ENERGY EFFICIENCY SOLUTIONS FOR HISTORIC BUILDINGS

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A Handbook

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PREFACE

When I was asked recently what the most important development in the field of historic building renovation had been over the past few years, I observed that a noticeable development is a new willingness on the part of architects and conservators to cease excluding historic buildings from energy efficient retrofitting.

When the first version of the Energy Performance of Buildings Directive came out in December 2002 (Directive 2002/91/EC), there was a fear that old buildings would be disfigured, or ruined. This has now changed to a more constructive approach. We all want to preserve such buildings, we want to use them and also to make them more energy efficient. This has, of course, to be done in a way that is compatible with the heritage value of a building.

There are no standard solutions for an energy retrofit of a historic building, but with the right approach the appropriate solution for a particular building can be found. There are manifold technologies available; it is the task of the design team to select the right ones and adapt them to suit the needs of each building.

The design effort will usually be greater than in a standard retrofit, but this is a worthwhile investment. The effort spent in the early phases will save money not only during the implementation on site, where unwelcome surprises and costly adaptations are thus avoided, but also in the long term with lower maintenance costs and a building that is well preserved, comfortable to use, and has retained its original charm. Finally, I am convinced that the best solutions are not necessarily the most expensive ones – often it is just a matter of having the right idea.

The major challenge when it comes to implementing a renovation concept for historic buildings is for all stakeholders to communicate without any prejudices. The most appropriate solutions for a certain building are likely to be found if the conservation officer can raise awareness of the historic value of the building, if the technical experts consult the conservation officer at an early stage and if all parties communicate continually.

This approach is not very widespread yet. My vision is that conservation specialists, engineers and architects learn to talk to each other to find creative, individual solutions for historic buildings. This handbook should help to realise that vision.

Alexandra Troi
Coordinator of the European research project
3ENCULT – Efficient Energy for EU Cultural Heritage

1 INTRODUCTION

Zeno Bastian, Passive House Institute / Alexandra Troi, EURAC research / Ola Wedebrunn, The Royal Danish Academy of Fine Arts

The protection of built cultural heritage has been a field of scientific study and the subject of legal regulations in all European countries since the nineteenth century. The restoration works of the architect Eugène-Emanuel Viollet-le-Duc and the polemics of John Ruskin in the nineteenth century are sources for the basic principles of conservation. The rise of interest in monuments as well as vernacular traditions, the emergence of heritage societies and cultural authorities, and the development and protection of urban areas by modern architecture all contributed to the integration of heritage into discourse and active change throughout the twentieth century.

History, memory and continuing management of heritage are some of the reasons to preserve historic buildings, which form the distinctive character of many urban centres, creating continuity with the past, and providing a visual cultural reference.

Throughout the nineteenth century, heritage societies, architects, and architectural historians paid increasing attention to the qualities of historic buildings. Thus survey methods, documentation, and measured drawings have developed as means for understanding the history, location, and technology.

Historic buildings are sources of cultural identity. They contribute to the character and history of site and context. They form a link with our past, giving information about the changes of places over time. They are a unique perspective to history, and the balance of energy use and the preservation of cultural values. They are an important investment for the future.

At the times when what we now term ‘historic buildings’ were constructed, people relied on energy from local and natural sources such as wood for heating. Because of the limited quantities available and the relatively high effort to obtain wood, heating was restricted to only one or a few rooms and its duration was limited. In central and northern European climates, it was not uncommon for the temperature in rooms without an oven, such as bedrooms, to drop below freezing in winter. Technologies for active cooling, on the other hand, were not available at all. In summer, overheating could be reduced to some extent by passive measures such as shutters, thicker walls, and ventilation by opening windows at night. In winter, ventilation through windows was reduced to prevent lower room temperatures, leading to poor air quality (partly alleviated by poor airtightness).

In the twentieth century, energy generation from fossil fuels was rapidly and extensively developed, with vast quantities of oil, natural gas, and coal being widely available and affordable. This cheap energy supply, along with the development of modern heating and cooling systems, enabled a large part of the global population to maintain comfortable conditions in their indoor living and working spaces for the first time in history, especially in more economically developed countries. As energy prices were low, and energy efficient technologies were expensive and not widely available, investment in energy efficient buildings was often not economical and therefore not carried out.

This situation changed with the oil crises of 1973 and 1979/80, and again with globally rising energy prices after 2000. Apart from the fact that high energy prices made investment in energy efficiency more viable, the strong dependence on fossil fuel imports from foreign countries was identified as a threat to political independence and prosperity.

In addition to this, growing scientific insight into man-made climate change and its potentially devastating effects led to international conventions and treaties with the aim of limiting CO_2 emissions. This started with the 1992 Earth Summit in Rio de Janeiro, and continued with the 1997 Kyoto protocol and the 2012 negotiations for a second commitment period.

With progress on an international level being so slow, concerned individuals, NGOs, and small innovative companies started taking action, with the means available to them, to mitigate climate change and reduce high energy costs. Today, technology to greatly reduce CO_2 emissions in the building sector is available, and its implementation is also financially rewarding. Energy standards such as the Passive House standard and the related EnerPHit standard for energy retrofitting with Passive House components both reduce energy consumption for heating by approximately 90%. If the energy demand is reduced by such a degree, meeting the remaining demand with renewable energy sources will be feasible. The European Commission has therefore defined a comparatively high efficiency standard in the recast Energy Performance of Buildings Directive (EPBD), which will come into effect in the member states from 2020.

Even though historic buildings are currently exempted from most EPBD requirements, there is a growing awareness that cultural heritage preservation and preservation of the natural basis of life are equally important goals.

Some statistical data on historic buildings in Europe are available (see [Troi 2011]): 14% of the EU27 building stock dates from before 1919 and 12% from between 1919 and 1945 (with considerable national differences), corresponding to thirty and fifty-five million dwellings respectively, with 120 million occupants. Combining these figures with current information on climatic regions and building performance gives an estimated total heating demand for these buildings of 855 TWh – corresponding to more than 240 Mt CO_2. Refurbishment can save 180 Mt CO_2 by 2050 (3.6% of EU27 emissions in 1990). Finding conservation-compatible solutions for these buildings can thus contribute a significant share to the EU's CO_2 emission reduction goals.

In recent years, however, there has been insufficient interdisciplinary communication between stakeholders in the fields of cultural heritage preservation and energy efficiency. Conservation experts have expressed concerns that the implementation of energy efficiency measures would threaten the heritage value of historic buildings, while energy consultants have complained about overly restrictive building conservation authorities obstructing energy efficiency improvements.

The European research project 3ENCULT aspires to bridge the gap between cultural heritage and climate protection, using a multidisciplinary approach to develop a pool of solutions and, above all, communicating productively to find the right solution for a particular building.

Heritage preservation and energy efficiency need not be mutually exclusive aims. Conservation planned by an interdisciplinary team of experts will balance the values of energy and culture. The basic principles of 3ENCULT are subject to a balanced assessment, bringing a diversity of interests and disciplines to a project and becoming an information source for performing surveys, detecting diverse aspects, and planning to actively develop the conservation project. Developing historic buildings and their environments, balancing their cultural and energy needs, is a long-term perspective of cultural value and behaviour.

3ENCULT clearly demonstrated that cultural heritage preservation and energy efficiency go hand in hand. Many energy efficiency measures even support the preservation of the historic substance. Moisture-related structural damage and mould growth are a frequent problem in historic buildings that are subject to modern usage conditions. Energy efficiency measures such as thermal insulation, improved airtightness, and heat recovery ventilation can stop the moisture accumulation that causes structural damage. Energy efficiency measures also improve the usability of historic buildings by enhancing thermal comfort, preventing health risks, and dramatically lowering energy costs. This is a good basis for ensuring that the building will be used and maintained in the future.

Nonetheless historic buildings which undergo an energy retrofit that respects their cultural value will generally not reach the same efficiency levels as highly efficient new buildings. A frequently expressed notion is that the higher energy consumption should be compensated for by on-site use of renewable energy sources (RES) such as photovoltaic and solar thermal panels or biomass boilers – and that if renewables were to make up a sufficiently high proportion of the energy used in a historic building, energy efficiency measures could even be omitted. Approaches that limit the perspective to an individual building fail to recognise that the supply of renewable energy sources is limited and that, for example, the biomass used for heating a house will no longer be available for other purposes such as transportation. Thus if historic buildings are viewed as interconnected with a complex energy system on regional, national and international levels, it becomes clear that both energy efficiency and RES production should be optimised independently and as far as compatible with cultural heritage preservation.

