple way for each situation, which is applicable for approx. 70% of all remediation cases. This processing method is marked in green. In some cases, more or less extensive examinations or further verification are necessary to assess the construction during planning. In these situations, the user is guided through the yellow or even red paths.

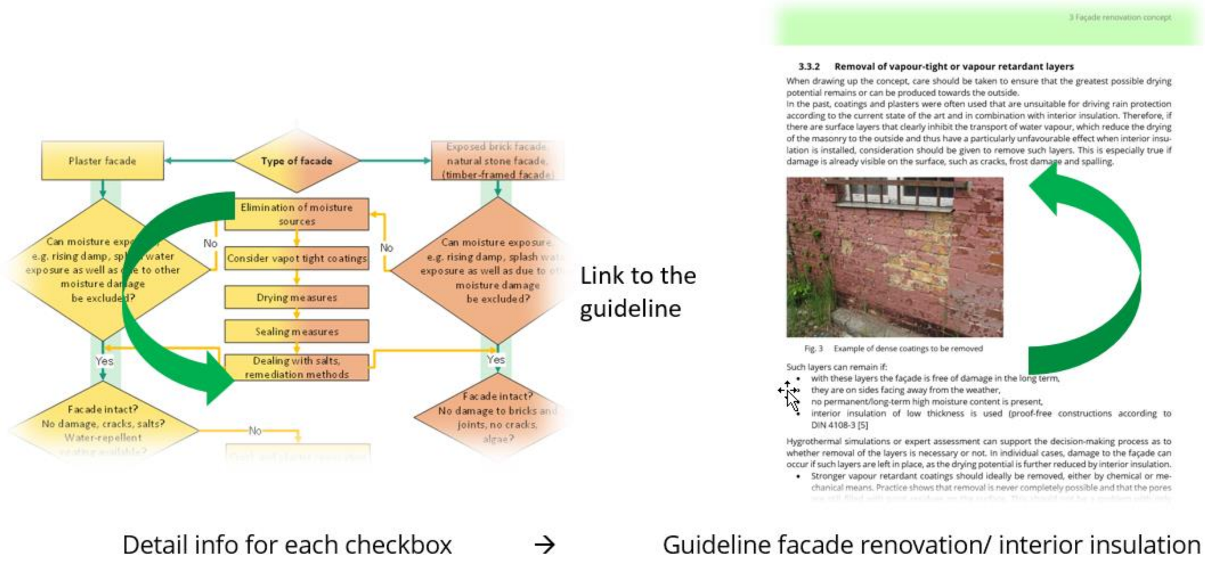


Figure 11: Example of link between flowchart and guide

In the **façade renovation concept** section, general advice is given, e.g. how to deal with moisture loads, dense façade coatings, salt loads or exposed façade elements. Furthermore, drying measures are described, methods for creating functional sealing systems are presented and the connection between interior insulation and driving rain protection and the resulting conclusions are explained. Depending on whether the building under consideration is a rendered or exposed brick façade, different necessary and optional measures and examinations are presented in order to obtain a driving rain-proof façade as a basic prerequisite for the application of interior insulation. In the case of rendered façades, this is easy to achieve in most cases. In the case of exposed brick façades, more extensive renovation measures are often required. This ranges from advice on cleaning the façade, crack and joint repair, criteria for material replacement to possible façade coatings and impregnations to ensure protection against driving rain.

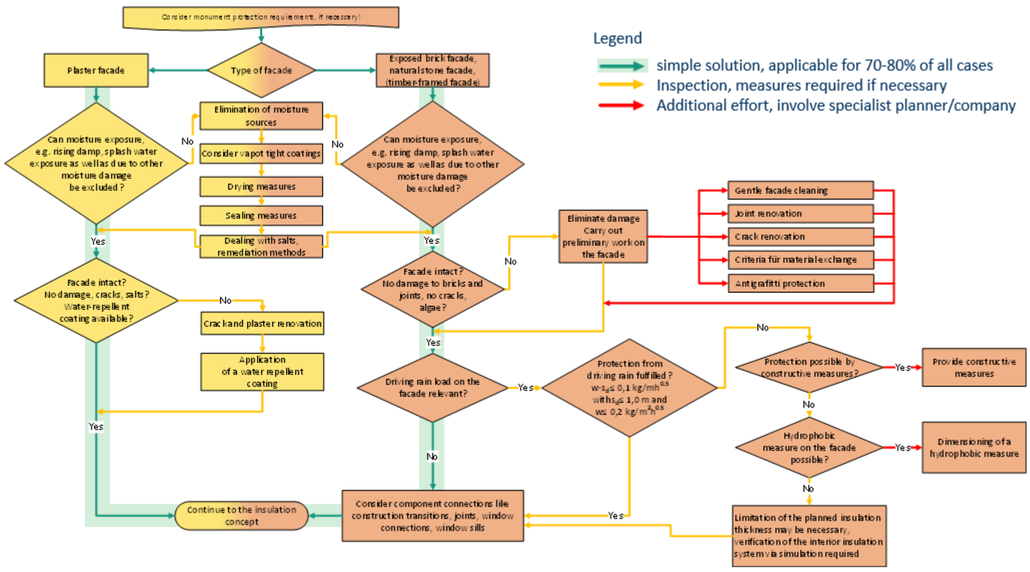


Figure 12: Flow chart of façade renovation concept, illustration of the simple solution (green arrows) and the additional measures (yellow and red)

The change from the flow chart to the guideline is illustrated using the example of the criteria for material replacement in brick façades. A link (here outlined in blue in Figure 13) opens the corresponding section in the guideline. At the end of the section, another link takes readers back to the flow chart.

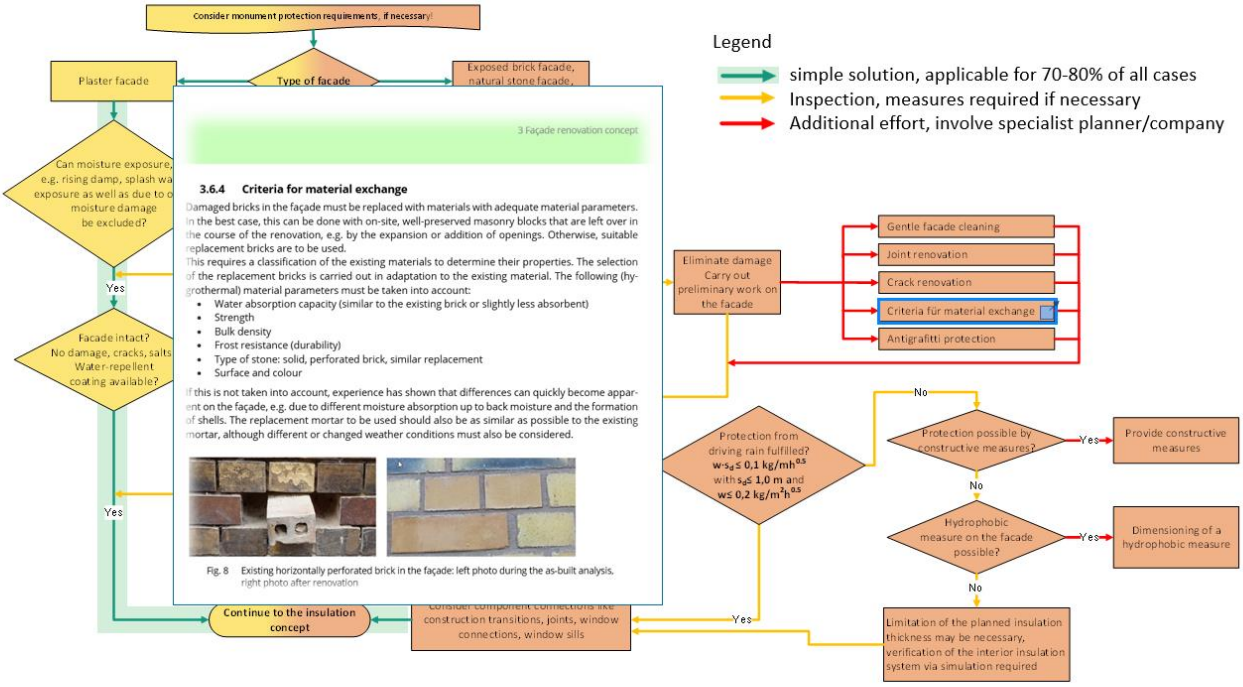


Figure 13: Flow chart for façade renovation concept, example of the linking to the corresponding chapter in the guideline

In the **Insulation Concept** section, the user receives assistance in the procedure for creating his insulation design. First of all, he is supported in the selection of possible insulation systems depending on various influencing factors. The systems are classified into different insulation categories (from vapour-permeable and capillary-active to vapour-retarding and vapour vapour-tight systems). In addition, recommendations for the selection for different application scenarios as well as an overview of the most important evaluation criteria for the application of interior insulation are given.

Subsequently, the different levels of proof (proof-free, simplified proof, proof by means of hygrothermal simulation) with the possibilities and limits of applicability are presented and explained for the dimensioning of interior insulation systems.

Within the scope of the project, an additional extended classification for capillary-active, vapour-permeable insulation materials was developed, for which the existing simplified verification procedure is not valid or appropriate. This procedure is described in chapter 4.

For the third stage of the verification, the hygrothermal simulation, the general procedure, the definition of the boundary conditions and other input data, the assignment of the outputs and the selection of the evaluation criteria are described. The proof of suitability is explained using examples of component simulations carried out.

In the section **Design of constructive connection details**, typical connection details are presented whose execution must be given special consideration in connection with interior insulation measures.

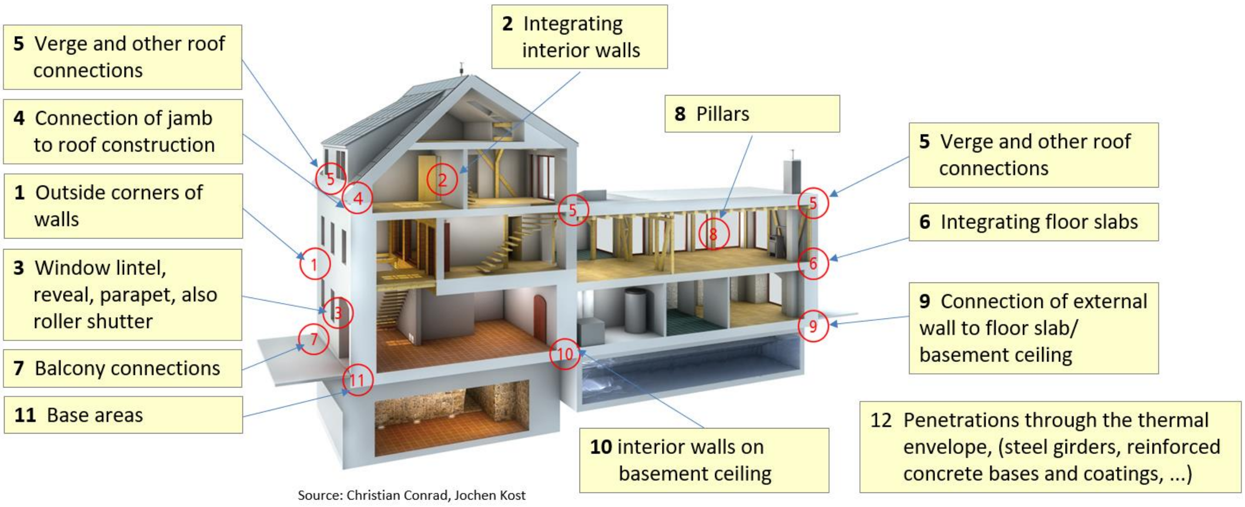


Figure 14: Illustration of common critical connection details in buildings with internal insulation

In addition, general dimensioning recommendations are given as rough preliminary dimensioning for the most important connection areas, such as window reveals, window sills, connection of solid ceilings and existing interior walls with identification of suitable materials and flanking measures.

In addition, criteria are described that are relevant for the selection of critical connection details for verification (thermal bridge calculations or hygrothermal component simulations). Possibilities for mitigating these details and alternative solutions are presented and demonstrated by means of detailed calculations.

A catalogue for common detailed solutions for the most important connection areas provide readers with practicable suggestions and specifications for planning and execution.

The guide also contains other often requested information, such as how to fix loads or how to deal with sockets in internally insulated exterior walls.

3 New Limit Criteria for Resistant Wood Fibre Insulation Materials

Renewable and sustainable building materials become more important concerning different aspects: reduction of the carbon footprint and the waste problem in the building sector, but also increasing the comfort with moisture and temperature buffering and natural materials. However, an extended use of the materials is often hindered by their sensitivity to moisture and the imprecise knowledge of the durability of the materials.

Also in the project EneffID [10] the unknown moisture limits for interior insulations made of wood fibres limited their use significantly more than the one of competing materials, as only the rather general and careful limit of 18 % by mass (wood moisture) was available, which is normally recommended to ensure strengths values of load bearing wooden materials. Due to this fact, in the current project, additional investigations were performed to compare the moisture and decay fungi resistivity of wood fibre interior insulation materials to the one of solid wood at different critical temperature and humidity conditions. This means a first step into the direction of a more accurate transient evaluation of the hygrothermal conditions occurring in wooden and other natural fibre materials with regard to infestation by wood decay fungi.

For solid wood, many investigations on its durability and moisture resp. decay fungi resistance have already been performed. Also moisture and temperature dependent limit curves ([18],[19],[20],[21]) as well as transient evaluation models are either already available or will be available in near future ([22],[23]). Such transient models allow for a more sophisticated evaluation depending on coinciding heat and moisture conditions and their duration.

Based on these results, the more resistant wood fibre materials can be evaluated like solid wood. Thus, their performance can be predicted more accurately by hygrothermal simulations and their application fields can accordingly be extended.

3.1 Test setup in the laboratory

For the lab tests, four typical wood fibre materials, which are used as interior insulation according to the specifications of the manufacturers, were used and compared to pine sapwood, which can be considered the most sensitive solid wood. The materials represent typical categories like rigid insulation boards or flexible mats, different levels of hydrophobization as well as dry and wet production process. Test specimens of 50 mm x 50 mm are used with a thickness of 40 mm for the fibre insulation and 10 mm for the solid pine sapwood samples. The products are described in Table 2. A photo of the specimens is provided in Figure 15.

Table 2: Wood fibre insulation materials for interior insulation used for the lab tests

	Short description	**Production process / Impregnation / Other**
A	Dry Insulation board 0.5 %	dry production process, density 110 kg/m³ with hydrophobic agent: 0.5 % by mass

B	Dry Insulation board 0.8 %	dry production process, density 150 kg/m³ with hydrophobic agent: 0.8 % by mass
C	Flexible Fibre Mat	dry production process, density 60 kg/m³ with fire protection agent / no hydrophobic agent
D	Wet Insulation board	wet production process, density 160 kg/m³ no hydrophobic agent
Pine	Solid wood	Solid Pine sapwood

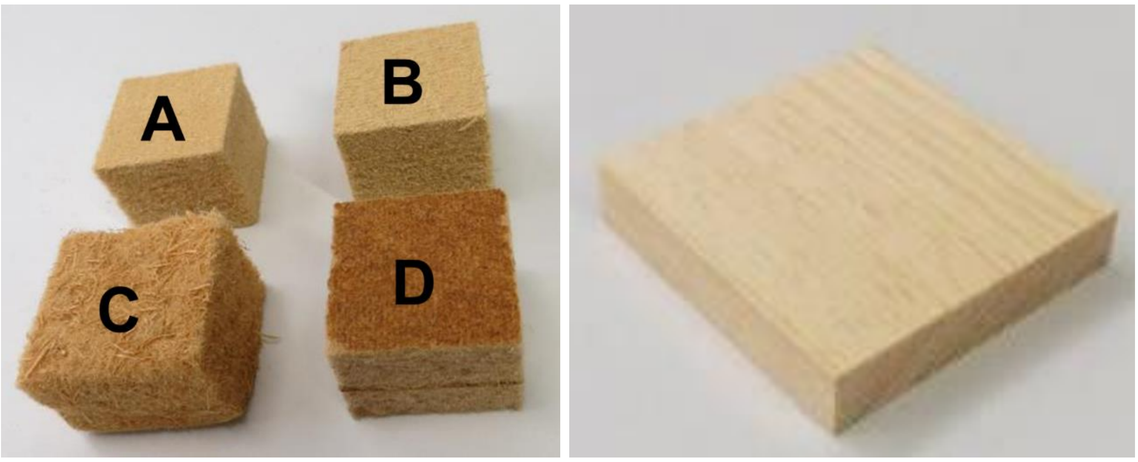


Figure 15: The four investigated wood fibre insulation materials A, B, C, D described in Table 2 (left) and the reference material solid Pine sapwood (right)

As test fungi four different decay fungi are used, which are either commonly used for decay tests in the standards or are under suspicion to have a high affinity for wood fibre materials. *Coniophora Puteana* is the most common test fungus, known for its rather low demands on the moisture level in the material. *Trametes Versicolor* is another frequently used test fungus for decay tests. *Schizophyllum Commune* is less typical for solid wood investigations, but was added, as it apparently shows a higher affinity to wood fibre materials according to experiences in tests at the IBP lab. The last fungus, *Serpula Lacrymans*, is related to many severe damages in building practice. Its English name *Dry Rot* suggests a low demand on the humidity in the material - but this is only true, when the fungus has access to humidity at another position. Without such access, the required humidity level seems to be much higher. To confirm that *Serpula Lacrymans* without contact to water only begins to grow at rather high moisture contents, it was chosen as the fourth fungus for the studies.

In difference to previous investigations like [18] or [23], in the current lab tests, the inoculation with the test fungi was performed by overgrown wooden dowels. Therefore the dowels are placed on a nutrient medium in a petri dish and inoculated with freshly prepared mycelium. Once the fungus has completely overgrown both the nutrient medium and the dowels (Figure 16, left), they are transferred to the test specimens by inserting them into drilled holes like shown in Figure 16, right. Both, the wooden dowels and the test specimens were sterilized before; the dowels in an autoclave and the wood fibre insulation by Gamma radiation to avoid a change in biological and hygrothermal properties of the test specimen due to excessive temperatures and humidity.

Figure 16: Overgrown wooden dowels with test fungi *Coniophora Puteana* (left) and transfer of the dowels into the test specimen (right).

Each specimen is equipped with four dowels, overgrown with the four different fungi. While the growth of the different species, on and from the dowels, can be observed separately, the mass loss can be only measured as one single value. An assignment to the single fungi is therefore only possible indirectly via other indications. Despite these disadvantages, this procedure was chosen to reduce the number of specimens to a feasible level of 180 in 6 incubation units in view of the limited space in the laboratory. The still high number is necessary, as after the more detailed assessment of the specimens like opening or drying and mass loss measurement, the specimens are either destroyed or cannot be investigated further.

The inoculated test specimens were placed in sterilized and air tight boxes (incubation units), which are stored in a climate chamber at a defined temperature of 25 °C, a generally favourable temperature for decay fungi from former investigations ([18],[22],[23]). The boxes have a glazed lid, which allows a permanent visual observation of the specimens without opening the box, which reduces the risk of contamination (e.g. with mould spores). The boxes have air in- and outlets to supply filtered and preconditioned air. The preconditioning is carried out over warm water baths, the temperature of which is controlled so that the desired humidity levels of 95 %, 97 % and nearly 100 % can be reached in the boxes (Figure 17). At 95 % RH just no or only very slow growth of the fungi can be expected. 97 % RH should already allow for some recognizable growth, while at 100 % the conditions are in the optimal range. These moisture steps were chosen to ensure that the ratio between the growth intensity on the fibre materials and the one on the reference sapwood is valid for the whole moisture range of relevance.