This 3ENCULT handbook on energy-efficient solutions for historic buildings is intended as a support in finding optimised solutions that take into account the differing requirements of historic buildings. It combines the essence of the results of a large international project, comprising twenty-one partner organisations from many European countries, with the experience and knowledge of the experts involved, and should thus be helpful for many building owners and professionals undertaking the renovation of their specific historic building. The book starts with a general introduction to the basic principles of building physics and cultural heritage protection. After that it follows the typical sequence of a renovation project from pre-intervention analysis and general planning guidelines, to a more detailed description of technical solutions. These include new solutions developed in 3ENCULT as well as existing energy efficiency solutions for historic buildings. After the renovation has been completed, a building management system can optimise the operation of the technical systems, while a monitoring system can be used to check whether the expected improvements have been achieved. Frequently, mistakes in planning or workmanship can be identified with a monitoring system and can subsequently be rectified. The 3ENCULT handbook ends with a description of the project and the buildings in eight case studies, in which many of the technical solutions were implemented.

Reference

Troi, 2011 Troi, Alexandra, 'Historic buildings and city centres – the potential impact of conservation compatible energy refurbishment on climate protection and living conditions', int. conference *Energy Management in Cultural Heritage,* Dubrovnik, April 2011.

2 BASIC PRINCIPLES

2.1 BUILDING PHYSICS

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2.1.1 Thermal comfort

In 1970 P.O. Fanger published the ground-breaking book *Thermal Comfort* [Fanger, 1982], in which the requirements for thermal comfort were comprehensively laid down. The current international standard [ISO 7730] *Ergonomics of the thermal environment* is based on this publication in large parts.

2.1.1.1 PMV and PPD

ISO 7730 evaluates the indoor climate based on two parameters: PMV and PPD. PMV (predicted mean vote) describes the expected, mean user appraisal of the climatic conditions on a scale from +3 to −3 (+ = warm, − = cold). The maximum thermal comfort is equivalent to 0.

The abbreviation PPD (predicted percentage of dissatisfied) describes the fraction of people who are expected to feel uncomfortable i.e. who rate the indoor climate as too hot, warm, cool or cold.

Beyond the room climate itself, there are other factors that can affect PMV and PPD. They include the level of activity and the thermal insulation provided by clothing.

2.1.1.2 Local thermal comfort

PMV and PPD each describe a general sensation experienced with the whole body. However, thermal discomfort is often caused by differing climatic influences affecting different parts of the body [ISO 7730]. Such uneven indoor climate conditions typically occur in old buildings with little or no thermal insulation or heat recovery ventilation and with low levels of airtightness and include draught, large temperature differences between head and feet, as well as high or low floor temperatures. A further frequent cause of discomfort in old houses is uneven surface temperature (e.g. cold window surface on one side and warm interior walls on the other).

2.1.1.3 Thermal comfort categories

ISO 7730 defines 3 comfort categories. The highest comfort level is associated with category A, which has a PPD of <6 %. This level is frequently achieved in buildings with a high level of thermal insulation, such as passive houses, or old buildings after a deep energy retrofit. The two lower categories are B (PPD <10 %) and C (PPD <15 %).

2.1.1.4 Thermal comfort requirements

One of the objectives of modernisation work is to provide a comfortable indoor climate for the occupants. The prevention of perceptible radiant heat deprivation, draughts and cold feet is therefore essential.

In this context, it is important to limit the difference between the indoor temperature and the temperature of the surfaces enclosing the room. As long as the temperature difference between the perceived indoor temperature and the temperature of the coldest surface is no greater than 4.2 K [Feist, 1998], neither uncomfortable radiant heat deprivation, cold downdraughts nor cold-feet effects will occur. This comfort criterion, based on temperature difference, is functional and independent of climate and should therefore be observed in any case.

Since the temperature of the inner surface depends on the outside temperature, different measures have to be taken in different climates. Besides the outside temperature, the inner surface temperature depends on the thermal quality of a component, indicated by its U-value [W/(m²K)]. This results in different U-values for different climates (see Fig. 2.1). It is not possible to achieve the values shown here with old windows (only very small original old windows do not impair thermal comfort). So it is a good idea to improve the thermal properties of old windows. The benefits of such enhancement are higher comfort, less damage to the construction from condensate and mould, as well as lower energy demand, thus leading to reduced CO_2 emissions – and as an extra benefit, there is no need for a radiator below the window any more. One common solution is to keep the original window as it is and add an additional – highly efficient – window on the inside. If it is not possible to improve the window quality like this, a heat source should be provided underneath the window in order to achieve the desired comfort level.

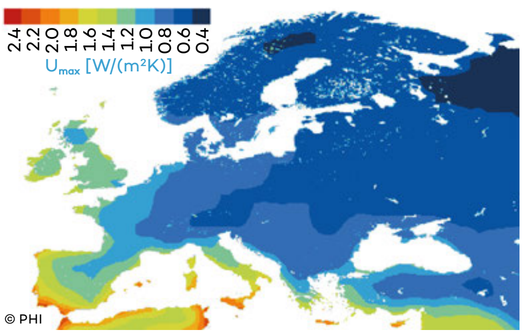

Fig. 2.1: Map of Europe with the U-values necessary for meeting comfort requirements

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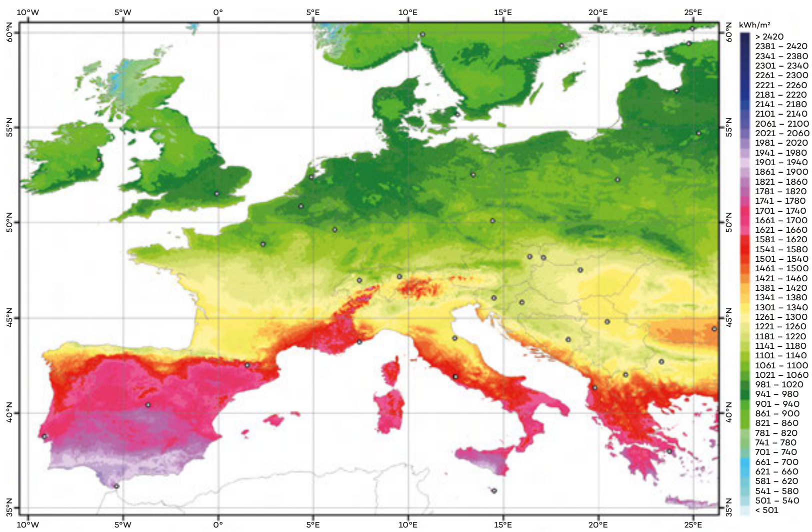
2.1.2 Climatic boundary conditions

Planning energy-efficient buildings essentially means optimising the design for the local climate conditions. The energy required to heat the very same building placed in Spain instead of Germany, for example, would be much lower. Beside the outside temperature, the deciding factors include the amount of solar radiation and the degree of humidity. The basis of every energy demand calculation is therefore the climate data.

The weather changes from year to year, which inevitably causes energy consumption to vary. In order to predict average performance, the climate data used for energy calculations should represent the typical average conditions at the building's location. Typical conditions can best be obtained from data collected over a long period. The World Meteorological Organization uses a period of at least ten years to determine average conditions, and thirty years for so-called climate 'normals' [WMO 2007]. The current standard reference period is 1961–1990, which in due course will be succeeded by the following thirty-year period: 1991–2020. As the climate does not only vary on an annual basis, but is also subject to more gradual change, it is advisable to use the most recent reference period available. The original ground-measured climate data can best be obtained from national or international meteorological institutions. There are different ways of processing such climate data, depending on the required format. Guidelines for calculation procedures are given in the ISO 15927 standard.

Worldwide climate data, processed into different formats, is available from various sources in addition to meteorological organisations. The climate data tool on the internet platform Passipedia, for example, provides worldwide climate information derived from satellite data for download in the format required for the Passive House Planning Package [PHPP]. Another popular example is the Meteonorm software, which can be used to generate and export climate data in a variety of different formats for any location on the globe. Regardless of the data source, climate data should be selected, processed and applied appropriately for the intended purpose.

Fig. 2.2: Map of Europe with the mean solar irradiation from 1986–2005



Global irradiation: long-term average 1986–2005

Averaged monthly values from the selected reference period are sufficient for a stationary energy balance, e.g. with the Passive House Planning Package [PHPP]. Such average climatic data is often provided in national regulations, though the data format varies. For Germany, for example, fifteen climate data sets are provided in DIN 4108-6/DIN V 18599-10. Similarly, the Italian standard UNI 10349 provides monthly temperature and irrradiation data for different regions within Italy. In Austria, the corresponding climate data can be downloaded for every location within the country from an online climate data tool. The PHPP contains monthly data in the required format for a large number of international locations. The data from specific locations is often used as a representative data set for the surrounding climate zone.