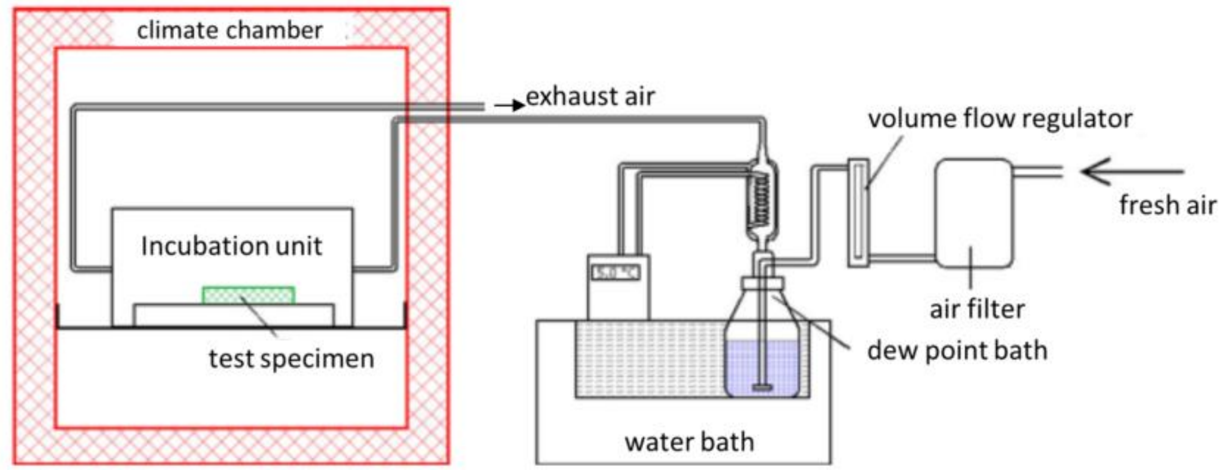


Figure 17: Test setup for the incubation period in the lab with climate chamber at 25 °C, incubation unit and supply of preconditioned and filtered air.

The duration of the test was initially planned with about 100 days (14 weeks). However, as growth and mass loss occurred later and slower than expected, the duration was finally extended to around 340 days. The final time line is presented in Table 3.

Table 3: Time line of lab tests with climate conditions and different evaluation measures

Incubation time		Condition of incubation units		Evaluation			
Days	Week	Relative Humidity	Temperature	Visual	Index	Surface cover	Mass loss
0 - 100	0 - 14	95 %, 97 % or 100 % poss. drier than planned	25 °C	regularly	regularly		
100 - 135	14 - 19	increased to planned values by different measures					
135	19	100 % in all remaining units	about 20°C	x	x		x
165	23			x			
185	26			x			x
200	29			x	x	x	
248	35			x			x
280	40			x			
338	48			x			x

3.2 Problems encountered during the investigations

Despite the filtered air, after about 12 weeks (about 84 days), some mould growth could be observed in two of the six incubation units. It was of course intended to avoid mould growth, as mould and decay fungi compete with each other for the available nutrients and could possibly also interfere with each other's growth. However, it is very difficult and hardly possible to avoid a contamination over longer periods of time - especially in case of external air supply.

Mould was first observed on the flexible fibre insulation C. Like the decay fungi, also the mould did not spread to the whole specimen, but remained limited to the dowels itself. This can be seen in Figure 18. At least at the surface of the materials, the mould seems to displace the decay fungi mycelium to a certain extent. And it is possible, that it is also due to the mould influence, that the mycelium hoods on the dowels disappeared again. But it is not clear, if the growth inside the specimens, which can normally hardly be reached by the mould fungi, is also affected. Due to the rather high quantity of specimens, it was possible in part to reduce the evaluated number of specimens and focus on those without relevant mould growth. Only at the end of the test period all remaining specimens were considered.

Figure 18: Visual observation after 25 weeks: Some mould growth appeared in two of the 6 incubation units. It was initially observed on the dowels of the flexible fibre insulation C after 12 weeks.

3.3 Growth of decay fungi and material degradation

The starting and proceeding growth of the decay fungi was observed by different methods. The initial assessment was made based on visual observation of the specimens in the closed incubation unit with the naked eye and stereo magnifiers. Here the growth of the fungi on the dowels as well as the transfer of the growth to the test specimens is evaluated. This evaluation is based on the visual appearance but also on a description of the recognizable biological processes. In addition the specimens were opened from time to time to verify whether the decay fungi had already spread from the dowel to the inside of the material. And in addition single specimens were dried and weighed to determine the mass loss caused by the decay process. The results are described below.

3.3.1 Visual evaluation

Visual inspection was carried out on an ongoing basis, and photographs were also taken regularly. However, only the more relevant points in time are shown in the report.

After three weeks of incubation no significant growth of the different fungi can be observed at first sight (Figure 19) apart from *Schizophyllum commune* on the tips of the dowels in the flexible fibre mat.

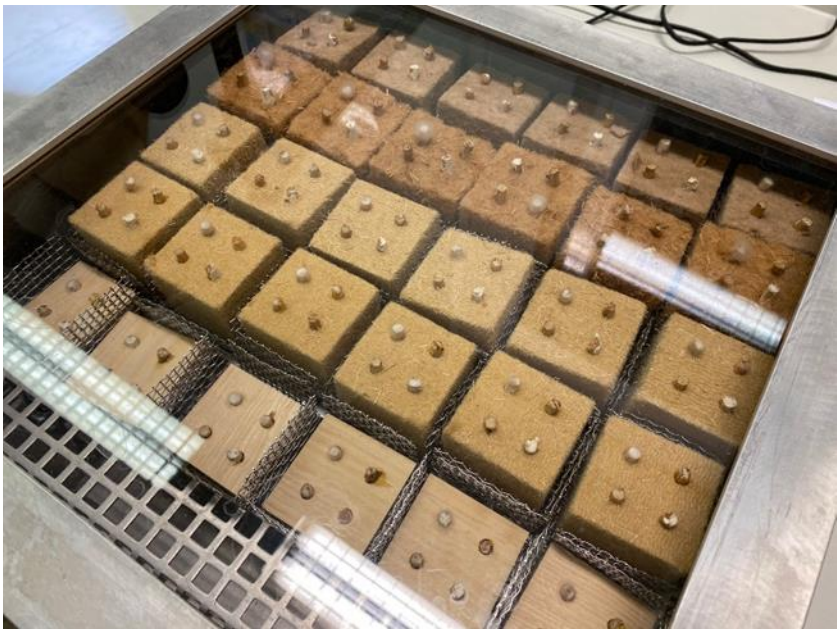


Figure 19: Test specimens with overgrown dowels in an incubation unit. View through the glazed lid.

In Figure 20, a spherical growth of the white mycelium is visible at the tip of the dowel of the flexible fibre mat after 8 weeks. The shape suggests, that the fungus keeps distance to the fibre material, while growing well on the solid wood dowel. A more detailed observation shows fine mycelium fibres also on the other materials, starting from the dowels and covering the specimens. Accordingly, the initial growth seem to be rather similar for the different specimens, but only in case of the flexible fibre mat, the mycelium remains limited to the dowel tip. A clear distinction between the different decay fungi is not possible without elaborate biological analysis– the mycelia are all more or less white. However, as the main goal of this project is to check, whether the fibre insulation materials are less damaged by decay fungi than solid wood, this distinction is only of little relevance.

Figure 20: Visual observation after 8 weeks: fungi growth on the dowels in the flexible fibre insulation C. While a strong mycelium growth of *Schizophyllum commune* can be detected on the dowel itself (but no transfer to the specimen) only moderate growth can occurs for the three other fungi.

After 8 weeks, the growth of the fungi was already visibly established on the materials A, B, D and the solid wood, while on the flexible fibre mat (C) still only the dowels were concerned, but not the material itself. Also around the dowels with the other fungi, growth and cover of the specimens with fine mycelium fibres gets visible – only the *Serpula Lacrymans* dowel hardly shows any changes, as expected. The situation after 14 weeks is rather similar and therefore not presented here separately. However, it seems to get already visible, that the growth on the pine wood may be a little bit stronger compared to the fibre insulations A, B and D.

Figure 21: Visual observation after 8 weeks: established mycelium growth on all specimens apart from the flexible fibre mat C

After 23 weeks (Figure 22) the mycelium has been further grown and is clearly visible on the materials A, B, D and best on the Pine sap wood. Despite the lower impregnation level of dry board A, the growth seems to be a bit less than on the other dry board B and the wet board D, while on material C still no visible growth can be detected, neither with the naked eye nor under the microscope. In addition, the initial mycelium hoods on the *Schizophyllum* dowel from Figure 20 have disappeared completely, while they were only reduced after 8 weeks. In turn, mould growth has now appeared on individual dowels. As the mould growth has a clearly different colour, while the decay fungi mycelia are pretty white, in the following a distinction is only made between the greenish, bluish infestation of mould and the white infestation of wood rot fungi.

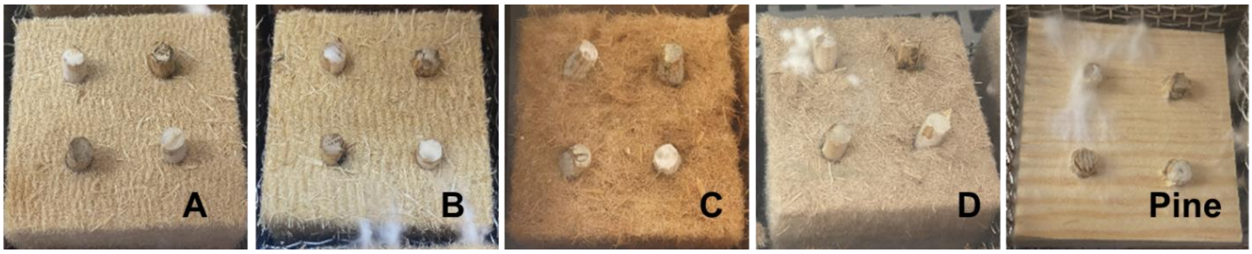


Figure 22: Visual observation after 23 weeks: Strongest decay mycelium growth on the Pine, followed by the “wet” board D and the “dry” boards B and A. C still shows no growth at all – also the mycelium on the dowel disappeared.

Figure 23 shows the visual observation after 40 weeks of incubation. The mould growth has continued and at the surfaces of the fibre materials only little decay mycelium can be detected any more. The mould growth is the strongest on the materials B and D which are adjacent to the flexible fibre mat C, where the mould growth was observed first. Nevertheless, material C still has mould growth only on its dowels, but not on the specimens itself, which can be seen in Figure 24.

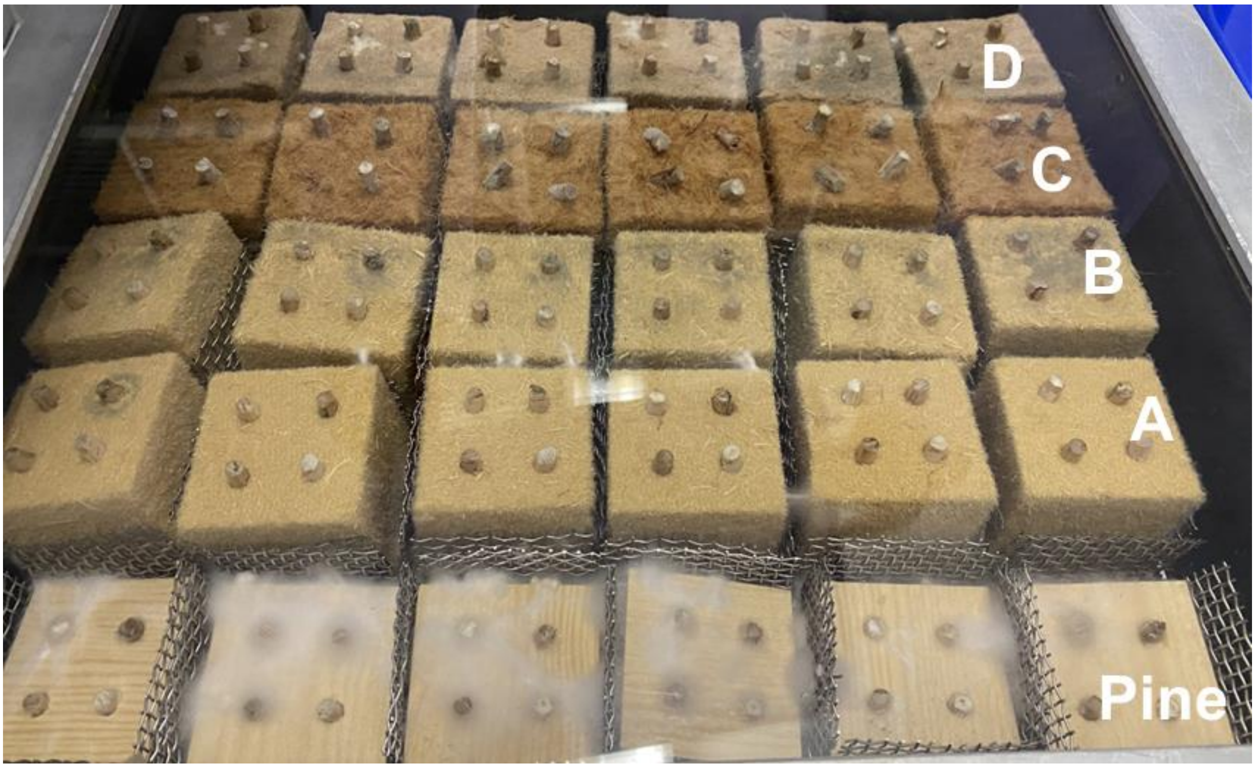


Figure 23: Visual observation after 40 weeks: Clearly strongest mycelium growth on the Pine, mould growth on materials B and D as well as on the dowels of material C. Some visible growth of mould and decay fungi on material A.

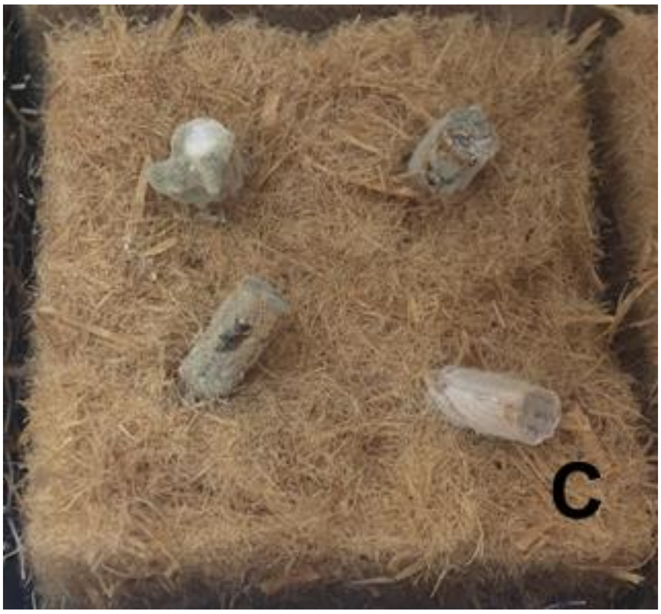


Figure 24: Visual observation after 40 weeks: Mould growth on the dowels of the flexible fibre mat C but not on the specimen.

The general visual appearance at the end of the test period after 48 weeks is not very different from the one after 40 weeks. However, the evaluation shows rather clearly that the wood decay fungi growth is strongest on the solid wood reference specimens compared to the four different fibre insulation materials. Second strongest growth can be observed on the wet fibre board D followed by the two impregnated dry boards B and A, while hardly any microbial attack can be observed on the flexible fibre material C.

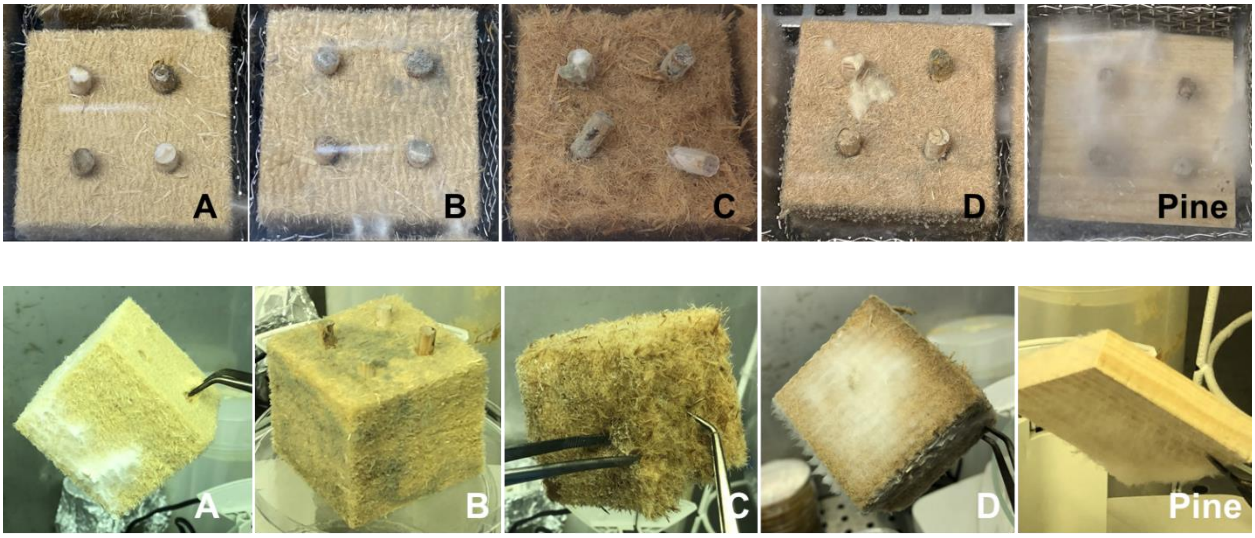


Figure 25: Visual observation after 48 weeks: View from the top (top) and from the bottom or side (bottom). Strongest growth of decay fungi mycelium on the pine specimen, but present also on all other specimens.

The decay fungi infestation of the two dry boards is not analogous to their impregnation level – a bit lower and later growth is observed on material A with 0.5 % impregnation, and a bit stronger and earlier growth on material B with 0.8 % impregnation. Even if mould appeared in the incubation units, the white decay fungi mycelium is still present on the different specimens (again apart from material C).

3.3.2 Evaluation of observed biological processes

Apart from the direct visual impression, a second evaluation describes the visible biological processes in a scale, which is described in Table 4. The scale is clearly non-linear and more qualitative than quantitative. However, levels 0 to 2 mean either no growth or growth mainly on the dowel, but not on the specimen itself. As mainly the specimen is of interest and only small influence from the material type on the growth on the dowels is assumed, primarily level above 2.5 or 3 is of relevance.

Table 4: Index of observed biological processes.

Level	Description
0	No Growth visible
1	Little growth on the dowel
2	Strong growth on the dowel
2.5	Growth also on the material around the dowel
2.8	Growth also visible on other dowels
3	Transfer of the growth over the whole specimen
3.5	Transfer of the growth over the whole specimen, white hyphens visible also in distance from the dowels
3.6	Transfer of the growth over the whole specimen, white hyphens visible also in distance from the dowels but stronger than at 3.5
3.8	Transfer of the growth over the whole specimen, white hyphens visible also in distance from the dowels but stronger than at 3.6

The evaluation according to this scale is presented for the first 133 days in Figure 26. The results show that, as expected, with higher RH level the microbial growth is accelerated. In the box with only 95 % RH most materials remain below 2.5 and only the dry board B just reaches 3.0. At 97 % RH, the pine wood samples show the most critical results above a level of 3 which is exceeded after 70 days. The wet board values increase slightly later and lower, the other boards do not exceed the value of 3.0. In the box with 100 % RH all materials except the flexible mat exceed 3.0 after about 40 days. Wet board and solid wood behave very similar and reach values of 3.5, the two dry boards remain slightly lower.

However, due to the non-linear scale and a certain dominance of the values up to 3.0, which are of little relevance for the assessment of the fibre materials themselves, this evaluation alone does not allow a clear differentiation between some materials.