Greater detail, with hourly values, is needed for dynamic building simulation. Test Reference Year (TRY) or Typical Meteorological Year (TMY) data is often used. To obtain such a representative data set, containing information for each hour of the year, statistical methods are applied for each month of the year to select the most representative values of the measured data period. These individual representative months are then combined into an artificial one-year data set. Guidelines for the methodology used to generate a TRY set from measured climate data are described in [EN ISO 15927-4].

As well as being used to calculate the energy demand for heating and cooling a building, climate data is needed for dimensioning the building services appropriately. In this case, the climate data must represent suitable boundary conditions from which a building's maximum load for heating and cooling can be determined. Once again, the corresponding climate data and procedures on how they are to be applied can be found in the respective national regulations.

The thermal dynamics of a building change with higher efficiency levels, as the latter usually result in much greater inertia. Applying conventional procedures therefore often leads to oversized heating and cooling systems in highly energy-efficient buildings. This can cause unnecessarily high investment costs and suboptimal system efficiency. The Passive House Planning Package (PHPP) includes an alternative heating and cooling load calculation procedure, which is suitable for energy-efficient buildings. The required climate data is included in PHPP climate files.

2.1.3 Heat transfer

Heat is the unordered kinetic energy of atoms and molecules. There are several heat-transfer mechanisms. Common to them all is that heat is always transferred from the system at the higher temperature to the system at the lower temperature.

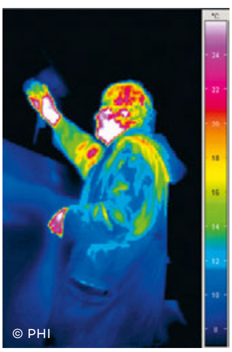


Fig. 2.3: Infrared image of a person. The skin surface has the highest temperature and thus the highest radiation. The hood and the pocket are the coldest parts with the lowest radiation.

2.1.3.1 Heat transfer mechanisms

Radiation Every object emits heat radiation. A thermographic image makes this radiation visible. In the image in Figure 2.3, the face and the hands are the warmest objects and thus have the highest radiative heat emission.

It may be surprising for many people that radiation is the most important heat-transfer mechanism in our surroundings. In a room at 21 °C, more energy is transferred as radiation between the room surfaces than by air flow. Radiation also plays an important role at exterior building surfaces. Radiative heat emission to the atmosphere – and from there to outer space – is the predominant cooling mechanism.

Heat conduction As soon as a temperature difference arises in any medium – whether it be in solid, liquid, or gaseous state – heat is transferred from the warmer to the cooler part. The principle behind heat conduction is the transfer of heat by the oscillation of particles and collisions between them. The ability of a certain material to transfer heat in this way depends on its structure and is described by the temperature-independent constant of 'thermal conductivity'. The amount of heat transferred depends directly on the temperature difference. If the temperature difference between the interior and exterior surfaces of a wall doubles, the heat loss likewise doubles.

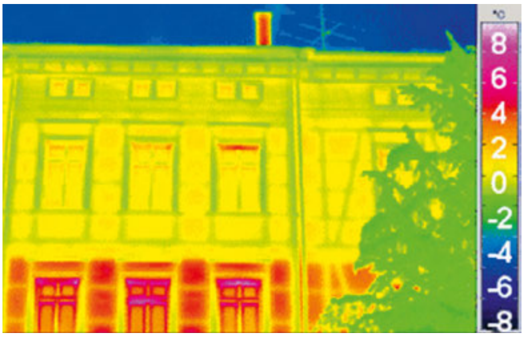


Fig. 2.4: Even a very cold object emits heat radiation. The tree in front of the house is still clearly visible at -1 to -2 °C. Even the sky emits atmospheric counter-radiation at -6 °C. The radiative heat emission of the chimney is greater than that of the rest of the building.

Convection Convection is heat transfer by the transport of particles. There are two types of convection:

→ free convection (particle flow with natural driving forces);
→ forced convection (caused by external mechanical force).

A typical example of heat transfer by forced convection is the use of heated air in a mechanical ventilation system for heating a building.

2.1.3.2 Stationary heat conduction and heat storage

The U-value is used for calculating the stationary heat conduction of a component (e.g. in the Passive House Planning Package [PHPP]). It describes the energy flow through a component per square metre and per degree temperature difference. The higher the U-value, the more heat can flow through the materials. A component with high thermal insulation has a low U-value. The U-value of a component depends on the thickness of its layers and their thermal conductivity.

Fig. 2.5: U-value calculation for an external wall in the Passive House Planning Package [PHPP]

Assembly No. 02ud — Building assembly description: Roof — Interior insulation?

Heat transfer resistance [m²K/W] — interior Rsi: 0.1 — exterior R_{se}: 0.04

	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	Chipboard	0.13					50
2.	Mineral wool	0.04	I-beam	0.374			400
3.	Gypsum plasterboard	0.7					13
4.							
5.							
6.							
7.							
8.							
	Percentage of sec. 1	98%	Percentage of sec. 2	2.0%	Percentage of sec. 3		Total 46.3 cm

U-value supplement W/(m²K) — U-Value: 0.108 W/(m²K)

The U-value only describes a steady-state heat flow through a component, i.e. under constant temperature conditions. When walls heat up or cool down, dynamic processes such as heat storage effects also occur. Temporary heat storage in walls and floors can stabilise the temperature in a room and can thus reduce the amount of energy used for heating or cooling. Different materials have different heat storage capacities.

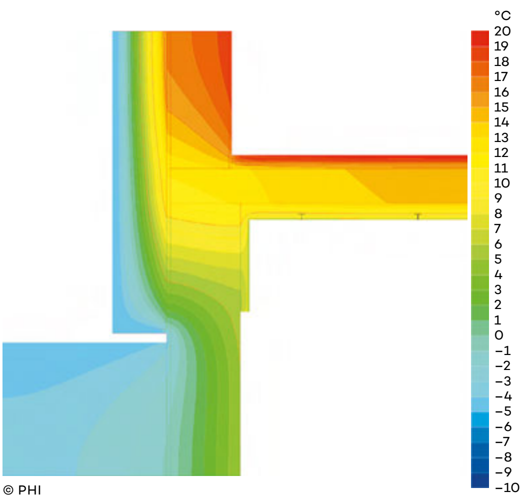
Long-term experience and the results of detailed dynamic simulations have shown that reducing heat loss by adding thermal insulation is far more important for reducing the heating demand than exploiting the heat storage capacity of the building is [Feist, 2000]. There is a simple explanation for this: Heat storage is a dynamic process that can only be used effectively if the stored heat is fed back into the room when it is needed at a later time. A solid wall without insulation absorbs heat from both sides on a sunny winter day and stores it. At night the exterior temperatures fall and the wall emits the stored heat to the surroundings. The interior space does not profit from this. The uncontrolled emission of stored heat is the main drawback of heat storage. Only by applying thermal insulation, which prevents heat from being lost to the exterior, can the storage capacity be used effectively.

2.1.3.3 Thermal bridges

Thermal bridges occur at the point of connection between two building components (structural thermal bridge) or – for example – in the wall at the corner of a building (geometric thermal bridge). Owing to the multi-dimensional geometry of the connection detail, the heat loss cannot be calculated on the basis of the U-value. The real heat flow can be determined by using two or three-dimensional thermal bridge software. The difference between the heat flow at a thermal bridge and the heat flow through the adjacent, uninterrupted, regular components is described by the thermal bridge heat loss coefficient, or Ψ-value. The heat losses at thermal bridges are frequently higher than in uninterrupted constructions. If this is the case, the Ψ-value is a positive number.

In new buildings, thermal bridges with high heat losses should – and can – be avoided. When old buildings are refurbished and insulated, a number of unavoidable thermal bridges usually remain. These include the basement walls that interrupt the basement ceiling insulation. When planning a refurbishment project, thermal bridges should be thoroughly investigated. Besides high heat losses, thermal bridges can also cause very low interior surface temperatures, which can lead to condensation and mould growth. If these problems are detected early enough by means of thermal-bridge calculations, countermeasures such as flanking insulation can be implemented (see Fig. 2.6). Most thermal-bridge problems can be solved by adding external insulation.

Fig. 2.6: Isothermal image from a thermal-bridge calculation of the junction between exterior wall and basement ceiling. Thermal-bridge effects have been mitigated by flanking insulation, resulting in even interior surface temperatures with no risk of condensation and mould growth.