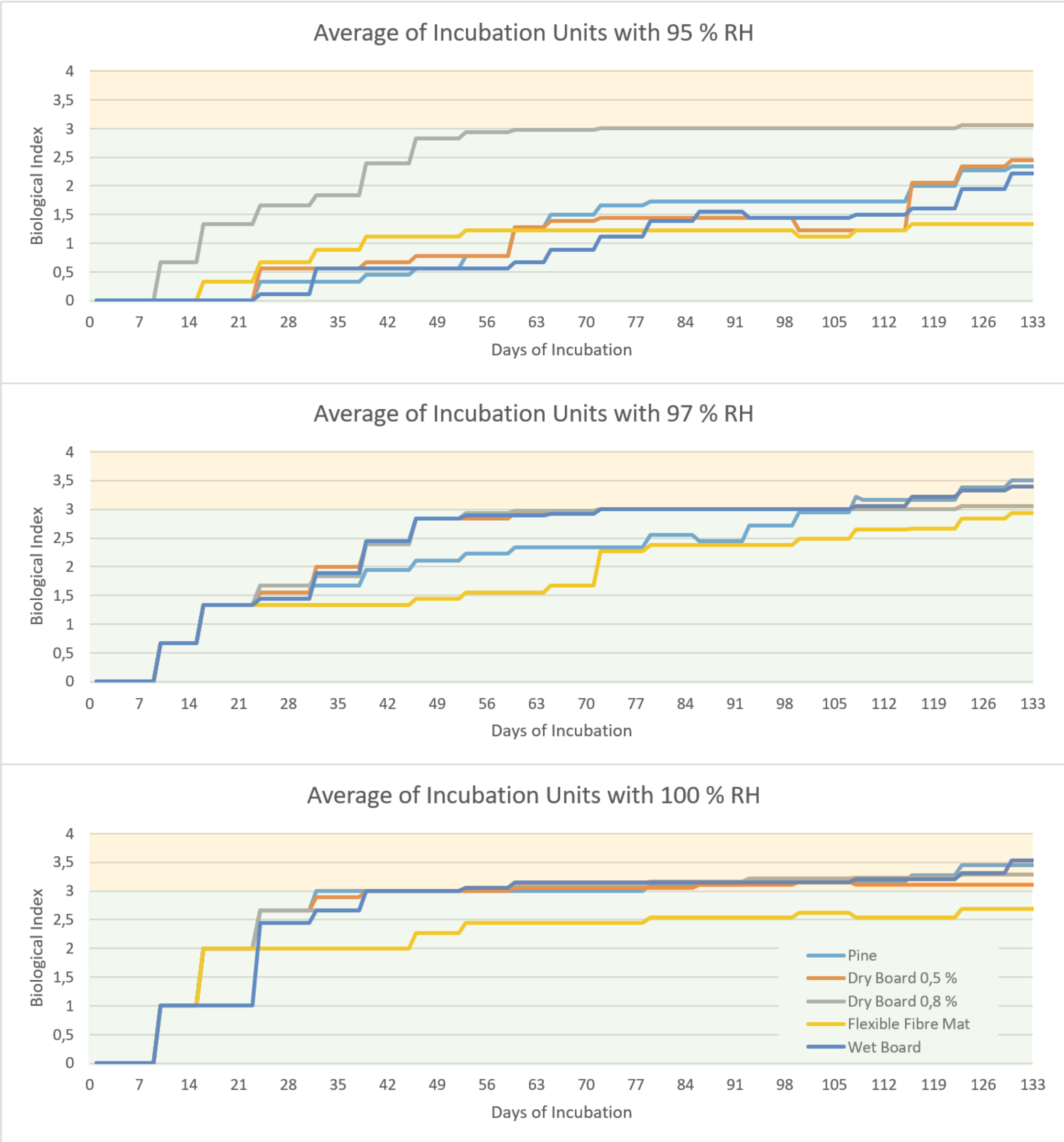


Figure 26: Evaluation of biological processes according to Table 4 during the first 133 days: Different growths speed on the dowels of the 4 test materials and the reference specimens. Only Pine and the wet board reach values up to 3.5 in that period.

Therefore an additional indicator was introduced: the cover ratio of the mycelium on the visible specimen surface in percent. This evaluation is presented in Figure 27 (bottom) after 200 days of incubation in addition to the previous evaluation, based on the scale (top) from Table

4. The scale value difference between the solid wood and the wet fibre board is with 3.8 to 3.6 only very small. If additionally the surface cover ratio is considered, the difference becomes much clearer with 23 % in case of the solid Pine wood to only 9 % in case of the wet fibre board. The two dry boards A and B only show a surface below 4 % and the flexible fibre mat still no growth at all. Thus, the surface cover for the solid wood is a factor of 2.5 higher compared to the wet board, 5 times higher than dry board B and 10 times higher than dry board A.

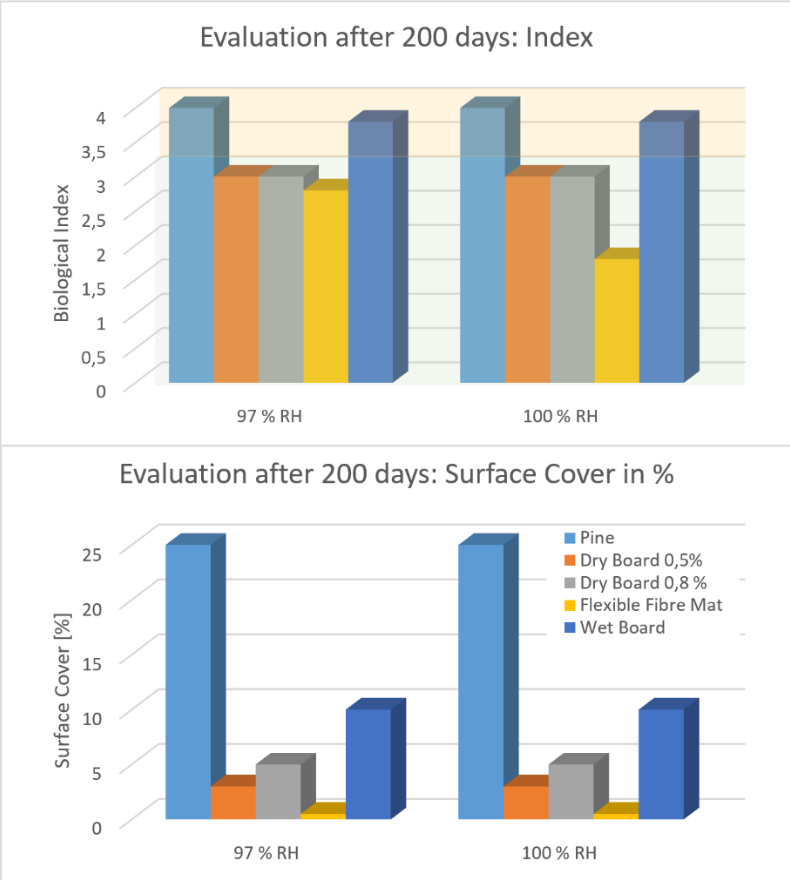


Figure 27: Evaluation of biological processes according to Table 4 after 200 days (top) and coverage of the specimen surface with decay mycelium in percent (bottom) at the boxes with initially 97 % RH (left) and 100 % RH (right).

3.3.3 Evaluation of mass loss

A further evaluation is based on the measurement of mass loss over time, which was performed after 20, 26, 35 and 48 weeks on three specimens in each case. The resulting average values are presented in Figure 29. First, two aspects must be mentioned: As basis for the mass loss, the density of the materials was used. The dry weight of the single specimens could not be determined beforehand anyway, as the high temperatures could influence the probability of biological infestation. Therefore, the average specimen weight was calculated from the materials bulk density, which as a consequence involves a certain inaccuracy due to the inhomogeneity of natural materials. As this is a normal influence for such materials, it is a common recommendation for decay tests in the laboratory that only mass losses in excess of 5 % are to be regarded as unambiguous. This limit is indicated as dashed red line in Figure 29. The second point is that the results of the flexible fibre mat are not reliable due to the following reason: While the complete mat is rather stable, the cut specimens loose many fibres at the edges and after longer test duration and at higher material humidity, this is also stuck to the baskets. The problem is exemplified in Figure 28. As within the first two evaluations no microbial growth can be observed on this material, it is very likely that the measured mass loss is only due to fibers falling off and getting stuck. The results of material C are therefore greyed out in Figure 29.

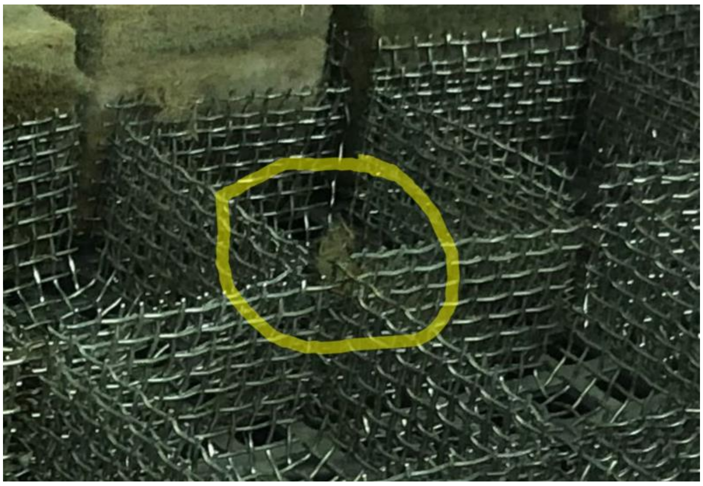


Figure 28: Parts of the flexible fibre mat stuck to the metal basket.

For the other materials, as expected, an increasing mass loss over time can be observed. Since also the cut specimens of the other fibre materials show a rather good stability, the mass loss can mainly be attributed to degradation by the decay fungi. With solid wood no material is lost at all during movement. The dry insulation board A shows values below zero for the first two weighings. As mass gains are unlikely, this could be caused by the mentioned inhomogeneity of the bulk density.

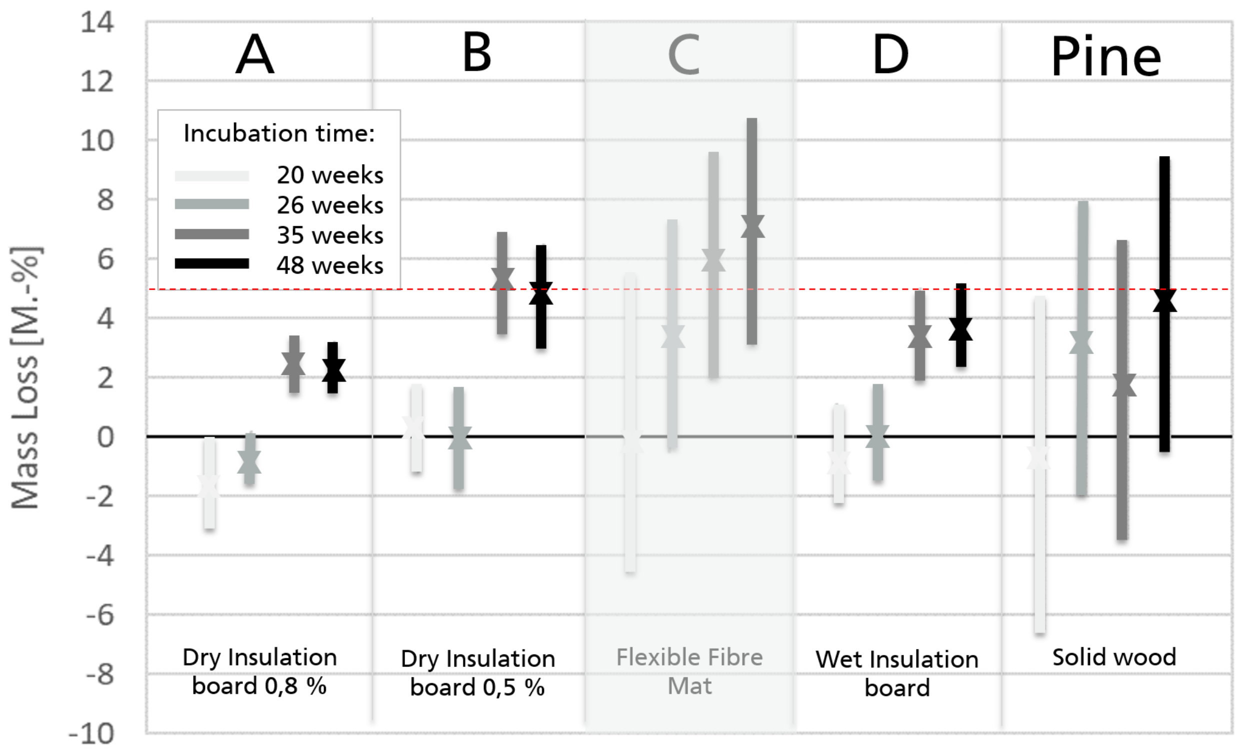


Figure 29: Evaluation of mass loss after 20, 26, 35 and 48 weeks.

This influence is also obvious for the first or the first two measurements of the materials B, D and the Pine samples. Considering all four measurements the mass loss of the Pine samples is higher than the mass loss of the three evaluable fibre materials A, B and D. Material B has slightly higher losses when only the third and fourth measurements are considered. However, some loss of fibers during movement should be also assumed for the other fibre materials. Therefore the ranking concerning the mass loss is as following: highest losses for the Pine specimens, similar but slightly lower values for the dry board B, followed by the wet board D and lowest losses for the dry board A.

3.4 Summary of the lab test results

That means that as expected, the four involved wood fibre materials show a rather good durability at high moisture levels and have proven to be more resistant against decay fungi than solid Pine sapwood. Therefore, the same ore even higher limit values or limit curves can be used for the evaluation of these materials like for solid wood. Such limits are currently available as limit curve depending on RH and temperature in WTA guideline 6.8 [21] but also as transient decay prediction model according to [18] as well as topic of current research in ongoing research projects.

In the first weeks of the test period, presumably slightly lower humidity conditions than planned prevailed in the incubation units. This slowed down and delayed the decay process to a certain extent. Also the occurring mould growth may have had a retarding effect on the wood rot processes.

However, significant growth of decay fungi mycelium and also mass loss was observed. All fungi were still alive at the end of the tests and the question, whether the examined wood fibre materials or the solid wood specimens are more resistant against decay fungi could be clearly answered - even if quantitative statements are only possible to a limited extent due to the partly unclear boundary conditions.

Considering all three evaluations methods presented in chapter 3.3, it can be stated that the solid Pine sapwood samples show the highest susceptibility to the investigated decay fungi. The wet insulation board D shows the second highest susceptibility concerning the visible decay fungi growth, but lies concerning the mass loss between the dry insulation board B with 0.5 % and the dry insulation board A with 0.8 % of hydrophobic agent. While the mass losses of the dry boards seem to be consistent with their impregnation level, the opposite is the case concerning the visible mycelium growth on the two materials. However, the overall performance of the three boards A, B and D is in a similar range, while the flexible fibre insulation mat C shows a clearly higher resistance against any microbial growth (decay and mould), provided that the mass losses determined are, as suspected, due to dropped fibers and not to material degradation.

That means that as expected, the four involved wood fibre materials show a rather good durability at high moisture levels and have proven to be more resistant against decay fungi than solid Pine sapwood. Therefore, the same or even higher limit values or limit curves can be used for the evaluation of these materials as for solid wood. Such limits are currently available as limit curve depending on RH and temperature in WTA guideline 6.8 [21] but also as transient decay prediction model according to [18] as well as topic of current research in ongoing research projects [24].

3.5 Critical check of the procedure used in this project and proposal for a future test procedure

The measured mass loss war surprisingly rather small – especially when compared to former investigations like [18][22], which showed under similar favourable conditions (temperature > 20 °C and high humidity near 100 % RH) sometimes more than 20 % mass loss after only 4 months. To ensure the evaluations, which indicate only little decay even after 40 weeks of incubation, some specimens were cut to check the interior of the specimens. Besides some discolorations, especially around dowels with *Coniophora puteana,* no degradation was visible, neither to the naked eye nor with the microscope (Figure 30).

Figure 30: Cut specimens after 40 weeks of incubation. Dry board A (left), flexible mat C (middle) were horizontal sliced and pine sapwood (right) was cut along holes,

To check whether the rot fungi have been affected by drought or mould, the vitality of the fungi on the dowels was verified by growing them again on nutrient medium in petri dishes at the end of the test procedure in the lab. After only four days mycelium decay fungi become visible again in all four petri dishes, although cross contaminations cannot entirely be excluded. This confirms that the decay fungi were still alive and active, even if no strong degradation could be observed.

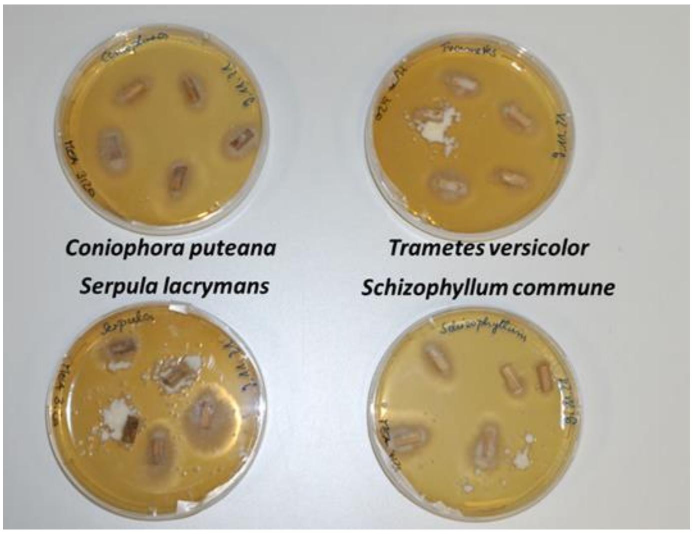


Figure 31: Re-inoculated dowels from the specimens at the end of the lab test investigations. After four days, new mycelium growth could be observed in all cases, which proofs, that the fungi were still alive.

The applied test method has the advantage in comparison with previous methods that more realistic start conditions for the infestation are used. For the tests performed here, still four decay fungi were used. But the results showed, that at least *Serpula Lacrymans* and probably also *Trametes Versicolor* are only of little relevance, while *Coniophora Puteana* and *Schizophyllum Commune* seem to be the more critical fungi for that purpose.

At different growths levels, rather analogous results between the different involved materials were obtained in all incubation units despite the different levels of moisture. Therefore, it can be assumed that a test at high RH close to 100 % and a favourable temperature around 25 °C with the most critical test fungi could be sufficient. Such a comparison between a specific test material and the reference Pine sapwood specimens should be representative also for lower RH conditions and other fungi species.

Both, detailed test conditions and choice of fungi species are currently further verified by additional investigations in the project CORNET ThermNat [25].

3.6 Update of the hygrothermal simulation procedure in WTA

The procedure for the evaluation of wood fibre insulation materials in WTA guideline 6.5 (and 6.8) is therefore refined according to the new findings. For wooden fibre materials which have proven a higher resistance against decay fungi compared to solid wood, also the same application and limit criteria apply like for solid wood. For untested materials or those, who show a lower resistance than solid wood in the test, still the limit of 18 % by mass applies.

Furthermore, at the revision of WTA guideline 6.5 it will be insisted that more space is given to the hygrothermal behaviour of the existing wall. This part has been largely missing from the WTA guideline up to now. The Part I of this guideline closes this gap, which has repeatedly presented planners with great, if not insoluble, challenges in practice.