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2.1.4 Air exchange

2.1.4.1 Indoor air contamination

As a result of increased comfort and energy efficiency standards, new buildings are more airtight than in the past. During energy retrofits of old buildings, airtightness should be improved too. A better level of airtightness always goes hand in hand with a ventilation plan – preferably the installation of a ventilation system with mechanical heat recovery. If this is disregarded, potentially harmful pollutants may not be vented off sufficiently. Moreover, if the moisture load produced by the occupants is not vented off, a very high relative humidity may result, increasing the risk of mould growth at thermal bridges. At a relative humidity of 60 %, mould growth can occur at surface temperatures of not above 15.5 °C. Such surface temperatures frequently occur inside old buildings with little or no insulation.

2.1.4.2 Sufficient air flow volumes

There are three main requirements for the air-change rates in buildings:

→ The supply air flow volume should be sufficient to vent off humidity, CO_2 and odours produced by the occupants. An air flow volume of 20–30 m³/h per person is recommended for this.
→ Air contamination, odours and humidity emitted in extract air rooms should be carried off by a sufficient extract air volume flow. Recommendations range from 40–60 m³/h for kitchens to 40 m³/h for bathrooms with showers or tubs and 20 m³/h for toilet rooms.
→ Independently of the number of occupants, a minimum air change rate of 0.3 1/h should be ensured at all times, in order to vent off background contamination and odours emitted by furniture, construction materials, laundry etc. In old buildings without any new furniture or building materials, the background contamination might be low, hence an air change rate of 0.2 1/h might be sufficient as a minimum.

The above recommendations should not be exceeded. Otherwise overly dry air may result during the heating period, with potential negative effects on the health of sensitive occupants.

2.1.4.3 Ventilation heat losses

Ventilation heat losses can be caused by free ventilation due to leakage and opened windows, as well as by controlled ventilation via a mechanical ventilation system. The heat losses from free ventilation cannot be determined exactly as a rule, because they depend on many unknown factors, such as user behaviour.

Ventilation through leakage is common in old buildings with low airtightness. However, as the air change rate can vary widely depending on the current wind and temperature conditions, these cannot be relied upon to ensure good air quality. Moreover, draughts may impair thermal comfort. Heat losses due to leakage ventilation can range from 20 to 50 kWh/m²a in old buildings.

Fig. 2.7: Installation of a heat recovery ventilation system in a retrofitted building. The white box is the ventilation unit with fans, filters and the heat exchanger. Visible at the top right are sound absorbers that eliminate any fan noise.

If airtightness is improved during an energy retrofit, periodic full opening of windows at least four times a day is recommended for sufficient air quality and prevention of mould growth. Partly opening windows over a longer period of time will lead to higher ventilation heat losses than fully opening the windows for approx. five minutes – while having the same effects on the air quality. At night (and during the daytime for working people) an adequate air exchange cannot be achieved via window ventilation.

Ventilation heat losses can be reduced dramatically (up to 90 %) by installing a mechanical heat recovery ventilation system. At the same time, comfort is improved because the supply air is preheated by the heat recovery. Additionally the occupants don't have to bother about opening the windows any more. Special systems adapted to the spatial constraints in old buildings are available. Efficient systems can save more than ten times the energy that is needed for operating the fans. However, a relatively airtight building envelope is a prerequisite for this.

2.1.5 Prevention of moisture-induced damage

The most frequent contributor to structural damage is inadequate protection against moisture. Thus the most important rules for healthy indoor conditions and the preservation of the building fabric are: design dry, build dry and keep the building dry!

Fig. 2.8: Slates as protection against driving rain on the windward side of a traditional German half-timbered house

Unwanted moisture accumulation can have several sources. These include water from the construction process, such as that from cement screeds. Also, large amounts of water can enter the construction if there is no adequate protection against driving rain. Another frequent cause of moist walls in old buildings without a horizontal damp-proof barrier is rising damp from the ground. Finally, the indoor air contains water vapour that can enter the construction by diffusion or convection.

2.1.5.1 Moisture storage mechanisms

Most construction materials have pores that can fill with water. The water is absorbed in three steps. At first water molecules accumulate at the pore wall in a process called 'sorption'. Secondly, smaller pores fill with water by capillary condensation. Only if the material is under water or below the dew point for a longer period of time will the pores fill with water completely. Besides driving rain and rising damp, sorption of water vapour from the indoor air is the main humidity source.

2.1.5.2 Moisture transport mechanisms

Of relevance for buildings is the transport of water in the liquid and gaseous states: Liquid water can be transported through solid building materials by capillary effects, amongst others.

The transport of water vapour molecules through solid construction materials is called 'diffusion'. Different construction materials obstruct the diffusion flow to different extents.

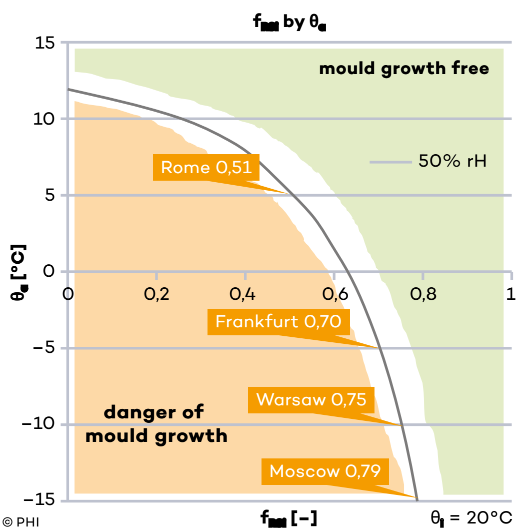
The transport of water vapour (mixed with air) as a result of pressure differences is called 'convection'. Water accumulation in the construction by this mechanism is only possible if there are leaks (gaps or holes) through which the air can flow. Condensation can occur when humid indoor air passes through exterior parts of construction elements at lower temperatures. Generally, the amount of water that can enter a construction by convection is dramatically higher than that entering by diffusion. That is why a high level of airtightness on the interior face of the building envelope (in cool-to-temperate climates, please note, because the location of the airtight layer varies depending on the climate zone) is indispensable for prevention of moisture-induced damage.

A vapour barrier is a membrane or board that has a high level of diffusion resistance. It thus prevents significant amounts of water vapour entering the construction. The vapour barrier should be installed in an airtight manner so that it simultaneously prevents convective vapour transport.

Sometimes, a water vapour-permeable airtightness layer is installed in combination with interior insulation materials with a high capacity for capillary water transport, such as cellulose fibres or calcium silicate. Such constructions can have higher tolerance for accidental water inflow from driving rain.

A third variant is humidity-adaptive vapour-retarders which display variable diffusion-resistance, depending on the relative humidity in their immediate surroundings. During the heating season the relative humidity is generally lower, thus the level of resistance to vapour diffusion increases and less vapour from the indoor air can enter the construction. In summer the relative humidity rises, causing the membrane to open up and allow the construction to dry out on the side open to the room. Humidity-adaptive vapour-retarders can increase the tolerance for unplanned moisture loads (e.g. caused by faulty workmanship) for some constructions. A specialist should be consulted in order to find out whether the use of such membranes makes sense in a given construction.

Fig. 2.9: Temperature factor (f_{RSi}) plotted against design ambient temperature (Θ_a)



2.1.5.3 Hygiene requirement

If there is too much moisture, mould can appear. For reasons of hygiene and to prevent damage to the original substance, conditions that encourage the growth of mould should be avoided. This can be achieved if the moisture level in the pores of a material or at the surface is kept under 80 % relative humidity. Because the relative humidity varies depending on the temperature, the temperature of the interior surface is crucial. An indicator [EN ISO 13788] for the temperature and simultaneously for the hygiene criterion is the temperature factor f_{RSi}. It describes the relationship between the ambient temperature and the interior surface temperature at a thermal bridge. The interior surface temperature depends on the ambient temperature and thus the 'minimum mould-free temperature factor' is climate-dependent. Figure 2.9 shows the temperature factor for mould-free conditions plotted against the design ambient temperature and the required factors for some European cities. Of course, this criterion is valid for walls and thermal bridges, too, but the coldest point on the inner surface of a window is, in most cases, the glass edge. Because of that, 'warm-edge spacers' are recommended for European climates.

2.1.5.4 Does a new condensation problem arise at the wall, if the window is no longer the coldest surface of the room?

The clear answer to this question is NO! This is why:

The thermal quality of the building envelope can be enhanced by adding insulation (internal or external) to the wall and/or by new or improved windows. In some cases, only the window quality is enhanced (for reasons of conservation or cost), whereas the wall is kept in its original state. The question raised above is frequently asked, because the incidence of moisture problems in building enclosures increases after the replacement or enhancement of windows. A misunderstanding of building physics had led to the statement that 'The window should remain the coldest surface within a room'. To answer this question, let us examine the situation before and after the replacement (or improvement) of windows:

In old buildings before renovation, single glazing (U-Value 4.8 W/m²K) or double glazing (U-value 2.2–2.6 W/m²K) without low-e coating and gas filling represent the coldest surface of the external envelope, which is in the range of 1.2 to 1.9 W/m²K in the case of old walls. In old buildings, the heating system generally comprised individual stoves, which created negative pressure within the building by exhausting the combustion air up chimneys. This way, dry ambient air is drawn into the building via gaps, openings and cracks within the building envelope throughout the heating season. Visible condensation on the windows often alerted occupants to the need for ventilation to remove interior moisture (so they opened the windows).

After renovation with new or enhanced windows, both the thermal quality and the airtightness of the window is higher. Consequently, the surface temperature of the glazing and frame (if both are enhanced) is higher than before. The risk of condensation at the window is reduced if the indoor air humidity is controlled by ventilation (mechanical or window ventilation). In many cases the heating system is changed from individual stoves to central hydraulic heating, thus eliminating the effect of negative pressure. If no controlled ventilation system is installed and the occupants ventilate rooms through windows in the same way as before, higher indoor air humidity will result. Owing to the higher surface temperature of the enhanced windows, no condensation is apparent at the glazing to remind people to open the window. The high surface humidity at the wall is invisible because of the sorption at its surface, but the long-term consequence is mould growth.

The two coupled, but contrary, effects – namely enhanced airtightness and higher surface temperatures – should be kept in mind when changing or enhancing windows in old buildings.

An adequate ventilation rate for dehumidification during the heating season must be guaranteed to avoid condensation at the walls and especially at potential thermal bridges.

The indoor air humidity has to be controlled by means of measurement rather than the original 'warning system' of noticing condensate at the glazing. Electronic humidity measurement is very cheap today and can easily be combined with an alert function.

Any changes made to the windows should avoid creating new thermal bridges; using single or compound windows instead of box-type windows will cause greater thermal bridge effects if no additional insulation is applied at the window reveals.

To think that condensation on the glazing reduces the indoor air humidity is to misunderstand building physics. This is only the case if the condensate is then removed. In general, however, the condensate trickles down and evaporates again, resulting in no change of the water content. Even if the condensate is wiped off, the amount of water removed is negligible and produces almost no change of indoor air humidity. In the case of residential buildings, a ventilation rate of at least 25 to 30 m^3/h per person is necessary for dehumidification.

The critical parts of the building envelope in terms of moisture problems are (after thermal enhancement of the windows) the remaining thermal bridges. The surface temperature of those regions should be kept above 12.6 °C (in the case of 50 % R.H.) or 15.5 °C (in the case of 60 % R.H.). As this is generally not possible if the old wall has been kept without adding any insulation, a controlled ventilation system is necessary to avoid severe mould growth. Even concentrated intermittent and cross-ventilation twice a day is not sufficient, as has been shown by [Feist, 2003] and [Feist, 2004]. The problem becomes even worse at lower air temperatures.

To sum up, it can be said that it is permissible for the thermal quality of the window to be better than that of the wall, but the regulation of indoor air humidity by ventilation is essential.

2.1.6 Daylighting

Good daylighting in interior spaces is important for proper visual perception of colour, contrast and detail. Beyond this, sufficient daylighting has a great impact on physical and mental well-being. Researchers report increased motivation, a stronger immune system and better coping with stress amongst other positive effects.

From an energy point of view, a high level of daylighting can reduce the amount of electricity used for artificial lighting.

Fig. 2.10: 'Expost' office refurbishment project, Bolzano. Angled window reveals serve as an architectural design element while keeping good daylighting and unobstructed views to the outside despite thick exterior insulation.

2.1.6.1 The daylight factor

The daylight factor describes how well a specific point in an indoor space is lit by daylight. It gives the relation between the natural illumination level of this point to the unshaded outdoor illumination level, as measured under overcast sky conditions (diffuse light). The following factors can influence the daylight factor:

→ window height: The upper edge of the visible window glazing should be as high as possible (best without window lintel). This has a significant impact on the daylighting level;
→ window width;
→ shading by window reveals and overhangs as well as nearby buildings and trees;
→ the luminous transmission of the glazing;
→ dirt on the glazing;
→ the relation of visible glazing to the window frame area;
→ room geometry;
→ reflectivity of surfaces.

2.1.6.2 Influence of energy retrofits on the daylight factor

The level of daylighting can be impaired if this aspect is not considered in an energy retrofit.

Shading by exterior insulation The window reveal and lintel depth is increased when exterior insulation is added, leading to decreased daylight irradiation. 25 cm of exterior insulation can lower the daylight factor by 15 % or more, depending on the window size. An easy countermeasure is to cut the insulation to a wider angle at the reveal and lintel. In the above example with 25 cm of insulation, the decrease in the daylight factor can be minimised to 4 % if the reveal angle is changed to 45° [Werner et al., 2012]. As an additional measure, white or metallic window sills are very effective at reflecting daylight into the room.

Glazing Replacing old single or double-pane windows with modern triple-pane low-e glazing saves energy and improves comfort, but as a side-effect the additional glass panes and low-e coatings reduce the transmission of visual light. In the last years, however, significant technological advances have been made by glazing manufacturers. Low-e triple glazing with the same luminous transmission index as conventional double glazing can now be produced with the help of antireflection coatings on the glass surfaces. An enhancement can also be achieved by daylight redirection elements (such as lamellae or prisms) integrated into the glazing (see Section 5.3).

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2.2 ECONOMIC ASSESSMENT OF ENERGY EFFICIENCY

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2.2.1 Introduction

The overall longevity of buildings implies that short payback periods cannot be expected; the economic assessment of buildings has to be based on life cycle costs. There are many methodological frameworks that fit more or less in this scheme: however not all methods fulfil the requirement of reflecting the whole economic picture. Furthermore, boundary conditions are as important as the method. Inadequate methods, assumptions or boundary conditions are the most important cause of extremely different results of empiric studies. The net effect of these influences is usually that the estimated economic saving is lower than the real saving, which creates a strong disincentive to the implementation of energy efficiency.

2.2.2 Investment theory

When investing in buildings, the whole life cycle and the interest should be taken into account. This approach is implemented in dynamic methods based on present values. In theory, economic activities are aimed at generating profit. Expenditure is made to achieve benefits that then become market commodities, and investments are made to yield revenues from commodities sold on the market. The goal of the investor is to achieve an economic advantage: an investment should be at least as attractive as its alternatives that are available on the capital market. Surpluses are gains when they are higher than those for an alternative, economically comparable, capital asset. For energy efficiency investment, the revenues consist of savings in operational (especially energy) costs and the benchmark is the return for comparable capital assets, or the interest on the loan.

The present value (or cash value) of a payment is the amount you need to save 'now' in order to pay 'later', when the expenditure (or revenue) occurs. Since the present values refer to the same point in time, all receipts and expenditures become comparable, but the result depends on the discount rate. High expected rates of return depreciate later revenues, thus the upfront investments. Therefore, the choice of an adequate interest rate is important.

The net present value (NPV) is the sum of all present values: costs (or payments, e.g. the investment) are negative, and revenues are positive. The NPV is the total gain of the investment when all lifetime costs and revenues are included. Therefore, a non-negative NPV means that the investment is profitable. As long as capital (including loans) is available, it is financially profitable to make any investment down to an NPV of 0.

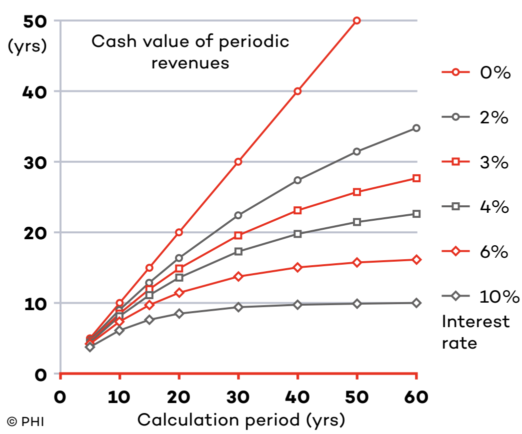

Fig. 2.11: Cash value (or present value) of periodic revenues r (in the table: scaled to a revenue of r=1 every year). The cash value depends on the number of periods and the interest rate. High interest rates depreciate the value of the revenues and thus of the market capitalisation

While our main focus is on the investment's object, investors may have a different point of view (equity perspective). Methods like the Discounted Cash Flow (DCF) or the Visualization of Financial Implications (VoFI's) are used to optimise financing, taxation, or liquidity aspects.