4 Characterisation of capillary active insulation materials

Conventional interior insulation systems protect the wall from condensation in winter by the help of vapor barriers or vapor retarding insulation materials. However, these solutions also reduce the drying potential of the walls towards the inside. This can be a disadvantage if wetting from the outside due to rain or other influences takes place and the drying potential to the outside is not sufficient. In such cases, so called capillary active materials can be an alternative, because they provide additional drying potential to the inside in summer thanks to a rather low vapor diffusion resistance. In winter they work without vapor retarders because they can store and wick water away from the condensation plane back towards the interior by capillary action.

In practice, there are currently many different materials under the label "capillary active" with a correspondingly wide range in terms of moisture storage, liquid transport and vapor diffusion resistance and it is difficult to decide which material is suitable for which application. There is still missing a common definition of the performance of these materials. While for most other materials already simplified design and application rules are available like for example in [31], capillary active interior insulation materials still require an individual design according to [32]. In order to simplify also their application, a classification of the moisture performance of capillary-active interior insulation, considering all influencing parameters of relevance was developed. On this basis also a simplified verification process and design rues become possible.

4.1 Quantification of the capillary back transport by specific lab tests

For hygrothermal simulations comprehensive and complex material parameters are required. In addition to steady state measurements for thermal conductivity, heat capacity or sorption isotherm, also dynamic experiments are used, especially the water uptake experiment and drying experiment to determine the liquid transport behaviour. The water uptake experiment resembles conditions when driving rain gets into contact with the building surface whereas the drying rain experiment represents the situation of a completely wet material that dries out constantly. Both experiments do not correspond to the climatic condition of an insulation material during the condensation period (winter).

Therefore, to quantify the specific liquid transport under the conditions within an interior insulation system, specific diffusion tests with a temperature gradient have been developed in the past years by both, IBP [28], [29], [30] and IBK [12]. These dynamic tests allow a more accurate determination of the hygrothermal properties of interior insulation materials than previous methods, especially concerning the starting liquid transport in the smaller pores caused by capillary condensation. Therefore the insulation specimens are exposed to a temperature and moisture gradient, similar to the conditions of an interior insulation in winter time, which lead to a moisture increase in the specimens (Figure 32). The moisture contents and moisture profiles are measured regularly over a time period of several weeks or up to few months – depending on the speed of moisture uptake and back transport of the specific materials. For the so called “Kapi test” of IBP, the distribution is measured on smaller specimens (0,05 m side length) by the help of an NMR (nuclear magnetic resonance) scanner which is limited in specimen size.

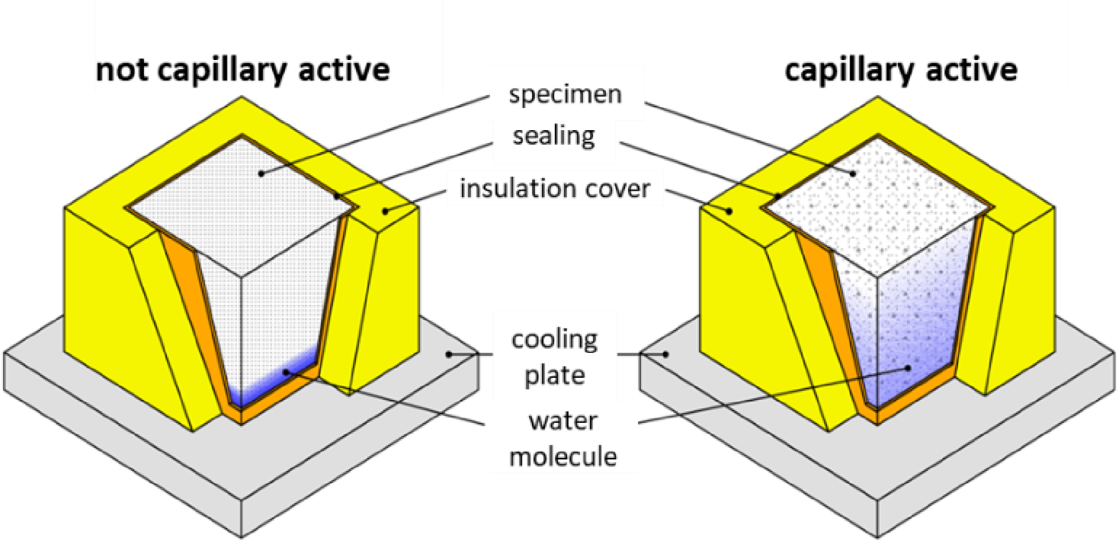


Figure 32: Schematic moisture distribution in two interior insulation materials without liquid transport (left) and with significant liquid transport (right) during the Kapitest.

The IBK introduced the “Condensation Test” (for test set-up see Figure 33), in which larger, laterally insulated specimens of approx. 0.10 m side length are exposed to similar conditions ([12], [37]). At the end of the condensation test, the specimen are cut into slices and the moisture contents of the individual slices are weighed to determine the moisture profiles. This test can be carried out if a laboratory is not equipped with an NMR (nuclear magnetic resonance) device to measure the moisture profile [38]. The duration of a test is usually about 60 days.

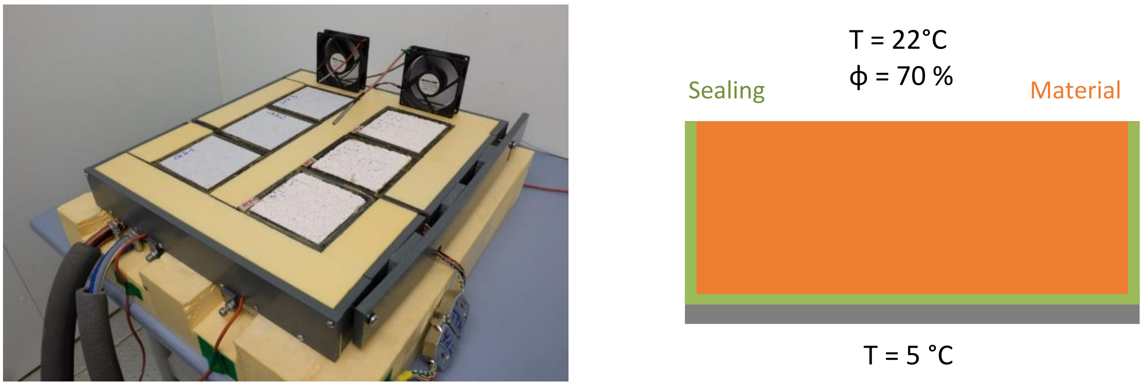


Figure 33: Left: schematic structure of the condensation test, right: boundary conditions during the test

In both cases the exact liquid transport in the materials is quantified by a hygrothermal simulation, which reproduces moisture increase and profiles, measured in the lab tests, by adapted liquid transport properties. By that procedure also the just beginning still week liquid transport can be quantified in a suitable way.

With the refined liquid transport parameters, the performance analysis of capillary active interior insulation systems by hygrothermal simulation became more reliable and the use of such materials more safe. However, the specific liquid transport in the insulation is only one aspect amongst others, which decides over the hygrothermal performance of the systems. Therefore up to now, always a specific simulation of the individual situation is required.

4.2 Evaluation of the insulation system alone can lead to misjudgement

In recent years, there have been some attempts to establish an assessment and classification for capillary-active interior insulation systems. The problem with this, however, was that the evaluation of the strength of capillary transport alone does not allow any statement to be made about the functionality of a system and thus has almost no practical use. This is only achieved when at least all relevant properties of the insulation system itself are taken into account, i.e., not only the capillary conductivity but also the diffusion resistance and the moisture storage capacity. This is because with higher diffusion resistance and higher storage capacity, only lower capillary conductivity is required for equally favorable humidity conditions. There is a tendency, that well performing capillary-active interior insulation materials show a high A value of > 20 [kg/m²√h] as well as a significant liquid transport strength already at 80 % RH with D_{ww80} > 1.0E-10 [m²/s] combined with a high free saturation level > 500 kg/m³ and a not too high vapor diffusion resistance value $\mu < 3$. However, there are many exceptions and differing combinations, which also perform well and neither one single value nor a meaningful mathematical combination of the different values could be found to create a simple and comparable characteristic parameter for the evaluation of the insulation systems.

Therefore, in the following, an evaluation of the moisture conditions of the insulation systems is carried out by means of a hygrothermal simulation under the Kapitest lab conditions on a water tight substrate at 12 °C on the cold side and 23 °C and 65 % RH on the warm side, in order to check to what extent the systems are able to limit the moisture conditions to an uncritical level. The thickness of the insulation material are adjusted to reach an improvement of the R value ΔR of 2.0 m²K/W. Thus, the thickness of the considered 24 materials varies from 34 mm to 118 mm depending on their thermal conductivity (about 0.015 W/mK to 0.06 W/mK). The simulation is performed over a period of three years. Only insulation systems were considered for which the complete hygrothermal material parameters including liquid transport on the basis of the Kapitest are available.

For the evaluation of a sufficient limitation of the moisture increase, it proves to be easier to define criteria which conditions should not occur than to define the moisture conditions to be achieved "positively". Therefore, the following three contra-indicators have been defined, by means of which it can be recognized that an insulation system tends to have insufficient functionality:

1. The total water content increases significantly and continually
2. The water content on the cold side reaches high absolute values
3. The relative humidity on the cold side reaches condensation conditions rather quickly (≈ 100 % RH)

The following figures show the three evaluations for a total of 24 insulation systems, most of which are capillary-active to a greater or lesser extent and, accordingly, some of which are also suitable for use without a separate vapor retarder. However, also non-capillary-active vapor permeable fiber insulation were used for differentiation. In the case of the lat-ter, it has now been shown that these do not have to be treated separately, but can be evaluated according to the same criteria as the normal capillary-active systems. The color coding of the different materials or systems is uniform in all three figures and is based on the overall evaluation: green means that none of the contraindicators apply and the system can accordingly be classified as suitable in terms of moisture without further measures. Yellow indicates that one or two of the contraindicators apply, but not the third - here, the suitability is accordingly uncertain and requires further examination. Red means that all three contraindicators apply and the system is therefore generally unsuitable for use with-out further measures (e.g. separate vapor retarder).

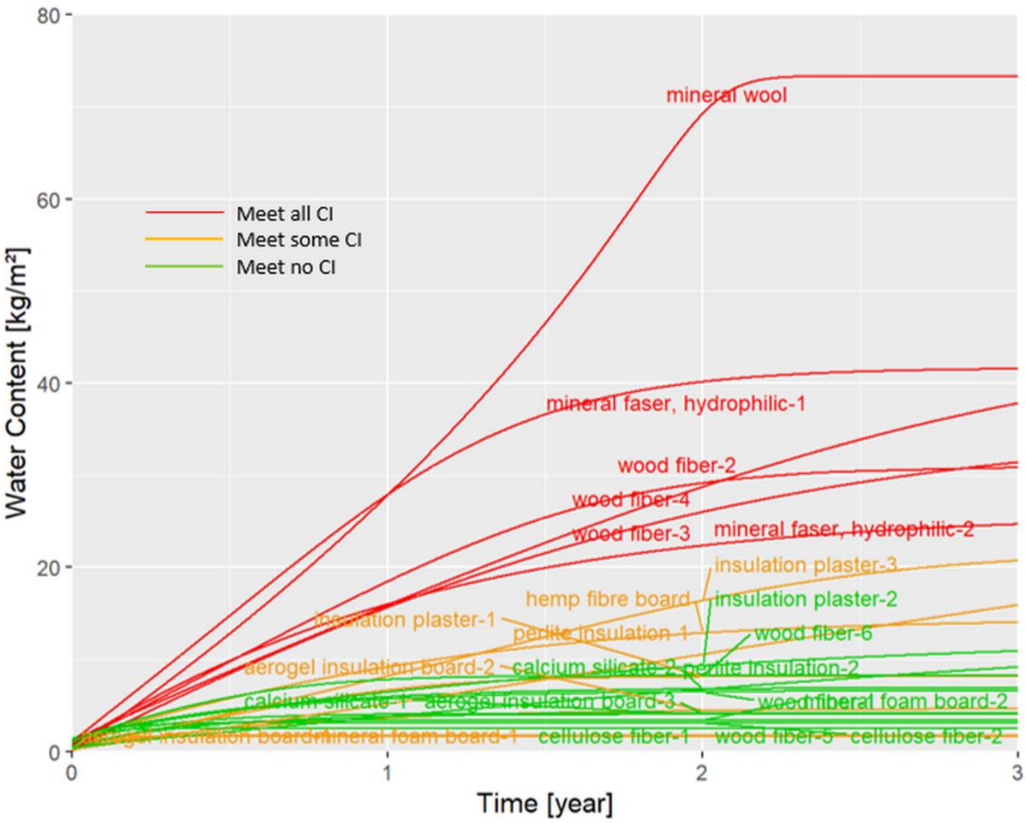


Figure 34: Development of the water content in the interior insulation material over three years. Contraindicator (CI): significant and continuous increase of total water content.

Figure 34 shows that with regard to the development of the total water content in the insulation system, the top six curves are all red, i.e. correlate well with the other two contraindications. I.e. only in the case of unsuitable insulation systems is there an increase in the total water content to over 20 kg/m² wall area after about 2 years under the boundary conditions mentioned. The green curves also all remain at the lower end of the range and below a value of 10 kg/m² after 2 years. In the case of the yellow curves, which represent the systems that are not uniformly evaluated, there are individual ones right at the lower edge with values below 3 kg/m² but also those that remain just below the red curves. The criterion thus represents the tendencies well, but there are some exceptions that make a clear evaluation difficult.

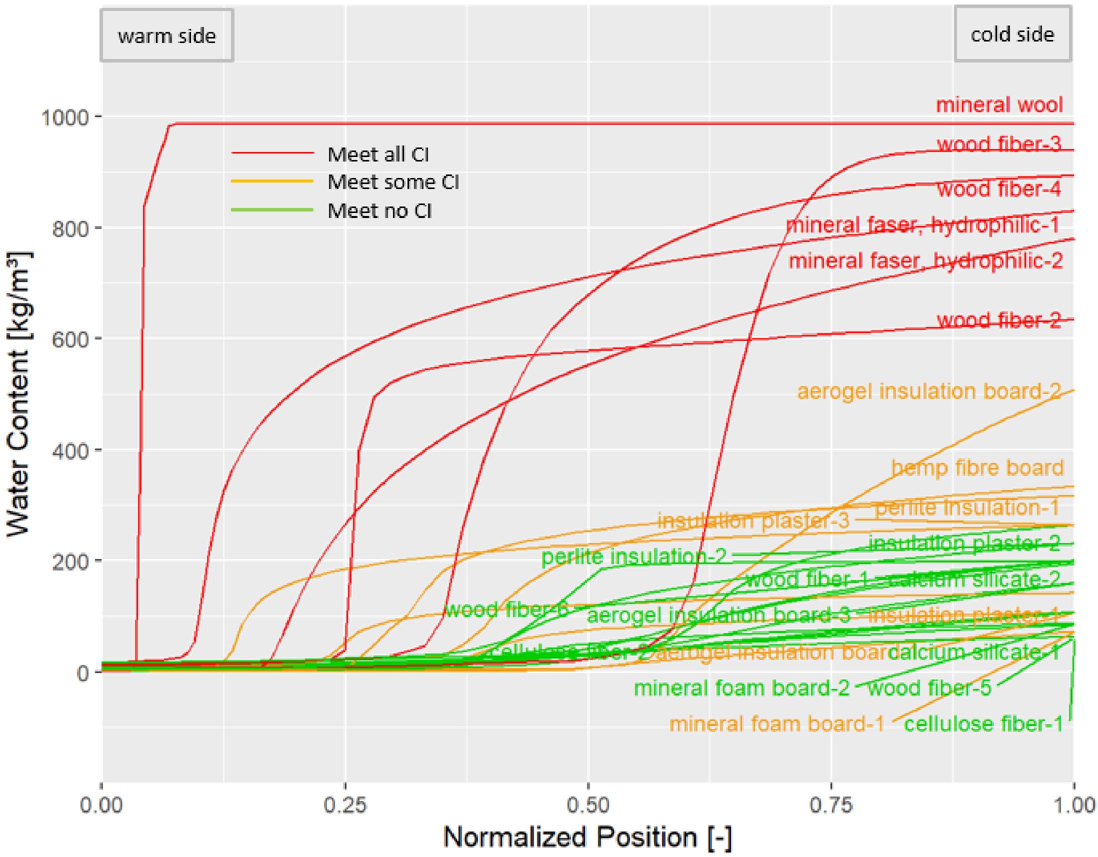


Figure 35: Water content profiles over the normalized thickness after three years of simulation. Contraindicator (CI): high absolute water content on the cold side.

The evaluation of the water content profiles over the normalized insulation thickness after three years of simulation shown in Figure 35 leads to a similar result like the one of the total water contents in Figure 34. The vapor permeable systems that are not suitable without a vapor retarder are at the upper edge, while the curves shown in green that are suitable without further measures are quite clearly at the lower edge of the range. Here too, however, some of the yellow curves are at the very bottom but also some at the top near the red curves.

Figure 36 shows the temporal course of the increase in relative humidity in the pores of the insulation material on its cold side over the first three months of the calculation. Although here, too, the red curves tend to be at the top, the green curves at the bottom and the yellow curves in the middle, interpretation is nevertheless particularly difficult, since values between 98 and 100 % RH occur on the vapor- and water-tight substrate in almost all insulation systems over the course of the three months, despite considerable differences in their material properties. In this case, the evaluation and color classification was only possible on the basis of the numerical values from the simulation.

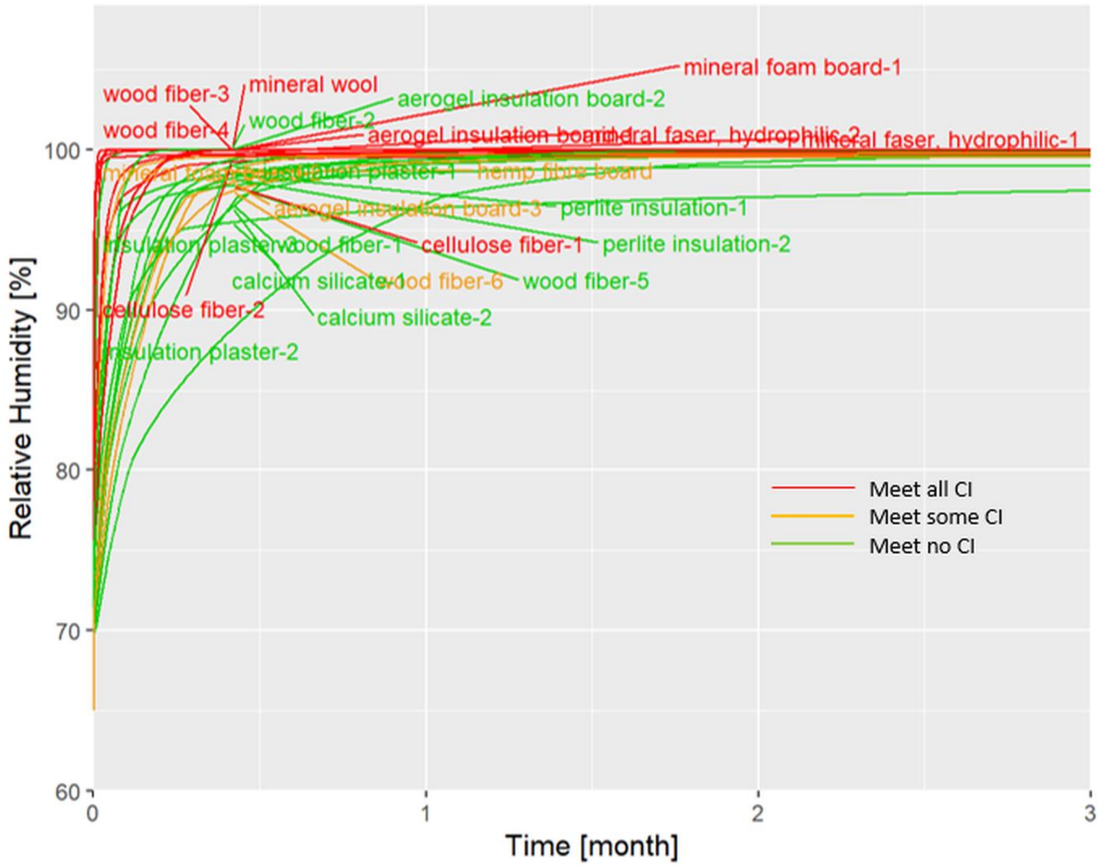


Figure 36: Development of the Relative Humidity in the pores of the insulation material at the vapor tight, cold side of the insulation layer. Contraindicator (CI): RH reaches 100 % on the cold side rather quickly.