2.2.3 Influencing factors: methods, boundary conditions, distortions

As long as the boundary conditions and perspectives are the same, the above mentioned dynamic methods lead to the same economic result, but they are very sensitive to the assumptions for the boundary conditions. Special attention has to be paid to all estimates of future data; in uncertain cases, sensitivity analyses shed light on the possible range of results. Otherwise, the economic assessment may be severely distorted. In particular, it is necessary to look at:

- → Proper attribution of investment costs: only (additional) investments that serve energy efficiency may be taken into account in the economic analysis;
- → Life cycle of the measures;
- → Residual values must be taken into account at the end of the calculation period;
- → Interest (discount) rates;
- → Maintenance costs;
- → Taxes and subsidies / incentives;
- → Future energy prices and price increases: assumptions about a constant rate of growth may lead to unrealistically high energy prices;
- → Does the measure fit within the normal renewal cycle, when minimal capital costs are achieved? Otherwise, a residual depreciation of the existing component has to be added;
- → Efficiency levels of existing components: existing medium quality measures reduce the potential for further energy savings and thus the revenue of any additional energy efficiency investment.

One of the most prominent distortions results from the frequent expectation of unrealistically high returns, which are the calculated interest rates in the dynamic economic assessment. High interest rates depreciate the capital-

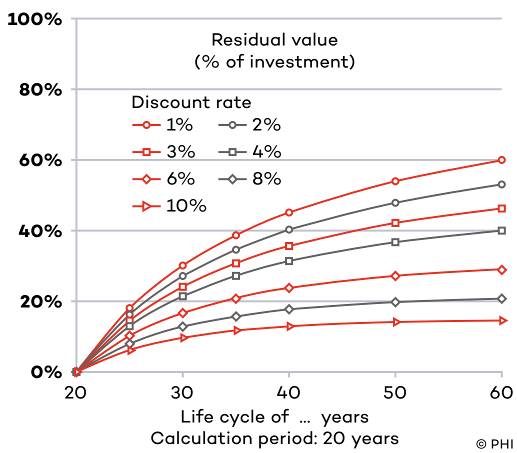

Fig. 2.12: Residual values for a calculation period of 20 years, depending on the discount rate. Residual values of the investment have to be regarded when the calculation period is shorter than the life cycle of the measure.

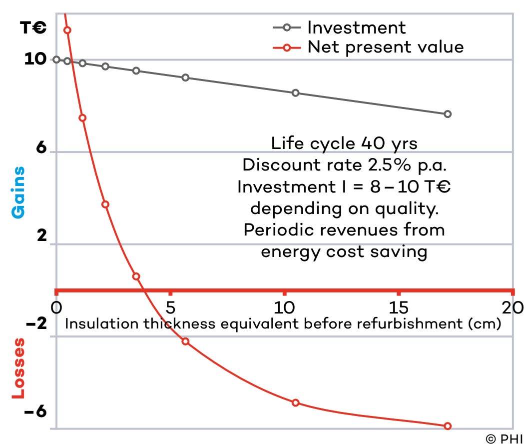

Fig. 2.13: Net present value dependent on energy efficiency standard before retrofit (here: wall insulation thickness equivalent). Medium quality reduces the revenues of the investment and turns possible profits (left side) into losses (negative, NPV, right side), thus creating a barrier to future energy efficiency investments. Therefore: 'when you do it, do it right' [EuroPHit].

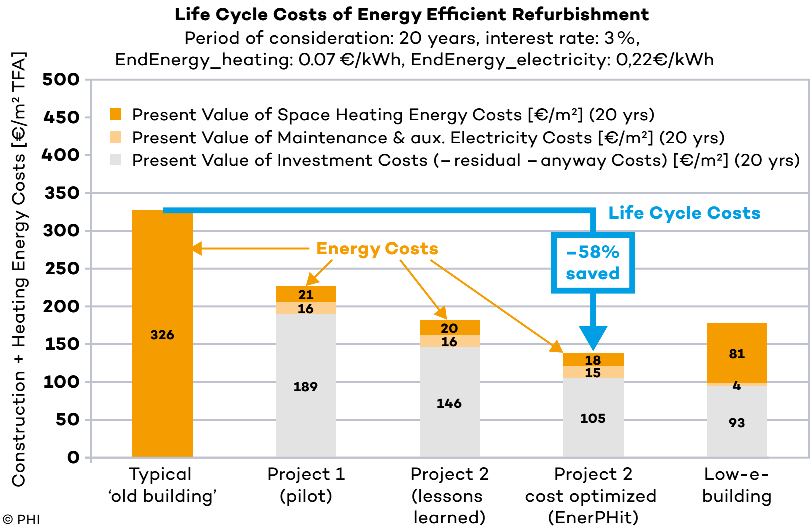

Fig. 2.14: Comparison of life cycle costs of renovation: a real case. The built EnerPHit variant [IEA 37] was cost optimal. Since 2008 the prices of Passive House components have dropped and refurbishment with Passive House components now looks even more advantageous. Shown costs = total energy-relevant costs over 20 years. The concept of cost optimality ('cost optimal level') based on life cycle costs has also become a major element of the Energy Performance of Buildings Directive.

isation of the revenues, but on the capital market, they are coupled with high risks. Investments can only be compared at the same risk level. Therefore, high-risk investments are not comparable alternatives to low-risk (or even risk-reducing) energy-saving investments [AkkP 42, 2013]. They should be compared with risk-free investments on the market. Usually, national bonds are considered to be risk free.

2.2.4 Evaluation of building and retrofit projects

A solid basis for all cost evaluations is provided by well documented retrofit projects, including the achieved savings and a thorough analysis of the investment costs for all building components. However, one key issue concerns separating extra costs for energy efficiency from the usual retrofit investment ('anyhow') costs. A comparison of projects by GAG in Ludwigshafen is shown in Figure 2.14. Retrofitting with Passive House components is highly profitable.

2.2.5 Cost optimality

According to the European EPBD, minimum requirements to be defined by the member states have to meet the 'cost-optimal level'. The economic criterion is the reference to life cycle costs for both new and retrofitted buildings and components. Passive House components for renovation projects are economically optimal when evaluated on the basis of correct life cycle costs. For such renovations, the 'EnerPHit' label was established. Depending mainly on the building conditions before refurbishment, high economic gain may lead to an extremely good rate of return with a low risk investment. In the case of cultural heritage, internal insulation is often applied. Due to thermal bridges and lost space, the optimal range for these is located at lower insulation thicknesses (see Fig. 2.15).

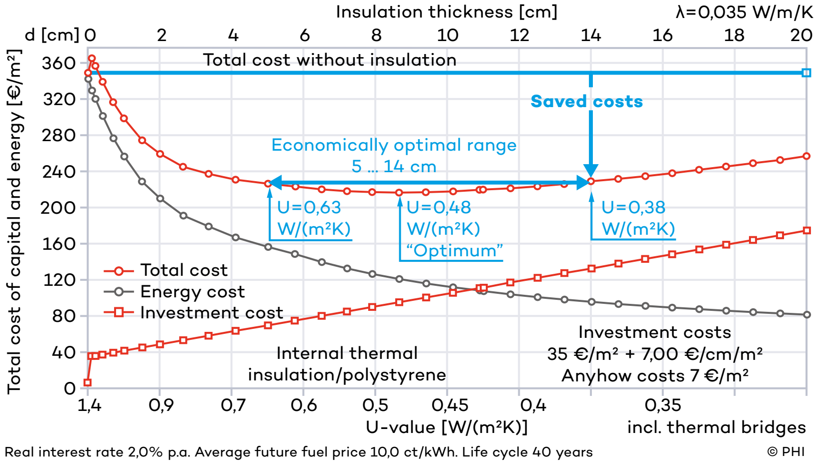

Fig. 2.15: Capital, energy and life cycle costs for energy efficiency measures depending on the quality (insulation thickness). While typically the cost optimum for Central European climate lies in the range of 0.15 W/(m²K), for internal insulation (refurbishment) the cost optimal range is lower. Lost rent for space is regarded as additional capital cost. The increased value of use because of improved thermal comfort is not assessed in this analysis. Combined with the energy retrofit of other components, factor 4 is often achievable, even with interior insulation [AkkP 32, 2005].

Cost optimality curves are usually flat; therefore very low additional efficiency investments fall within the uncertainty range with respect to cost optimality – but they reduce risk and provide cheap insurance against energy shortages and price rises.

The results may differ according to the location with its specific climatic conditions. This also applies to the cost optimal levels of components. PHI has analysed this relationship in detail in a global study [Schnieders et al., 2012], concluding that this principle always leads to a very low energy demand.

2.2.6 Incentives for energy efficiency

In the building sector, large capital is needed for investments, which in many cases cannot be covered by equity. Therefore, loans are often needed, with more or less attractive conditions and collaterals. Public financial support and incentives can help to overcome financial barriers. When an investment is not profitable on the basis of life cycle costs, especially in the case of cultural heritage, or in markets that are new to energy efficiency, a subsidy can make it economically feasible. This can be used to influence the market in an effective way: incentives should aim to support an effective and sustainable reduction of energy demand and carbon emissions, and to guarantee a good performance by means of quality assurance requirements.

If energy saving investments are already economically viable, public financial support should avoid contributing to high prices. Instead, financial aids should focus on:

→ improving liquidity and reducing the financial burden;
→ supporting collateral to facilitate access to attractive bank credits;
→ binding financial support for quality-assured design and guaranteed high performance.

One example is the German KfW loan programme (see Fig. 2.16).

Along with quality-assurance measures for achieving the goals, it can be shown that public financial support for energy efficiency measures also has

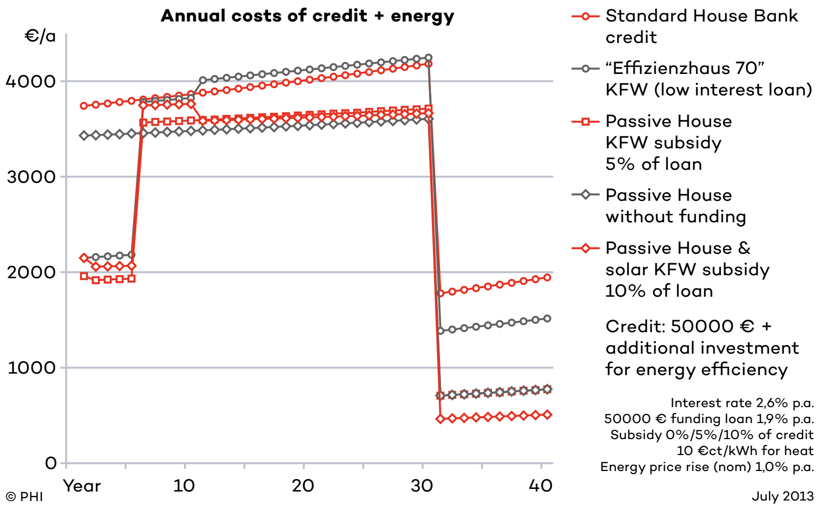

Fig. 2.16: The low interest loans from the KfW for energy efficient new and retrofitted buildings are coupled with direct subsidies depending on the energy efficiency level. The graph shows the cost advantage for passive houses with and without funding by the KfW, for every year starting with the investment. While in the long run, after the repayment of the loan, the energy savings are the reason for the good financial results, the low interest loan diminishes costs in the first years and results in better liquidity.

net positive effects for the state and the community, because the direct and indirect taxes and the savings in unemployment payments are higher than the incentive grants.

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2.3 CULTURAL HERITAGE

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2.3.1 Cultural heritage

Cultural heritage is a complex set of qualities with significance for individuals, communities, and society as a whole. It cannot be solely defined by physical values; it addresses senses and memory and includes tangible and intangible qualities. Historic buildings and cultural heritage are material and social constructs, expression of identity, economic benefits, and they represent cultural values. It is the responsibility of public and private owners to invest in appropriate craftsmanship and maintenance.

Cultural heritage is both a local and a global concern. Thus the concern for heritage requires a mode of engagement that involves continuity and change. Practical assessment from the standpoint of craftsmanship and history may be augmented by theoretical methods and standardised guidelines when it comes to deciding on a building's universal and local value.

The World Heritage Convention of 1972, United Nations Educational, Scientific and Cultural Organization (UNESCO), defines cultural heritage as follows:

monuments: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science;

groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science;

sites: works of man or the combined works of nature and of man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological points of view.'

Cultural heritage has gradually come to include new categories. It consists of the tangible qualities of artefacts, buildings and landscapes, and the intangible qualities of value systems, traditions, and oral history. This is perceived in cultural expressions through traditional skills and technologies, religious ceremonies, performing arts, and storytelling. Tangible heritage and intangible heritage are inseparable and included in all aspects of conservation.

Tangible heritage includes buildings, historic places, monuments, artefacts, etc. The preservation of heritage recognises and values history, the story of which is told by material, objects, and man-made constructions. Tangible heritage is an actual source of memory, making it literally possible to touch the past. This may, however, increase the risk of damage to places and objects as they become known, attractive, and overexposed. In reality all artefacts are in a constant state of change, that is, being altered and worn-out. Unless they are preserved, they risk being lost. With each generation, materials, objects, and man-made constructions change.

Intangible heritage is the non-physical aspects of culture and includes value systems, traditions, and social behaviour and its rules.

2.3.2 Basic declarations

Definitions of the modern understanding of cultural heritage are found in international agreements and declarations. The following quotes from the International Council on Monuments and Sites (ICOMOS), UNESCO, and the United Nations are official sources of the concept and definition of cultural heritage. They also reflect the changes in values, methods, and the significance of history, heritage, and architectural quality.

The Venice Charter, ICOMOS, 1964 The Venice Charter for the Conservation and Restoration of Monuments and Sites is the original and most important source of principles guiding to the preservation and restoration of historic buildings. It is a rich definition of cultural heritage that pays special attention to the concept of authenticity:

'Imbued with a message from the past, the historic monuments of generations of people remain to the present day as living witnesses of their age-old traditions. People are becoming more and more conscious of the unity of human values and regard ancient monuments as a common heritage. The common responsibility to safeguard them for future generations is recognized. It is our duty to hand them on in the full richness of their authenticity.'

World Heritage Convention, UNESCO, 1972 The World Heritage Convention 1972 links the concepts of nature conservation and the preservation of cultural properties in a single document. The convention recognises interaction with nature, the need to see the relationship between environment and culture, and the fundamental need to preserve a balance:

'Noting that the cultural heritage and the natural heritage are increasingly threatened with destruction not only by the traditional causes of decay, but also by changing social and economic conditions which aggravate the situation with even more formidable phenomena of damage or destruction.'

The Nara Document on Authenticity, ICOMOS, 1994 Using a different concept and value of time and heritage, the Nara Document broadens the definition of authenticity of cultural properties:

'We also wish to acknowledge the value of the framework for discussion provided by the World Heritage Committee's desire to apply the test of authenticity in ways which accord full respect to the social and cultural values of all societies, in examining the outstanding universal value of cultural properties proposed for the World Heritage.'

The Krakow Charter, ICOMOS, 2000 Referring to the Charter of Venice, the Krakow Charter states the plurality of heritage:

'... identities, in an ever more extensive context, are becoming characterised and more distinct. Europe today is characterised by a cultural diversity and thus by the plurality of fundamental values related to the mobile, immobile and intellectual heritage, the different meanings associated with it and consequently also conflicts of interest. This obliges all those responsible for safeguarding cultural heritage to become increasingly attentive to the problems and choices they need to face in pursuing their objectives.'

2.3.3 Heritage and legislation

Diverse interests and disciplines are involved with cultural heritage. In addition to the physical and natural context, it is important to acknowledge the interest of the stakeholders in the process to make it possible to find, claim, and acknowledge interests and rights, which in turn affect the cultural heritage. There are basic principles for the legal context of cultural heritage, and legislation guarantees the right to claim recognition and interests, whether the heritage is of public or individual character. Cultural heritage is secured by international conventions, national law, regional regulations, and as definitions based on findings and claims of individual interests.

World Heritage Convention	UNESCO
National and Regional Listing	National and Regional Law
Local Value	Local Regulations
Interests of Fund and Legacy	Private Property
Private Integrity	Owner and Authorship

The value of cultural heritage exceeds general means of calculation. Tangible and intangible, it may include change and have an effect on energy use within the given conditions of cultural heritage. Cultural heritage includes behaviour, function, and process of maintenance; it is of concern for the programme, process, and the possibility of change.

2.3.4 Conservation principles

Conservation principles are the lines of reasoning, methods, and tools used to meet the demands of change, theories, and diverse actions required to maintain cultural heritage. The principles include work processes that cover historical material, objects and constructions. The following definitions of the major processes involved in safeguarding heritage display are a broad representation of methodologies consistent with the ICOMOS Burra Charter for the conservation of places of historic significance. It presents a diversity of approaches to theory and arguments, and active interventions. Added to these principles are definitions of Reversibility, Authenticity and Integrity as by 3ENCULT.