Several years ago, the WTA Guidelines 6-4 [31] and 6-5 [32] on interior insulation established criteria that can be used generally or in individual cases to evaluate the moisture level on the cold side of interior insulation. Here, an equilibrium moisture level of up to 95 % RH is considered generally uncritical, at which neither frost nor rot damage to wood or natural fiber materials is to be feared as a rule. A higher humidity is permissible if the adjacent materials are resistant to frost and rot. This limit value has now been proven in practice for many years.

The fact that not a single insulation system remains on the cold side below the 95 % RH, recommended by WTA Guideline 6-5 [32], under the Kapitest boundary conditions also shows that these conditions are probably not well suited for a practical evaluation. In addition, control calculations showed that the sequence of the curves becomes very different if the substrate has even only a low liquid water absorbency, which is almost always the case in practice. Although the wall can then absorb nearly the same absolute amount of moisture per time with all insulation systems, this has a very significant effect on the relative humidity at this position, especially with materials of low storage capacity.

Due to these facts and in order to avoid a misleading evaluation of the systems for real applications, the approach of a separate evaluation of the insulation system without the wall is not be pursued further. The Kapitest boundary conditions are well suited to determine the liquid transport properties, but not to classify the performance of the materials.

4.3 More realistic evaluation of the insulation systems together with a critical representative wall

To ensure that the evaluation is as meaningful as possible for practical application, the capillary-active and hybrid systems are evaluated below on a critically representative existing wall with low absorbency on the basis of the relative humidity at the boundary layer between the interior insulation and the existing wall. The low absorbency of the substrate ensures, on the one hand, that even minimal absolute moisture differences cannot lead to condensation conditions and thus to the knockout criterion, and the limitation of the absorbency to a low value for practical construction purposes, on the other hand, that it is not the substrate that ensures functionality, but the insulation system itself. Figure 37 summarizes the various factors influencing moisture behavior - the properties of the insulation system itself are shown in green - the factors influencing the existing wall and the room climate are shown in blue.

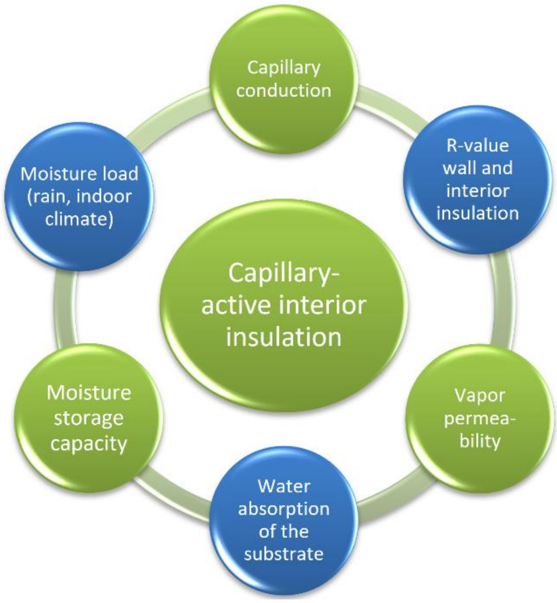


Figure 37: Development Influencing factors for the moisture performance of capillary-active insulation materials. The green factors are parameters of the insulation system, the blue ones factors of the boundaries and the substrate wall. By application limits the blue factors are eliminated to be able to focus on the insulation system itself.

The blue factors are narrowed down via the definition of the areas of application. For this purpose, largely the same application requirements apply like for the available simplified proof according to WTA Guideline 6-4:

- No rain load or good driving rain protection of the existing wall
- Interior climate with low or normal moisture load according to WTA 6-2.
- R-value improvement of interior insulation $\Delta R \leq 2.5$ m²·K/W
- R-value of the existing wall $R \geq 0.4$ m²·K/W
- Average annual temperature of the outdoor climate ≥ 7 °C

The absorbency of the wall surface is included in two levels: moderately absorbent with an A-value ≥ 0.2 kg/m²√h, which still covers almost all unsealed wall formers and concretes, or well absorbent with an A-value ≥ 1.0 kg/m²√h, which represents raw brick surfaces or unpainted interior plasters. In case of doubt, the A-value should be determined on site. Weakly absorbent substrates with an A-value < 0.2 kg/m²√h always require individual verification, as these are generally rather less suitable for capillary-active interior insulation. This results in the Application areas in Table 5.

Table 5: Application areas for the simplified proof of vapor permeable, capillary-active interior insulations resp. systems.

	Application area		
	I	II	III
Moisture load acc. to WTA 6-2	low	low	normal
Absorbency of the existing wall surface (comparable to WTA 6-4)	Well absorbent $A \geq 1{,}0\ kg/m^2\sqrt{h}$	Moderate absorb. $A \geq 0{,}2\ kg/m^2\sqrt{h}$	Well absorbent $A \geq 1{,}0\ kg/m^2\sqrt{h}$

For the evaluation, the respective interior insulation system is simulated on a critical-representative wall structure that just fulfills the above-mentioned requirements and thus represents the respective worst case. The exact parameters for the simulation are listed in Annex 10.2 A IV. The simulation are performed over three months at standard winter conditions of -5 °C according to the steady state evaluation method from DIN 4108-3 for Central European conditions. The indoor climate is chosen with constant 20 °C and 40 % RH for normal and 33 % RH for low moisture load. These constant conditions were derived from transient simulations with hourly measured outdoor climate conditions of Holzkirchen (as critical location for Germany) in a way that the moisture level in the insulation system with the steady state conditions remains slightly on the safe side compared to the transient results. Both assumptions can be seen as critical concerning the moisture accumulation in such constructions at operations with low or medium moisture loads – especially due to the clearly colder outdoor temperature assumption. Even in Holzkirchen as critical location for Germany, the average temperature in the months December to February is only about -3 °C.

The classification of the materials is based on the moisture level that occurs on the cold side of the insulation (Table 6). If the insulation material or the insulation system strongly counteracts the increase in the moisture level, so that the relative humidity can be limited to less than 95 % RH in interaction with the substrate within the framework of the above definition, the system can be used in the corresponding application area largely without restriction - it thus falls into category A: generally functional. Below 95 % RH, no other problems are to be expected apart from mold growth, which is prevented by avoiding air flow behind the insulation materials – normally by a mostly complete adhesion to the substrate. According to WTA Guideline 6-5 [32], wood and pure gypsum materials (without natural fiber components) also tolerate these conditions at low temperatures, so that frost damage is also not to be feared if the minimum R-value of the existing wall is maintained. If the moisture level exceeds 95 % RH, but remains in the range up to max. 99 % RH, the insulation material or system can be classified in category B: functional, if moisture resistant. If, on the other hand, even higher moisture conditions are reached, condensation cannot be ruled out and a general approval is therefore not possible.

Table 6: Classification categories according to the reached RH level

	Classification Category		
	A	B	[-]
Max. RH at the interface between insulation and wall during winter	≤ 95 % RH	≤ 99 % RH	> 99 % RH
Requirements on the substrate material and the insulation system	No (resistant up to 95 % RH)	Moisture, frost and rot resistant up to 99 % RH	Individual design according to WTA 6-5

For the investigated 23 exemplary interior insulation systems, the evaluation based on this method leads to the results in **Fehler! Verweisquelle konnte nicht gefunden werden.** For Application Area I with normal absorbent substrate, low indoor moisture load and a normal gypsum plaster with 0,1 m s_d-value, 13 of 23 materials can be classified in category A without further requirements and 10 into category B, which means, that they can be used without individual proof, as far as substrate and system materials are moisture, frost and rot resistant. However, additional simulations showed, that it is not always beneficial, to ensure an extremely low vapor diffusion resistance on the inside. Increasing the interior s_d value only slightly to 0,2 m allows to classify all systems into category A.

For Application Area II the substrate absorbency is only 0,2 kg/m²√h with otherwise identical boundary conditions. Here the lower A value of the substrate increases the moisture level at the evaluation positon. In Application Are III, the higher absorbency from Area I is kept, but the indoor moisture load is now normal instead of low. For both Application Areas II and III with the normal inner s_d value of 0,1 m, 9 systems are classified in category A, 6 in category B and 8 require an individual proof. Also in here an increase of the interior s_d-value improves the situation. However, to reach again an A classification of all investigated systems, a slightly stronger increase to 0,5 m is necessary, which is just a the upper end of the bandwith for a still “vapor permeable” system. For sure nor problem, was far as no additional moisture entry from the outside has to be feared – but in this case always an individual proof of the system should be performed, as rain water absorption normally very strongly influences the hygrothermal performance of the walls.

As the main application of so called capillary active interior insulation materials is related to older or historical buildings which have an operation with moistly low or normal moisture load and wall materials which provide a certain absorbency, the three defined application fields should cover the biggest part of usage in practice. If moisture ingress from the outside is not an issue, the s_d value at the interior surface should be chosen rather at the upper end of the range from 0 to 0.5 m for vapor permeable systems. This reduces the moisture level to an uncritical level for most systems, while it still allows for a sufficient drying to the inside during the summer period.

Table 7: Classification of the investigated internal insulation materials

Material	Application area					
	I		II		III	
	well absorbent substrate ($A \geq 1.0$ kg/m²√h) and low moisture load (WTA 6-2)		moderate absorbent substrate ($A \geq 0.2$ kg/m²√h) and low moisture load (WTA 6-2)		well absorbent substrate ($A \geq 1.0$ kg/m²√h) and normal moisture load (WTA 6-2)	
	sdi = 0.1 m	sdi = 0.2 m	sdi = 0.1 m	sdi = 0.5 m	sdi = 0.1 m	sdi = 0.5 m
aerogel insulation board-1	🟢	🟢	🟢	🟢	🟢	🟢
aerogel insulation board-2	🟡	🟢	🔴	🟢	🔴	🟢
aerogel insulation board-3	🟢	🟢	🟡	🟢	🟡	🟢
calcium silicate-1	🟢	🟢	🟢	🟢	🟢	🟢
calcium silicate-2	🟢	🟢	🟢	🟢	🟢	🟢
cellulose fiber-1	🟡	🟢	🔴	🟢	🔴	🟢
cellulose fiber-2	🟡	🟢	🟡	🟢	🔴	🟢
hemp fibre board	🟢	🟢	🟡	🟢	🟡	🟢
insulation plaster-1	🟢	🟢	🟢	🟢	🟢	🟢
insulation plaster-2	🟢	🟢	🟢	🟢	🟢	🟢
insulation plaster-3	🟢	🟢	🟢	🟢	🟢	🟢
mineral faser, hydrophilic-1	🔴	🟢	🔴	🟢	🔴	🟢
mineral faser, hydrophilic-2	🟡	🟢	🔴	🟢	🔴	🟢
mineral foam board-1	🟡	🟢	🔴	🟢	🔴	🟢
mineral foam board-2	🟢	🟢	🟡	🟢	🟡	🟢
perlite insulation-1	🟢	🟢	🟢	🟢	🟢	🟢
perlite insulation-2	🟢	🟢	🟢	🟢	🟢	🟢
wood fiber-1	🟢	🟢	🟢	🟢	🟢	🟢
wood fiber-2	🟡	🟢	🔴	🟢	🔴	🟢
wood fiber-3	🟡	🟢	🔴	🟢	🔴	🟢
wood fiber-4	🟡	🟢	🔴	🟢	🔴	🟢
wood fiber-5	🟡	🟢	🟡	🟢	🟡	🟢
wood fiber-6	🟢	🟢	🟡	🟢	🟡	🟢

🟢 Functional (category A)
🟡 Functional if insulation system and substrate moisture, frost and rot resistent (category B)
🔴 Condensation possible. Individual verification required.

4.4 Extended classification and simplified design rules for capillary-active interior insulation systems and materials

The presented classification procedure shall be introduced also to the WTA Guideline 6-4 as new simplified design rule for capillary-active interior insulation systems. The verification for a specific insulation system can then be carried out by the IBK or the IBP, if the comprehensive hygrothermal material parameters including capillary or condensation test are available. The classification can be specified for the application areas I to III and confirmed by a test certificate. It is then up to the manufacturer to decide whether only the insulation material itself or the entire system, possibly with an adjusted s_d-value, is evaluated. At the end of the process the classification can be introduced to the product information, which confirms, that the resp. application with that specific product is deemed to satisfy.

5 Design and Execution of Details

5.1 Durability of wooden beams

The joist supports of wooden ceilings enjoy special attention in the discussion about interior insulation measures. It is known that in dependency of the internal insulation system and climatic boundary conditions condensate can arise at the outer side of internal insulation systems. This often leads to the idea that joist ends could come into contact with the condensate and suffer damage. Therefore, a special chapter is devoted to this topic.

In the past, the project participants were involved in four research projects dealing with this subject ([1],[2],[3],[26]). These projects included measurements in laboratory test rigs and in renovated buildings, as well as hygrothermal simulations and the further development of damage models and software.

Figure 38: Left: Test house at the BBRI test facility; right: One of the two test chambers at the BBRI test facility from the inside. From left to right: non-insulated wall, EPS, mineral wool and calcium silicate. The three beams per wall represent a different connection between masonry and beam. The top beam parallel to the wall only serves as a structural support for the wall

During this research project, a long-term field study (2.5 years) at the BBRI research facility on various test walls with wooden beams was analysed (Figure 38, left). Different 30 cm thick masonry walls were constructed without external render (which corresponds to a common Belgian dwelling built prior to 1945), each having a different composition (e.g. different interior insulation system, Figure 38 right). The measurements show that the use of vapour permeable interior insulation systems has only a slightly favourable impact. On the other hand, measures to lower the moisture content of the wall have a significant effect, either by locally interrupting the insulation at the beam junction or by applying a water repellent treatment. Controlling the rain load on the wall seems to be a key point towards a moisture-safe application of internal insulation with embedded wooden beams. These insights have been used in the practical recommendations in the guide. More information about the field study can be found in a conference paper that has been written in the framework of this research project [39].

The results of this and many other projects ([40],[41],[42],[43]) and specialist articles have also been revised and taken into account here. Furthermore, headed by the IBK, a WTA guideline [44] is currently being revised that deals specifically with the renovation of joist ends in historic buildings, also in connection with interior insulation measures. This WTA guideline summarises the previous findings on this constructional detail in a short and concise form. The results of the mutual exchange in this committee are also considered.

The recommendations given in the guide are very practice-oriented. First of all, the importance of the stock survey is pointed out and that beam heads should be inspected at least selectively for hidden damage. How the main cause of damage to beam heads, insufficient protection against driving rain, can be countered is explained. There are different ways to insulate exterior walls in the area of wooden beam ceilings, the preferred variant is highlighted in the guide. Information is also provided on the various interior insulation systems (vapour-permeable, -inhibiting, and -tight) and their advantages and disadvantages.

In particular, the type and quality of the sealing of the beam supports is discussed, as different opinions are widespread on this issue. As a solution for high moisture loads, both chemical wood preservation and constructive changes are proposed.

The drawings with the recommendations on structural details (following chapter) contain a total of six detailed drawings of joist ends respectively trimmer beam (Figure 40).

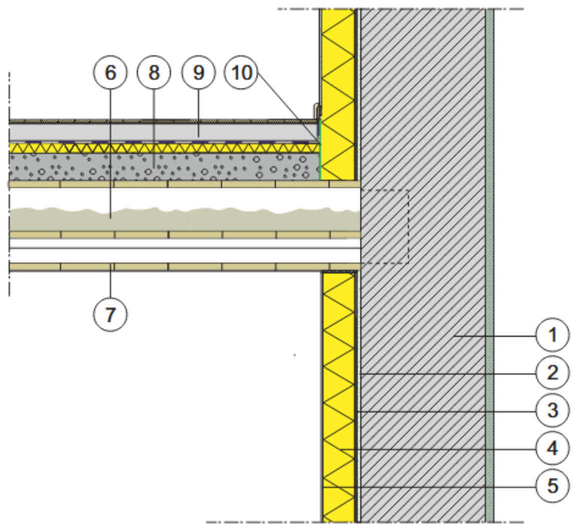


Figure 39: Detailed drawing for the insulation of a joist support in case it is not possible to open the ceiling between two floors

5.2 Best practice solutions for construction details

When planning interior insulation, special attention must be paid to the execution of the connection details. There are many standard details that occur in all buildings, but there are also building-specific details. In the guideline rough dimensioning recommendations are given for preliminary planning for frequently occurring detail connections. In addition, the guideline contains a collection of validated best practice solutions for common construction details on different areas of the building, such as connections to interior walls, windows and floor slabs.

6 Smart monitoring system

Smart, consistent and accurate measurements allow a follow-up of the hygrothermal behaviour of internally insulated walls, which can especially useful for (larger) buildings involving risks. Usually, these risks can be minimised with a detailed building assessment and a proper design and execution of the insulation system. In some situations however, not all risks can be excluded, for instance, in case of a building that is exposed to a lot of driving rain, where rain protection cannot be applied due to the heritage value. In these cases, it can be useful to monitor the hygrothermal situation so that additional measures can be taken if the situation is not acceptable (heating, ventilation strategy, a new or renewed rain protection …). Moreover, such measurements could be used to validate and improve simulation tools.

Within the framework of this project, two smart monitoring systems have been developed, one by both the Institute for Building Climatology at the TU Dresden (IBK) and the Fraunhofer Institute for building physics (IBP), and another one by the Belgian Building Research Institute (BBRI). During the development of the monitoring system, it is aimed to integrate the following specifications:

- autonomous, i.e. as independent as possible on the building's power supply and the local network for data transfer
- flexible, i.e. able to accommodate different sensors and to be parameterised
- minimally invasive, i.e. small in size, communicating wirelessly and requiring no intervention from the building occupant
- sending data remotely, making it possible to consult data in real-time
- reliable, both on the retrieved data as on the operation of the system
- low-cost

6.1 Monitoring system developed in Germany

The Institute for Building Climatology at the TU Dresden (IBK) and the Fraunhofer Institute for building physics (IBP) have developed and tested a newly designed low-cost measurement system in the IBP outdoor test facility. In addition, individual sensors were tested under laboratory conditions.

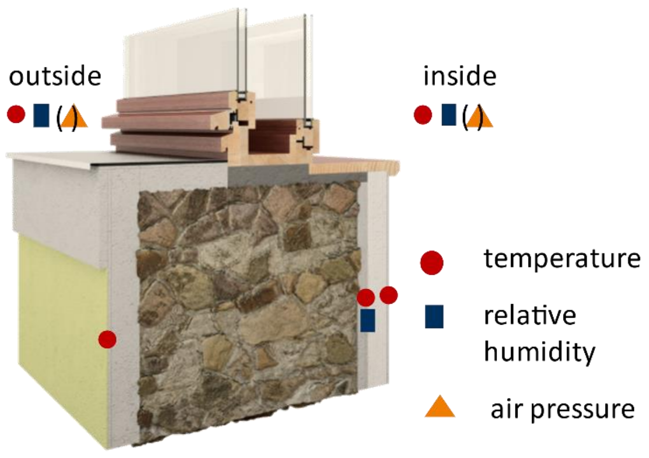


Figure 40: Position of the sensors for an interior insulation measuring section

Throughout the project the measurement setup shown in Figure 40 has proven its worth. Using data loggers with recording function it enables decentralised, precise measurements.

For the measurement in the building structure and on the surface, expensive laboratory measurement technology is currently used. After the projects, the cost-intensive sensor technology remains in the building components.

With the tested sensors and microcontrollers it has been proven that low-cost long-term monitoring is possible. The main cost-pusher is the working time for research and development of the prototype which is usually done starting from "scratch". The open-source approach used here intends to reduce costs and thereby broaden the application of internal insulation monitoring. In the appendix there are instructions for the production of a complete prototype system including the choice of microcontroller and sensors, data recording on SD card and its programming.

The measuring device consists of a commercially available board with microcontroller and sensors connected via bus system (Figure 41). As a very well documented, widely used and well supported board, the Arduino Uno R3 is a good base for a prototype (Figure 42). The more powerful microcontrollers ESP 8266/ESP 32 come with WLAN. This allows the transmission of the measured values via internet. The ESP uses an own in-build web server. ESPs are available in many different versions. This fact and the different firmware versions require a constant adaptation of the program libraries.

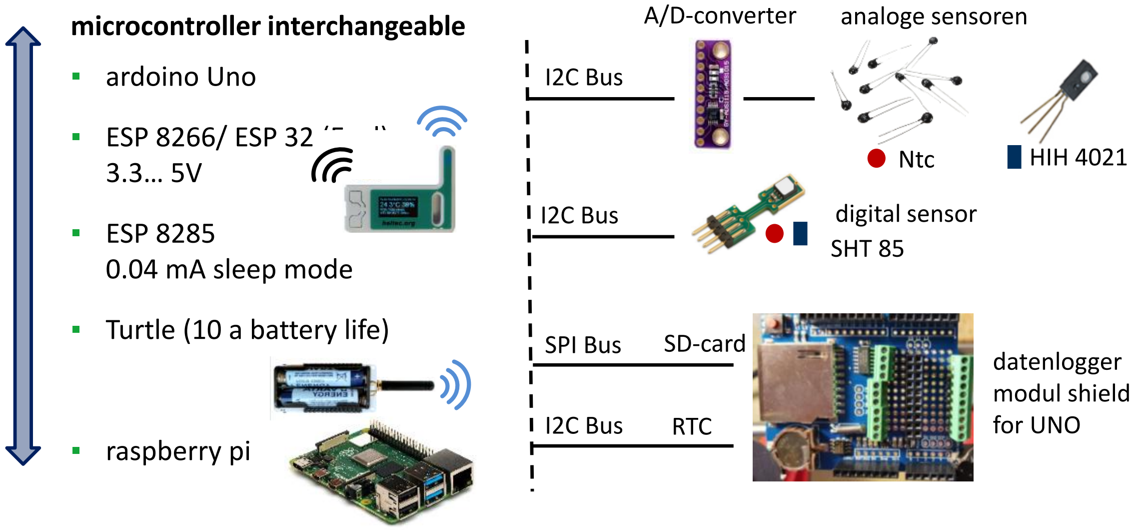


Figure 41: Commercially available board/microcontroller and sensors connected via bus system

The Turtle board is particularly economical. Battery runtimes of up to 10 years are possible when connected to a LoRa (Low Radiation) radio network. The Raspberry Pi's are more powerful boards and are far from being fully utilized with the measurement tasks (Figure 41).

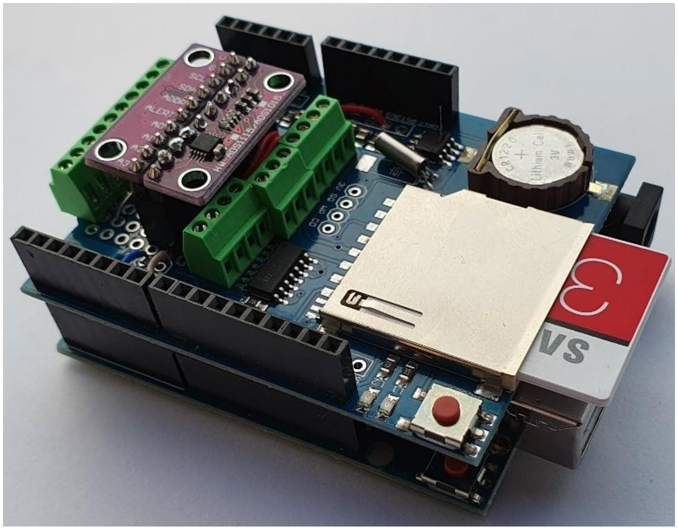


Figure 42:
Prototype setup consisting of an Arduino UNO R3 with a data logger-module (SD card with RTC real time clock), 5 x NTC, 1 x HIH 4021 and 5 x I2C bus (2 x AD converter)

The connection of the sensors, the SD card and the RTC are done via bus systems (Figure 42). Test setups with the direct connection of analogue sensors to the board revealed inaccuracies and fluctuations that were too large. With the bus connection of a 16-bit A/D converter, measurement tasks of analogue sensors can be achieved with a high accuracy like the laboratory measurement technology used so far.

Several boards were tested with a test setup using a plug-in board. The programming was realised with the integrated development environment Arduino (IDE).

The prototype setup consists of an Arduino UNO R3 with a data logger-module including SD card with RTC real time clock, five NTC (negative temperature coefficient) sensors, one HIH 4021 and five I2C bus (2 x AD converter, see appendix).

6.2 Laboratory test

In addition to the consideration of the entire measuring system, the two most frequently used sensors in the laboratory were also examined with the help of a calibration bath. In this process, a temperature and a humidity curve is traced under controlled conditions and at the same time the sensor values are compared accordingly to this curve.

6.2.1 NTC-resistor (temperature sensor)

NTC resistors were used as temperature sensors. NTCs belong to the group of temperature-dependent resistors and conduct the current better with increasing temperatures. During the project, NTC`s which already have an insulated wiring were used, as shown below in Figure 43.

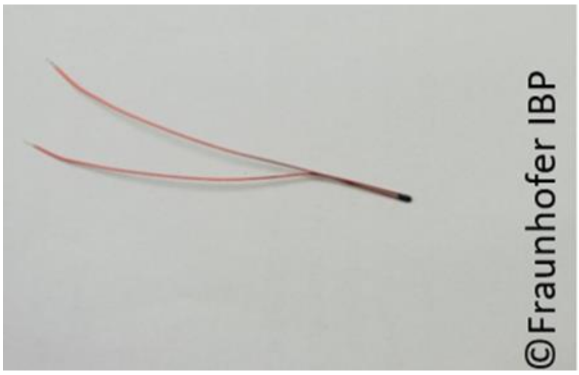


Figure 43:
NTC with preinstalled insulated wiring

This design has the advantage of being easier to install and connect to the measuring system. It also reduces the risk of incorrect measurements due to a short circuit.

The sensors were compared with a reference sensor in a calibration bath from the company Rotronic. A climatic cycle (temperature and rel. humidity) was set within the calibration bath and the measured values of the sensors were compared with reference measurements. The measurement setup used in IN2EuroBuild is shown below in Figure 44.

The result from the calibration measurement of the temperature depicts Figure 45. Figure 45 highlights, that the NTC`s measure nearly the same temperature curve as the reference sensor. The mean deviance over the evaluated period is 0.2 K only. For this reason, the quality of the sensor can be labelled as very good.

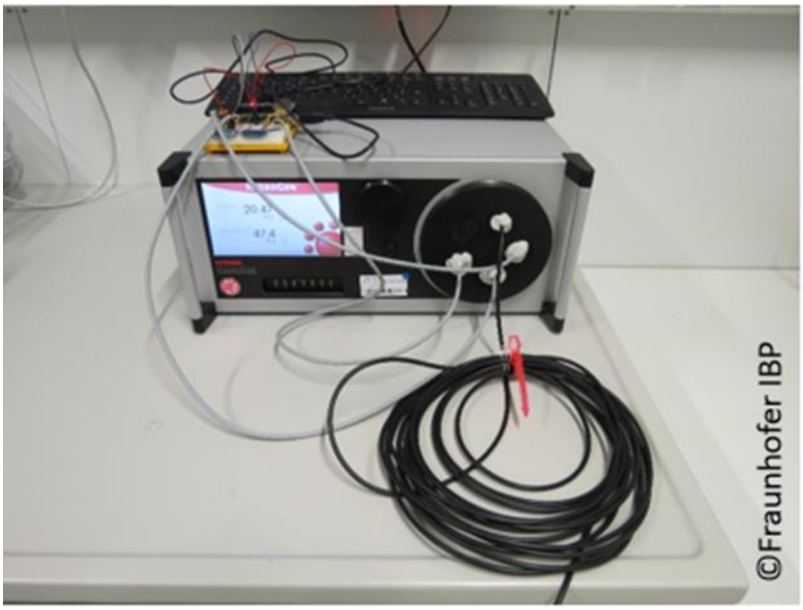


Figure 44:
Calibration bath to determine the accuracy of the used sensors

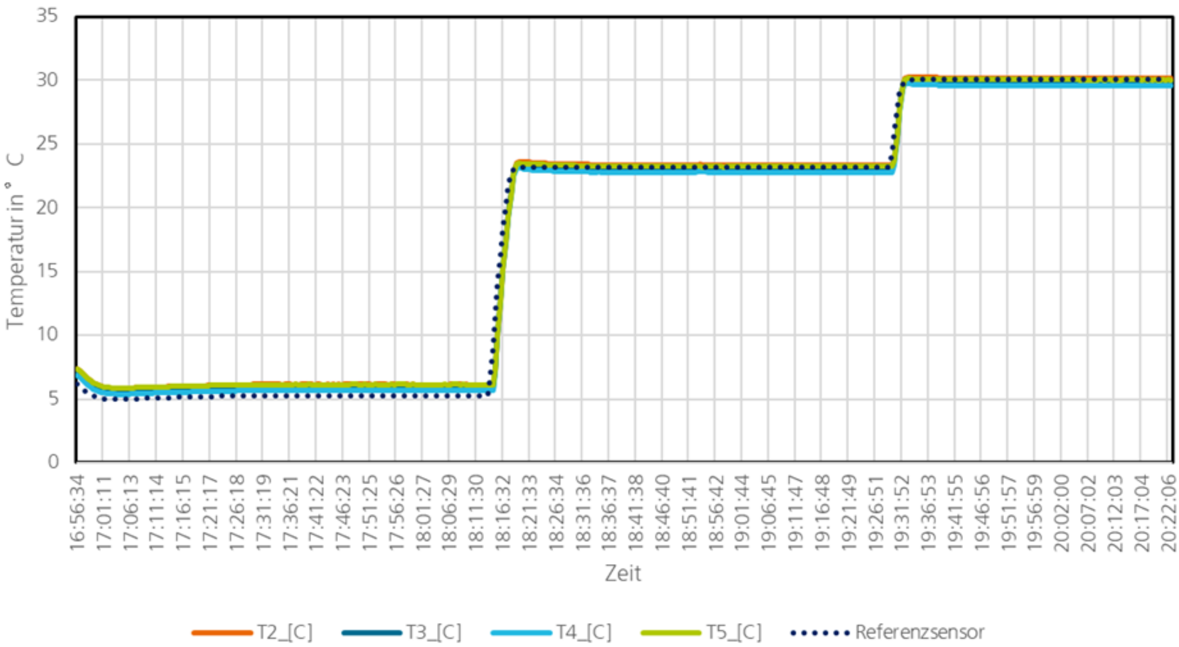


Figure 45: Calibration measurement of the used NTC`s in comparison with the reference sensor.

At the IBK, NTC temperature sensors with the same characteristics (cf. Figure 46) were tested with insulated connecting wires. These were soldered to the cables and insulated with heat shrink tubing. At low temperatures in the climatic chamber, condensation occurred up to failure in 2 of 6 sensors. A condensate-proof connection was achieved by using liquid plastic.

Calibration of the sensors was performed over a wide temperature range from -20 degrees to +100 degrees in the climatic chamber with high accuracy reference sensor. Without recalibration, the NTC's are sufficiently accurate in the relevant range of -20 to 40 degrees (Figure 46). For each NTC type, a separate calibration curve must be created.

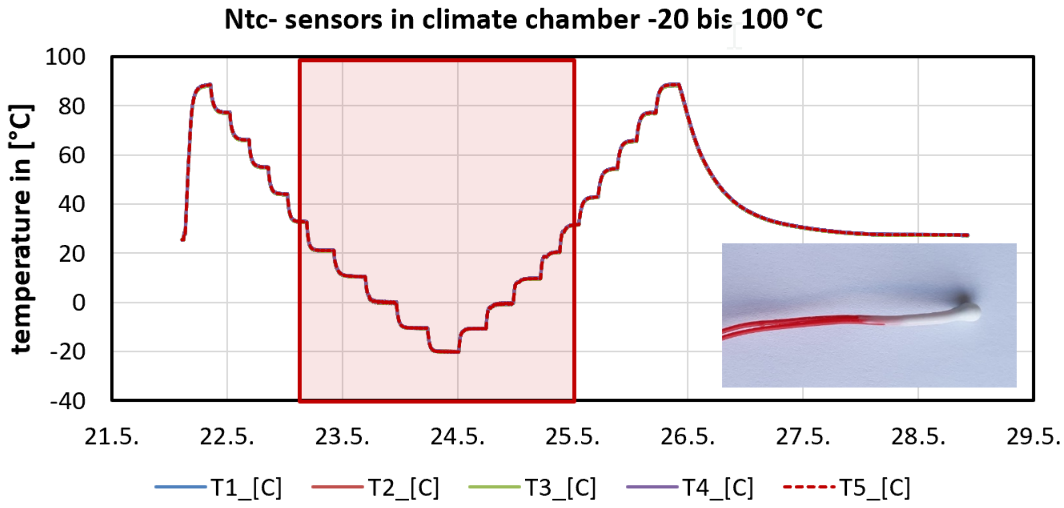


Figure 46: Testing in the climatic chamber, NTC with liquid plastic

6.2.2 HIH-humidity sensor

The used HIH sensor requires an external power supply and generates an analogue measurement output signal. The sensors which were used within the project had a calibration certificate from the manufacturer which indicates an accuracy of 3.5% at 25°C ambient temperature. In the project, the wiring contacts were soldered and insulated against each other with a heat shrink tubing to prevent a short circuit. An example of such a sensor with the connection wiring is shown below in Figure 47.

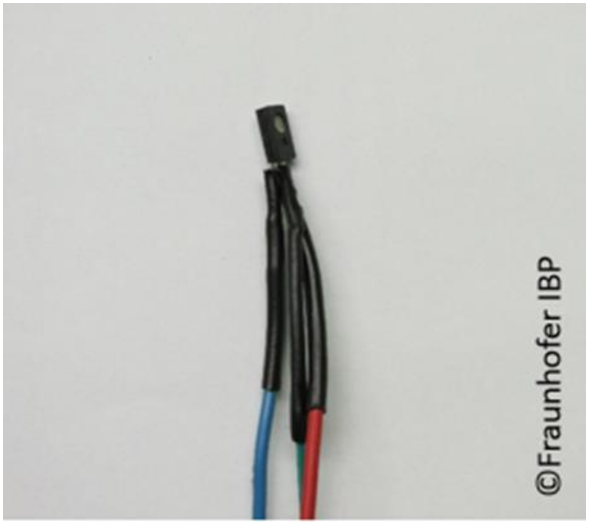


Figure 47:
Calibration measurement of the used NTC`s in comparison with the reference sensor

This sensor was also placed in the calibration bath and compared with a reference sensor. The humidity range varied between 40 % RH and 80 % RH. The comparison with the reference sensor is shown below in Figure 48.

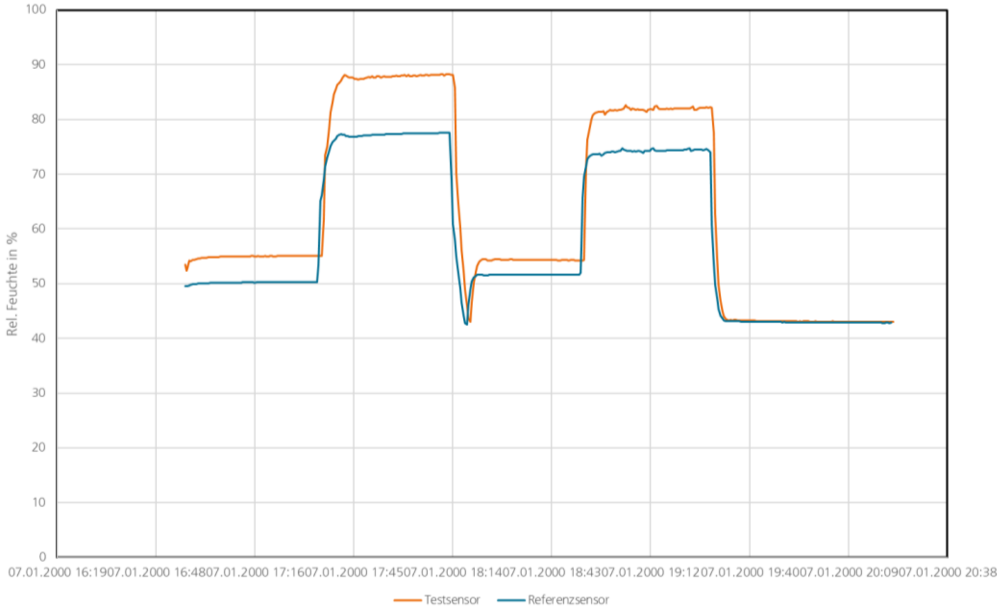


Figure 48: Calibration measurement of the used HIH sensor in comparison with the reference sensor

Figure 48 shows, that the HIH sensor follows the temporal approach with a feasible accuracy. On the other hand, the course of the curves are shifted parallel. The HIH sensor measured over the evaluation period a 6.4% RH higher relative humidity.

The HIH humidity sensor is resistant to condensation. At the IBK, calibration was carried out using a desiccator with 3 humidity levels. In the desiccators, a very stable relative humidity is established above the salt solutions. In [33] the accuracy is given as a function of temperature (Figure 49).

Salt	Humidity level in [%] [33]	Middle value voltage in [V]	Sensor HIH middle value in rh [%]
K_2CO_2	43,15 ± 0,39	2,088	41,08
NaCl	75,37 ± 0,12	3,338	83,08
KH_2PO_4	96,61 ± 0,16	3,884	100,00

Figure 49: Calibration by means of desiccator with 3 humidity levels

In contrast, the calibration certificates of the individual HIH sensors are very inaccurate. From a group of 5 sensors a generally valid formula for this sensor type was derived. With a linear function, a higher accuracy can already be achieved than with the calibration certificates when using a polynomial function: Here, the maximum deviations are ±2% up to 75% RH and ±3% up to 96% RH (Figure 50).

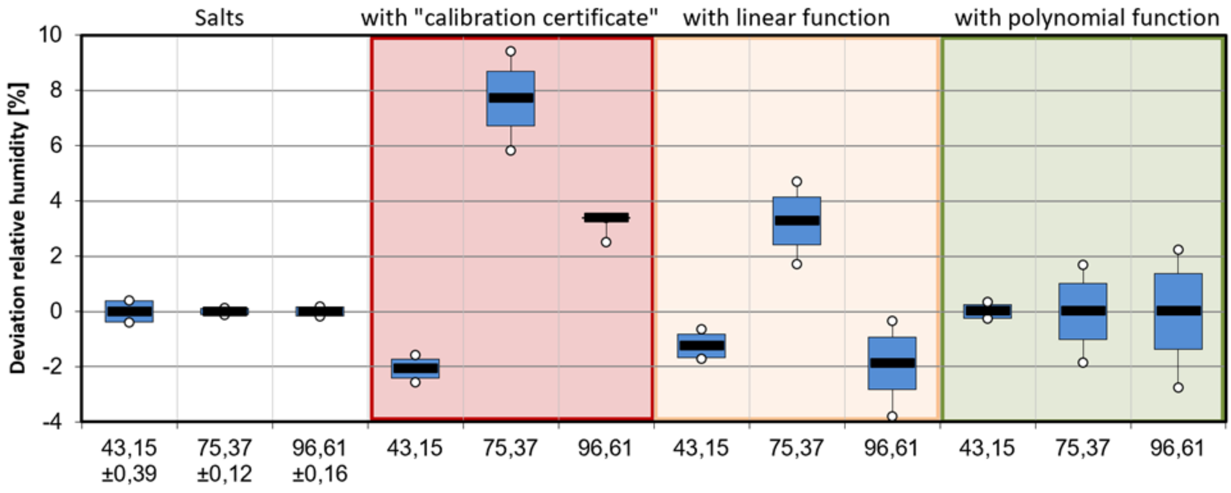


Figure 50: Accuracy data for the HIH humidity sensor using desiccators with 3 humidity levels

6.3 In situ testing of the developed measurement system

6.3.1 Field testing

At the field test site at IBP in Holzkirchen, the measurement system was installed in a test specimen with a side length of 50 cm. The exterior plaster was removed in the lower part of the exterior surface (Figure 51) to obtain the highest possible driving rain penetration. The block was then installed in the test wall, which is oriented to the west, and exposed to weather for several months. The installation situation is shown in Figure 51.

Figure 51: Installation situation of the measurement system in the outdoor test facility at the Holzkirchen site. Left: the test specimen in its installed state. Right: the figure shows the surface design of the test specimen with the exterior plaster removed

An interior insulation system based on mineral fibre insulation was applied on the internal side of the test specimen. The sensors for temperature and relative humidity were installed reversible in perforated plastic tubes. The pipes were sealed off from the interior climate with a permanently elastic sealing compound. The room side was sealed with a taped vapour retarder and a plaster-board. The installation is shown in the following Figure 52.

Figure 52: Perforated plastic tubes for the installation of the temperature and rel. humidity sensors within the interior insulation system

The measurement system is described in detail in chapter 6.2. For the field tests it was applied on an electrical pin board for the power supply an USB power supply was used.

6.3.2 Flat roof test bench

The second test was carried out on the flat roof test bench at the outdoor test site. This is a wooden pitch roof open on three sides and mounted on a flat roof at a height of approximately 5 m above ground. The roof surface slopes towards the west. The measuring section was installed in the area of the middle rafter and recorded the outdoor climate without the influence of precipitation and global radiation. Figure 53 shows the test stand.

.

Figure 53: Flat roof test bench within the field test facility at the Fraunhofer IBP in Holzkirchen

The outdoor climate was measured on a meteorological station on the terrain of the field test facility. The readings from the measurement system could be compared with the measured values from the meteorological station. For comparison reasons, the outdoor air temperature was measured with 4 identical NTC resistors. For the measurement of the relative humidity only one slot was available. For the period from 9.7.2021 till 3.11.2021 the courses for the temperature are opposed in the following Figure 54.

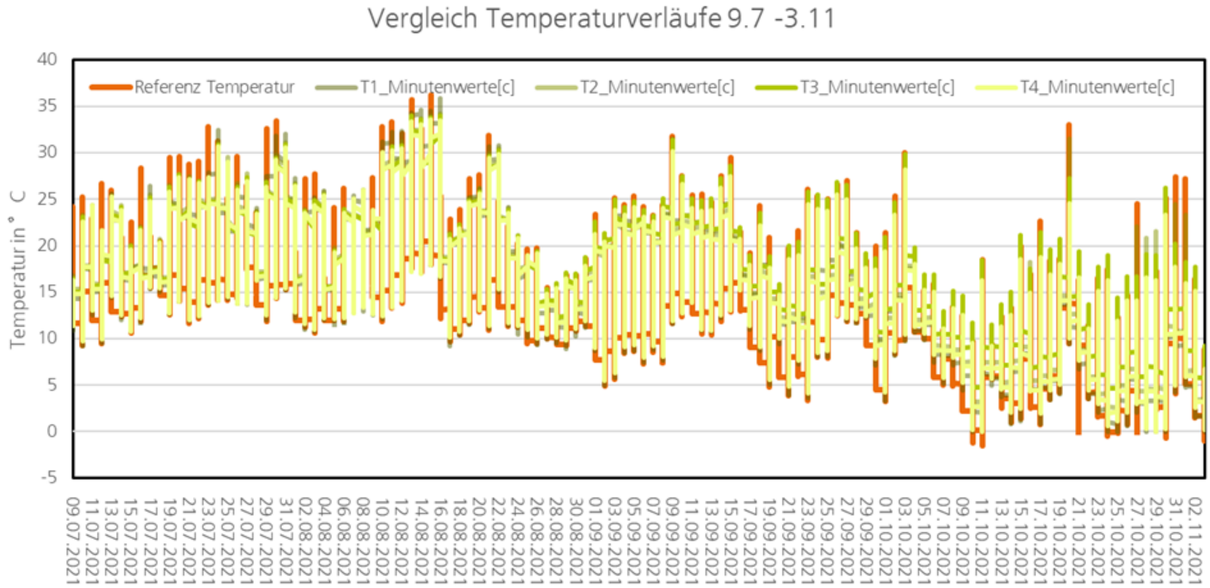


Figure 54: Results from the flat roof test bench within the field test facility at Fraunhofer IBP

Figure 54 visualizes a good correlation between the reference sensor and the new measurement system. The maximum mean deviation over the evaluation period is 0.64 K between sensor T4 and the reference sensor.

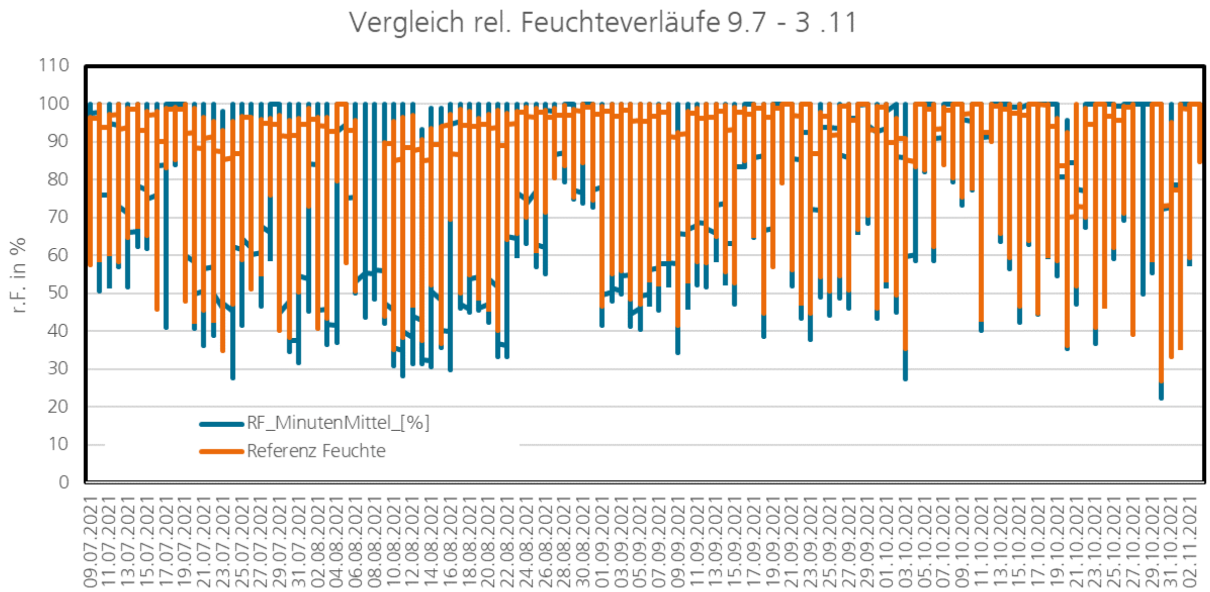


Figure 55: Comparison of the relative humidity between the newly invented measurement system and the reference measurement at the meteorological station.

The measured relative humidity was also compared with the reference measurement at the weather station in Figure 55. Figure 55 shows a deviation between the reference measurement and newly invented measurement system. The relative humidity of the new system is higher than the reference measurement. Over the evaluation period the mean value is 1.8% higher.

6.4 Summary

The evaluation of the newly invented measurement system has shown, that even with a minor financial effort a feasible measurement system for the analysis of interior insulation systems can be realized.

The evaluation within the field test facility shows, that the conditions create higher requirements on the durability of the measurement system, the prevention of short circuits and loose contacts as within a laboratory. For installation within the interior insulation systems, a reversible installation as described in chapter 6.3.1 has proven its advantages. In this way, the sensors could be manually removed and re-dried when saturation occurred.

The usage of NTC`s for temperature measurement is approved within the field test facility as well as in the laboratory. The accuracy of the measurement is sufficient for an evaluation of an interior insulation system.

The measurement of the rel. humidity with HIH sensors has shown a significantly larger deviations within the range of 2 % till 6.4 % occurred here. This must be taken into account and there has to be an additional safety reserve for the design of an interior insulation system. The laboratory measurements have also shown that even manufacturer certificates for calibration cannot provide any additional safety. An alternative could be the use of digital humidity sensors. These provide a digital output signal that can be read in the measuring system without an additional 16-bit A/D converter as in the current setup. This reduces the susceptibility to errors and increases the accuracy of the measurement.

6.5 Monitoring system developed in Belgium (BBRI)

The smart monitoring system should be autonomous, flexible, minimally invasive, able to send data remotely, reliable and low-cost. In order to meet these requirements, various technical solutions were explored. These solutions are described in the following section. They are all based on microcontrollers developed for the Internet of Things, integrating a radio module and capable of communicating with various precision digital sensors.

The final prototype that has been developed, is based on small microcontroller units (MCUs) in-stalled near the sensors and connected to them in a wired manner (measurement node). The sensors themselves are positioned in the wall, allowing the hygrothermal measurement in the wall construction. Different solutions exist to send the data to the user and ensure data storage and visualisation.

The following paragraphs explain each element separately. First, the choice of the sensor is presented. Second, the composition and set-up of the measurement node is explained. Third, different possibilities for data transmission and data visualisation are presented and discussed. Finally, a case study is presented in order to evaluate its functioning.

6.5.1 Sensors

The purpose of the monitoring system is to evaluate the hygrothermal situation of the wall. Therefore, at least the monitoring of temperature and relative humidity within the wall and in the environment is required.

The temperature and relative humidity sensors used are Honeywell HIH 8121 digital sensors (Figure 1Figure 56). These sensors are very small (3.9mm x 4.9mm) and very cheap (5-10 EUR per sensor). They combine a temperature and relative humidity measurement with a very good accuracy (±2% RH and ±0.5°C).The sensors are available with hydrophobic condensation-resistance filter, allowing it to be used in condensing environments.

They communicate digitally via an I²C bus and are addressable, which makes it possible to interrogate several sensors from a single microcontroller.

The sensor has a 4 pin housing (power supply, ground, I²C clock and I²C data). As shown on the circuit in Figure 56, the supply should be connected to ground via a 0.22 µF condenser, and both I²C clock and data should have a 2.2 kΩ pull-up resistor.

For this monitoring system, the use of this sensor alone is sufficient. The monitoring system is however flexible and easily extended with other sensors, of which Figure 57 give some examples (which haven't been tested.

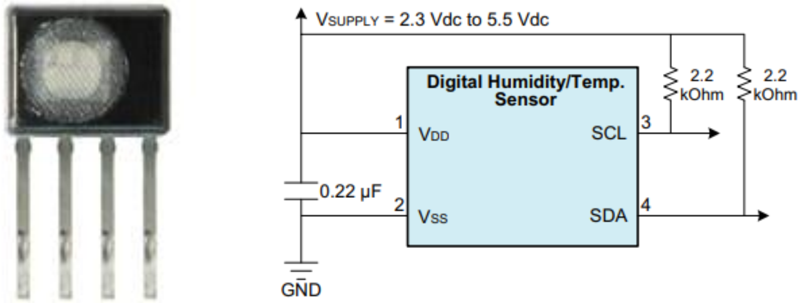
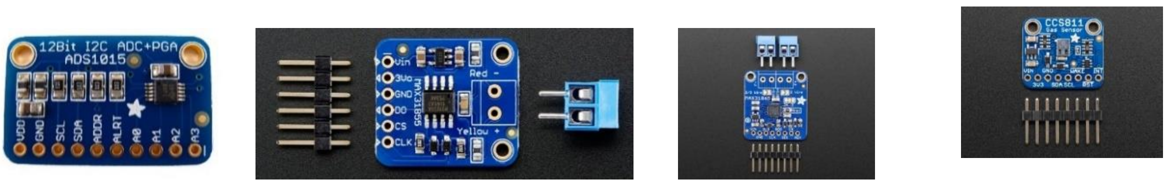


Figure 56: Honeywell HIH 8121 sensor and its typical application circuit (source: Honeywell)



ADC | Thermocouple | RTD (Pt100) | Air quality (VOC – eCO_2)

Figure 57: The measuring instrument can be easily expanded with these sensors (not tested)

6.5.2 Measurement node

The measurement node is the ensemble that allows sensor reading and data transmission. Each measurement node consists of a programmable microcontroller unit (MCU) equipped with a data transmission module, an I²C bus for communicating with the sensors and components that allow it to be put into a “deep sleep” mode between two measurements (this leaves only a low power coprocessor and RTC timer running, which allows very low power consumption).

The MCUs from the Pycom company has been used for the monitoring system. These MCUs have the following advantages:

- Low purchase cost (20-40 EUR)
- Easily programmable with MicroPython programming language
- Very low power usage
- Flexible: fits in a standard breadboard (with headers), no need for soldering
- Works with multiple networks: WiFi, Bluetooth, Sigfox, LoRa …

More specifically, we tested out the Pycom WiPy3 (for data transmission with WiFi) and Pycom LoPy4 (for data transmission with Sigfox). Each MCU is installed on a breadboard on which an electrical circuit is made to communicate with the sensors and to monitor the voltage of the battery supplying the MCU. The whole system is installed in a box which integrates the battery support and which is fixed to the wall. For data transmission using Sigfox or LoRa, an antenna is connected to the MCU. (Figure 58)

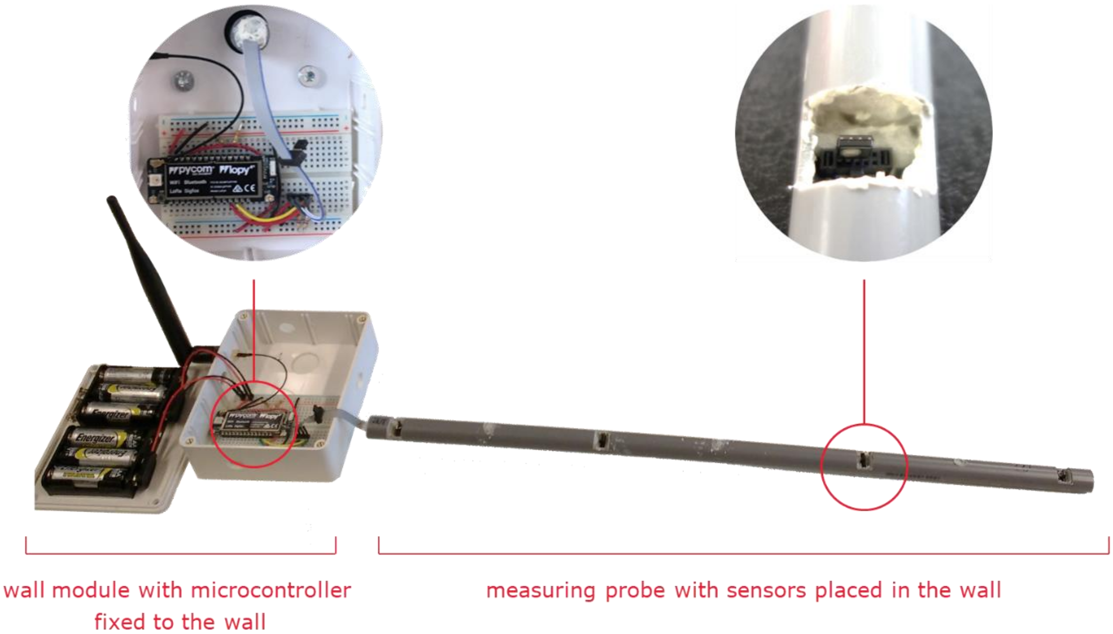


Figure 58: Overview of the measurement node

The MCU require an input power between 3.5 and 5.5 V, which in the prototype is delivered by connecting 3 AA batteries (nominal voltage of 1.5 V) in series. In general, a second pair of 3 AA batteries was connected in parallel to increase the total battery capacity. Our experience shows that 6 AA batteries with the Sigfox configuration corresponds to a battery life of more than one year. Moreover, these standard batteries are easily replaced by the building owner.

The MCU has different pins. In this prototype, only the pins selected in Figure 59 are used:

- Sigfox/LoRa antenna if these networks are used
- Vin: the 3.5 - 5.5 V power supply, provided by the batteries
- GND: ground
- 3V3: the regulated 3.3 V output supply is connected to the power supply of the sensors
- Internal ADC for battery voltage reading (pulldown resistances are necessary as ADC pin input range is 0-1.1V)
- SDA: connected to the sensor I²C data
- CLK: connected to the sensor I²C clock
- Pycom LoPy4 pinout with the pins used in the prototype indicated in red

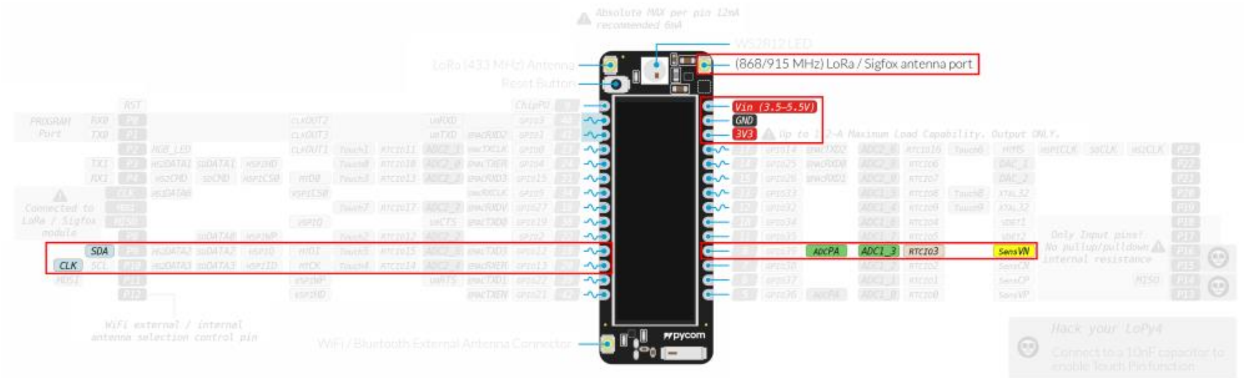


Figure 59: Pycom LoPy4 pinout with the pins used in the prototype indicated in red

For the connection between sensors and breadboard, a flat 10 core cable is used. On the position of the sensors, a 10-way female cable mount connector is clipped on the flat cable in which the 4 pins of the digital sensor are connected. The 4 cores of the flat cable used for the sensors (6 of the 10 cores are not used) are soldered to a 4 contacts pin header wire-to-board connector which is inserted in the breadboard. This sensor to breadboard connection might be optimised in future prototype versions.

The measuring probe with the sensors are installed in the walls to be monitored after the insulation has been laid. The sensors are positioned in a PVC tube filled with insulating PU foam and drilled only at the sensor locations. The sensors are thus precisely positioned in the wall and the thermal disturbance caused by the installation of the sensor bundle in the wall is very limited. Alternatively, if the wall is being constructed, the sensors could be installed in the wall during construction, limiting the influence of the measuring probe (Figure 60).

Figure 60: Installation of measuring probe in the wall, either using a PVC tube (left), or during construction (right)

6.5.3 Data transmission

Wi-Fi

In the first prototype, each measurement node sends the sensor data via Wi-Fi to a central point called the gateway. This gateway is constantly monitoring for data sent to it. It collects this data, formats it if necessary and transmits it via the internet. A router enables communication between the nodes and the gateway via a local Wi-Fi network and between the gateway the external user via a 4G network. (Figure 61)

The gateway developed was based on a Raspberry Pi3 B+ mini-computer. The advantages of this type of computer are as follows:

- Compact (10 cm x 10 cm x 4 cm)
- Low cost (30-50 EUR)
- Linux operating system
- Programmable with Python (same language as the nodes)
- Fully configurable

The software implementation of the gateway is based on a mosquitto MQTT server. This type of server allows a simple and efficient exchange of short messages between the clients of the server. Clients can publish data on topics. These are defined on the fly and are organised hierarchically. Clients can also subscribe to existing topics, and then receive all messages that are published in these topics (Figure 62).

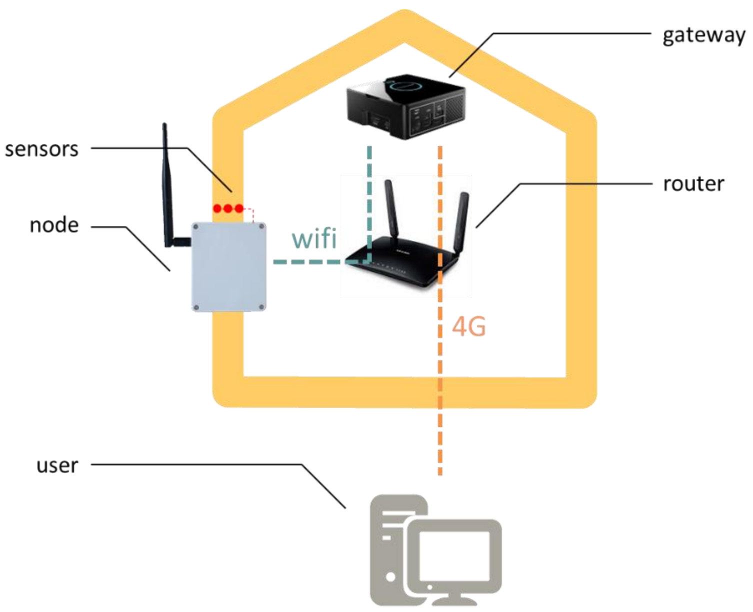


Figure 61: Principle of data transmission using the WiFi configuration

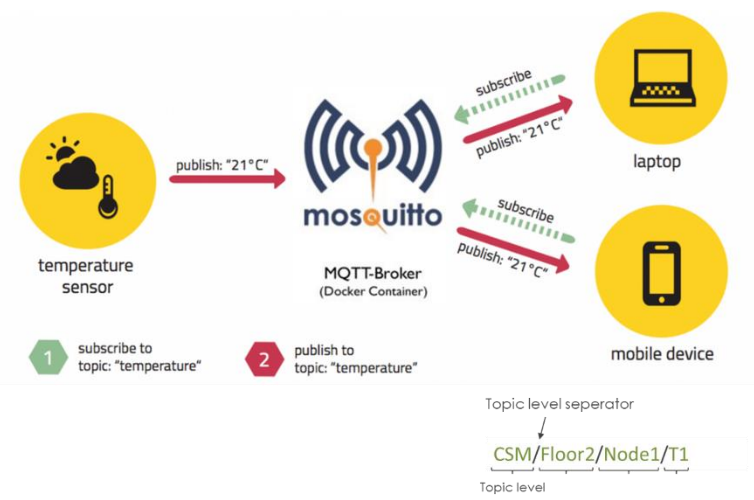


Figure 62: General principle of a MQTT server

The Wi-Fi configuration has the following drawbacks:

- Additional costs of router, gateway and 4G data subscription
- Dependency of building's power supply for router and gateway
- Limited Wi-Fi network range, depending on distance and physical obstacles
- Relative high power consumption

Sigfox

The second prototype is a variant of the first one, in which the MCUs transmit the sensor data directly to the external user using a 0G network (LPWAN, low-power wide-area network), in this case Sigfox. In Belgium, the Sigfox network it covers more than 97% of the territory (> 99% of the population) and is operated by Citymesh. The Sigfox technology is based on a radio signal modulation technique in the free ISM frequency band (868 MHz in Europe). Sigfox subscription is very cheap (3 - 7 EUR per year per MCU).

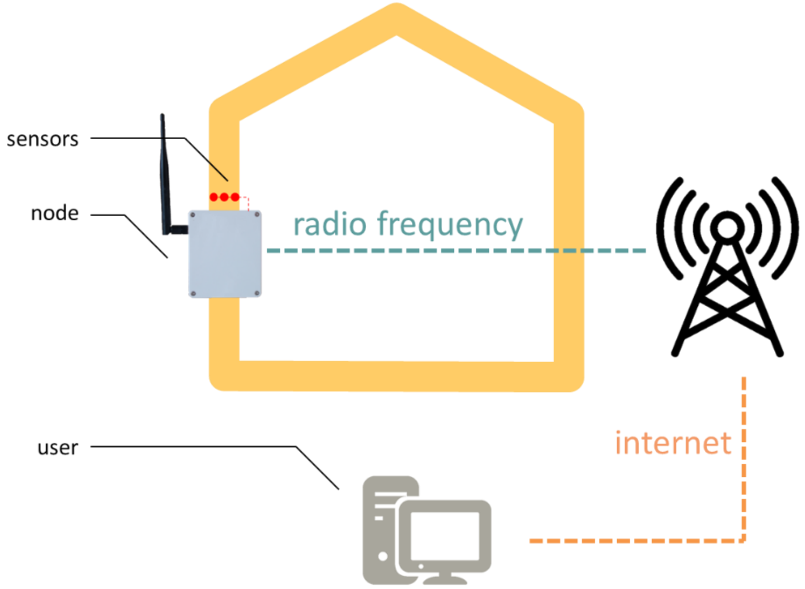


Figure 63: Principle of data transmission using the Sigfox configuration

No gateway is installed in the building. The data are directly transmitted by the MCUs and received by the Sigfox Cloud. They are then accessible through the backend offered by Sigfox and its API. (Figure 63)

It provides an answer to the disadvantages of the Wi-Fi prototype, as no additional router and gateway are required. The system is thus independent of the building's power supply, as it only needs its own power provided by the AA batteries. The data transmission only requires a little amount of energy which ensures a long battery life (about 1 year and 2 months with 6 AA batteries). No local Wi-Fi network, with limiting range, is required.

Devices need a network to send messages to. The coverage of the network depends on:

- The number of dedicated connected antennas (base stations). Some regions have many antennas, others few or none. In Belgium, the Sigfox network it covers more than 97% of the territory (> 99% of the population).
- Surroundings. The range is on average 10 km in an urban environment and 40 km in a rural environment.

Even though coverage is very good in Belgium, one of the 9 case studies, which was situated in a very urban area, showed a poor network signal with considerable data loss. If necessary, coverage can be expanded using network repeaters or a micro base station.

The maximum of 140 messages a day equals around 1 message per day. For the purpose of monitoring, this is largely sufficient. In the data transmission protocol of this prototype, one message every 30 minutes was chosen.

The maximal message payload (own user data) is 12 bytes or 96 bits. A well-considered choice must therefore be made to structure the data in this limited message size. In this monitoring system, the data contained 4 temperature readings with a data resolution of 0.049°C and a range of -20 to 80°C (11 bits per reading), 4 relative humidity readings with a data resolution of 0.049% and a range of 0 to 100% (11 bits per reading) and 1 battery voltage reading with a resolution of 0.012 V and a range of 2 to 5 V (8 bits per reading). The resolution of much smaller than the sensor precision and largely sufficient for this purpose.

The drawbacks of the Sigfox configuration are:

- Additional cost for the Sigfox connectivity (however very small: 3 - 7 EUR per year per MCU)
- Sigfox coverage necessary.
- Limited data transmission (max. 140 uplink messages / day, max. 12 bytes / message)

LoRa

A third alternative was only conceptually conceived but not tested. It has the same setup as the configuration with Wi-Fi transmission, but here the nodes communicate with the gateway using a local LoRa (LPWAN network, similar to Sigfox). Compared to the Wi-Fi setup, the energy consumption for the node is lower and the signal range is higher (> 100m). For large buildings or even an entire site, one gateway should be enough.

6.5.4 Data visualisation

The **data recuperation** is different for the two configurations. When using Wi-Fi, the files are received by the BBRI FTP server. When using Sigfox, the software Node-RED is used, a very flexible and powerful tool for graphical programming to make hardware, services and APIs interact. In this case, this tool is used to query the Sigfox server via its API at regular intervals, retrieve the binary data sent by the measurement nodes and convert them into physical values (temperatures, relative humidity ...), and introduce these data into a **data storage** system. The data is stored in InfluxDB, a database optimised for the storage and consultation of large time series.

Data visualisation is done by the platform Grafana. It allows querying a large number of databases, visualising the data in a very clear and interactive way, defining alerts and analysing the data. As the platform is installed on a server, the defined dashboards can be viewed by several users simultaneously. From the interface, it is possible to select data ranges and export them for further analysis. (Figure 9)

This setup not only allows a real-time visualisation of the measurements, but also makes it possible to set up alerts. This could be, for instance, a certain voltage level to inform the owner that batteries will soon need replacement, but also critical levels of humidity at a certain position, which would inform the owner that the hygrothermal behaviour of the wall is not optimal and certain measures might be necessary (e.g. better heating and ventilation strategy, examination of rain protection …):

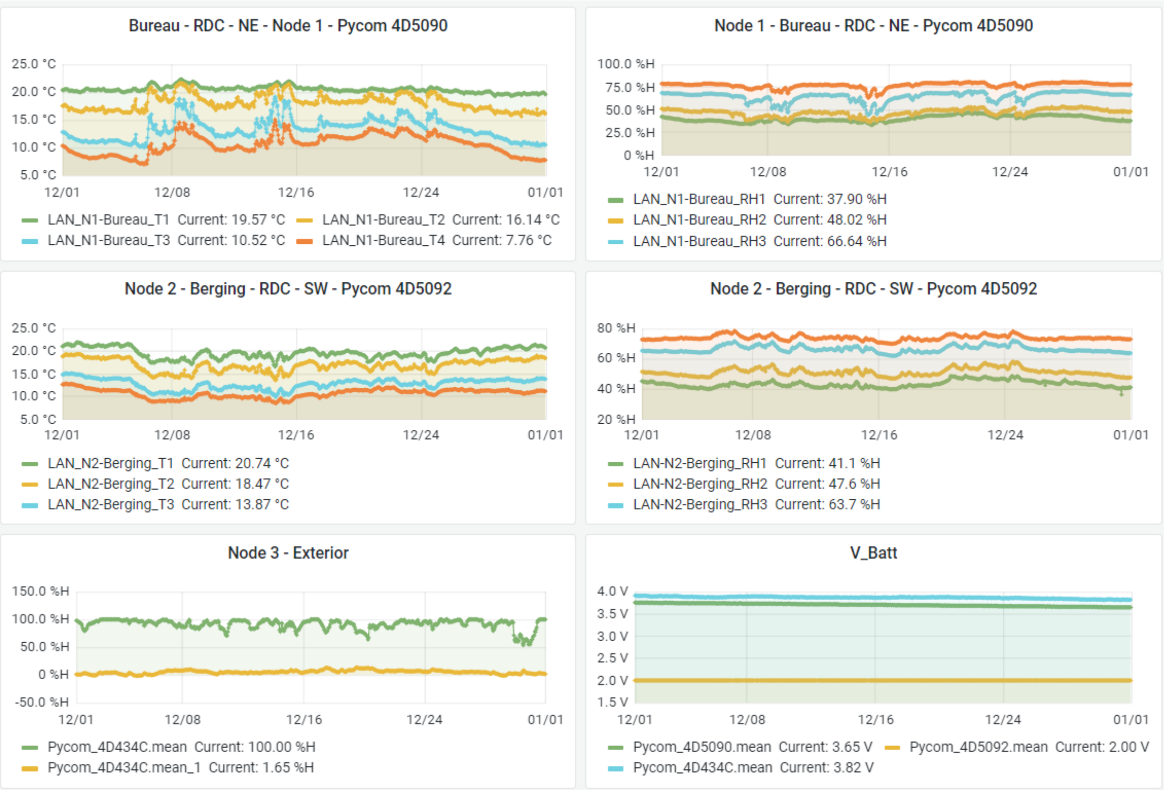


Figure 64: Example of data visualisation in Grafana. Two nodes measure temperature and relative humidity inside the wall, a third one measures the outside conditions. Battery voltage of these three nodes is also visualised.

6.5.5 Case study

In Wavre, an existing building was renovated in the course of 2018 and 2019 (Figure 65). This building is divided into two zones: a living area and an office. In total, a measurement probe is placed in five different places in this building: three in the living area and two in the office. The measurements started about half a year after the main renovation works. However, some works were only placed during the measurement campaign (such as the interior and exterior plastering in certain places).

The walls of these buildings were insulated with prefabricated lime hemp (hempcrete) blocks on the inside, on the outside or both. The measurement positions are chosen so that different orientations, different wall structures and different building functions are taken into account.

For the purpose of this document, only one of the five measurement nodes will be discussed. It is located in the office part of the building. The wall is oriented to the north, where small rain load is expected, and is insulated on the inside (6 cm) as well as on the outside (20 cm) with prefabricated hempcrete blocks. The detailed wall composition and sensor location are shown in Figure 66.

The measurements (Figure 66, red curves) give expected results. The course of the relative humidity at the interface between clay plaster and masonry is similar to the indoor environment, while the one at the outside of the outdoor insulation is similar to the outdoor environment. This behaviour is to be expected as lime hemp is vapour permeable and there are few other sources of moisture (e.g. little driving rain). The temperatures of the first three sensors are very similar to the indoor environment, as the external insulation represents most of the thermal resistance of the wall. The temperature of the outermost sensor is similar to the outdoor environment, as expected.

The measurements were validated using hygrothermal numerical simulations with the software Delphin 6, with which the coupled heat and moisture transport in porous building materials can be calculated. There is a very good agreement between measurements and simulation, especially given the uncertainty regarding the material properties of the existing brick (Figure 66, grey curves).

Figure 65: Building in Wavre where the monitoring system was tested

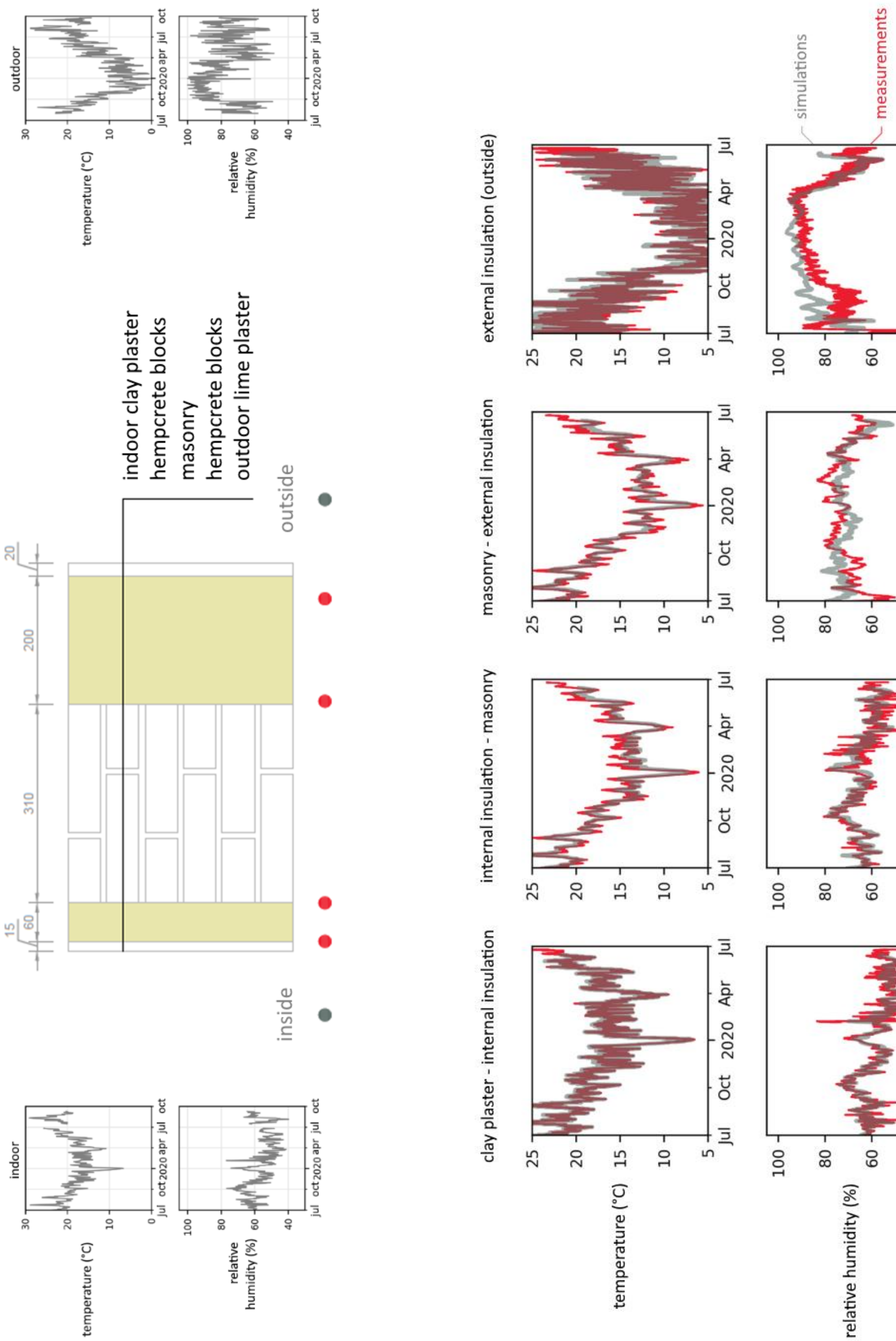


Figure 66: Composition of the wall with sensor locations (left), and measurement results validated with simulations (right) for the case study in Wavre

6.5.6 Summary

The monitoring system developed by BBRI meets the predefined specifications very well:

- Autonomous: the system is powered by batteries and (when using the Sigfox or LoRa network) doesn't rely on a local network.
- Flexible: the MCU is easily programmable and the system easily allows a different setup (e.g. different number of sensors, different type of sensors …).
- Minimally invasive: it is unavoidable that a hole is made in the wall at the location of the measurement point, however the installation is very quick and after installation only a small white box is visible.
- Sending data remotely: the measured data is directly sent using either Wi-Fi, Sigfox or LoRa, allowing to consult data in real-time and even setting alarms when certain threshold values would be exceeded.
- Reliable: the reliability of data has been tested in lab and on site, and validated with numerical simulations; the reliability on receiving the data is in most cases very good, only one case study, situated in a very urban area, showed a poor network signal with considerable data loss using the Sigfox network. This could however be solved by installing Sigfox network repeaters or a micro base station, or by using another data transmission mode.
- Low-cost: the purchase cost is very low, 50-100 EUR per measurement node.

The measurement system is however still a prototype and the construction requires a certain amount of manual operations (e.g. fitting of all elements on the breadboard, installing the sensors on measuring probe, welding the connection pins for the plugging of the measuring probe to the breadboard). These manual operations are possible weak points prone to errors and can be optimised in future prototype versions.

In total, 25 measurement nodes were installed with a total of 103 T/RH sensors, divided over 9 buildings. All measurement data were in line with the expected hygrothermal behaviour. This extensive case study analysis confirmed the reliability of the monitoring system.

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