Conservation This is an overall concept for cultural heritage. It encompasses all aspects of protecting a site or remains so as to retain their cultural significance. It includes maintenance and may, depending on the importance of the cultural artefact and related circumstances, involve preservation, restoration, reconstruction, or adaptation, or any combination of these. [ICOMOS Burra Charter]

Preservation Maintaining the fabric of a place in its existing state and retarding deterioration. Preservation is an appropriate concept where the existing fabric itself constitutes evidence of specific cultural significance, or where insufficient evidence is available to allow other conservation processes to be carried out. Preservation is limited to the protection, maintenance, and, where necessary, stabilisation of the existing fabric. [ICOMOS Burra Charter]

Restoration Returning the existing fabric of a place to a known earlier state by removing accretions or reassembling existing components without introducing new materials. It is appropriate only (a) if there is sufficient evidence of the earlier state of the fabric, and (b) if returning the fabric to that state reveals the significance of the place and does not destroy other parts of the fabric. [ICOMOS Burra Charter]

Reconstruction Returning a place to a known earlier state, as nearly as possible. It is distinguished by the introduction of materials (new or old) into the fabric. Reconstruction is appropriate only where a place is incomplete through damage or alteration and could not otherwise survive. Reconstruction is limited to the completion of a depleted entity and should not constitute the majority of the fabric. [ICOMOS Burra Charter]

Adaptation Modifying a place for compatible use. It is acceptable where the adaptation does not substantially detract from its cultural significance and may be essential if a site is to be economically viable. [ICOMOS Burra Charter]

Maintenance The continuous protective care of the fabric, contents, and setting of a place. Maintenance is to be distinguished from repair, which involves restoration or reconstruction. [ICOMOS Burra Charter]

Balance of energy and culture In addition to the principles above, conservation will include the balance of energy and culture, the physical qualities of comfort of behaviour. Thus the balanced program of energy can be a resource to a dynamic living culture. [ICOMOS Burra Charter]

Reversibility Unavoidable changes that may be detrimental to the significance of a building should whenever possible be fully reversible. Adoption of this principle means that even if the significance is temporarily obscured, the historic fabric can be returned to its original state without damage after the lifetime of the relevant addition has expired. [3ENCULT, 2011]

Authenticity By respecting the history and fabric of a building, its authenticity can be safeguarded. This implies that:

→ all new work should appear as of its time (but it is nevertheless recommended that it should be subservient to the old)

- → all past phases of the building's history should be allowed to be clearly read
- → speculative restoration should be avoided (although it may be justified where clear documentary and / or physical evidence of previous form is available)
- → nothing important to the significance should be removed [3ENCULT, 2011].

Integrity Integrity is a measure of the wholeness and intactness of the natural and / or cultural heritage and its attributes, as stated by ICOMOS in Tallinn 2010.

Any works that would affect the character of the building or have a material or visual impact should be carefully considered. In specific cases, relaxation of requirements may be acceptable to the local building control authority, if it can be shown to be necessary in order to preserve the architectural integrity of the particular building. [Energy Efficiency in Traditional Buildings, Ireland, 2010]

2.3.5 Cultural heritage practice

In addition to international theories and guidelines, national strategies are developed. These strategies clearly demonstrate the need for support and guidance that characterises the practical application of energy and cultural heritage.

Irish Guidelines (Ireland 2010) The Irish Guidelines refer to embodied energy and whole-life costing. When describing case studies, three kinds of assessment are distinguished: energy assessment, conservation assessment, and lifecycle assessment.

'... upgrading the thermal efficiency of the existing building stock is a challenge, particularly where the building was built using traditional materials and construction methods and it is of architectural or historical interest.'

Save and Preserve (Swedish Energy Agency 2006) The goal of the research programme of the Swedish Energy Agency is to develop and disseminate information and technology solutions contributing to improvements in the energy efficiency of cultural heritage buildings. It declares that:

'Balancing the needs of heritage preservation and energy conservation is a challenge for decision-makers in the cultural heritage field. Making sustainable solutions requires an interdisciplinary approach and the use of research results from different fields such as energy engineering, building physics and conservation science. Save and Preserve contains bibliographic records on articles and books dealing with energy efficiency in historic buildings.'

English Guidelines (English Heritage 2011) The English Guidelines for cultural heritage focus on quality, comfort, and economy. They address the single case as well as they lift the guidelines to a strategic vision of public interest.

'Improving the energy efficiency of your home, whether it's listed, in a conservation area or pre-1919, can be done sympathetically and without compromising its historic character. Many energy conservation improvements can be carried out to older buildings, often at a relatively low cost, significantly enhancing the comfort of the building for its users, as well as providing savings on fuel bills. Such improvements can also help in meeting the government's greenhouse gas emission reduction targets.'

2.3.6 Cultural heritage and energy

The combination of culture and energy is a resource for conservation. It generates visionary theories and concrete actions. To meet the challenges of the environment and the climate by balancing energy needs and cultural needs, ICOMOS has formed the International Specialist Committee on Energy and Sustainability (ISCES).

As with 3ENCULT, the aim of ICOMOS is to bring energy and sustainability into the cultural heritage dialogue.

To meet needs and to identify and maintain continuity, the international community is aware of heritage principles as potential dynamic of information and technology, as comprehensive concepts of energy and sustainability.

ICOMOS, International Scientific Committee on Energy and Sustainability (ISCES) The Committee's objectives are to:

- promote awareness of the conservation of heritage places as part of the conservation of the world's scarce resources and of the energy conservation and sustainability inherent in heritage places;
- serve as a body of international experts in the application of energy conservation and sustainability principles;
- promote research in the area of energy conservation and sustainable development affecting heritage places;
- provide a forum for discussion and for the exchange of information, regionally and internationally, on matters of principle and of technical, legal and administrative;
- provide information for governments, the general public and political organisations about the application of energy conservation and sustainability principles in the conservation of heritage places.

ICOMOS, 3ENCULT, and other national programmes are focusing on the dynamics that characterise conservation of heritage and historic buildings. The aims for cultural heritage are represented by concrete examples, with a sustainable balance of energy and culture of individual buildings in the context of historic areas and environment. Different projects and programmes initiate discussions about international, national, and local actions to illustrate sensitive and practical solutions with concern for the diversity of cultural heritage.

ICOMOS ISCES presented in Paris in 2011 analyses of the value of existing buildings:

'Considering that the recently passed legislation, as well as government and industry standards calling for energy saving in buildings, fails to acknowledge the intrinsic energy efficiency qualities of existing buildings or their potential for energy upgrading and also fails to acknowledge the lifecycle costs of demolitions and replacements, and is therefore particularly unsuitable to the specifics of existing buildings … .' [17GA 2011/38]

2.3.7 Cultural heritage perspective

Cultural heritage is the recognition, integration, and identification of a culture with its history. It encompasses the right to represent history, actively or passively, and to continue to develop a framework of care for and engagement with the environment. Cultural heritage is the material presence of man-made constructions and their use of processes and production, including energy; it is physical experiences, often with a sense of permanence; it includes endurable, ephemeral, and independent properties, as well as properties of process. Cultural heritage is not about applying restrictions, but about considering the potential impact on space, matter, and the environment.

Cultural heritage focuses on identifying the complex values that balance energy and culture. The perspective of international charters, tangible and intangible values, and recently the international commitment to include culture, energy and sustainability correspond with the basic principles, active interventions, and methodologies as developed by 3ENCULT.

3ENCULT demonstrates the need to improve education and discussion regarding energy and cultural heritage and the identification of heritage. Sensitive and innovative care of historic buildings through active interventions, such as the premises of 3ENCULT, demonstrates architecture as balance of energy and culture.

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3 PRE-INTERVENTION ANALYSIS

3.1 CULTURAL SIGNIFICANCE AND CLASSIFICATION

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The classification of monuments varies significantly across European countries. In some current heritage protection laws a distinction is made between monuments of high, or national value and others of lower, or regional value; in other countries, in particular in Germany, classification – in terms of a ranking according to importance – is completely rejected. [Scheurmann, 2014] The funding policy clearly shows, however, that classification (also referred to as categorisation, hierarchisation, or priorisation) is established in the practice of conservation. Several case-related systems for evaluation are used to allocate the limited financial and administrative resources on the basis of comprehensible criteria. Furthermore, the ranking of monuments is bound up with the hope that a comprehensive indication of the extent of alterations required in the valuable building stock before intervention is possible. Practical approaches are currently achieved with the consideration of cultural heritage within the Environmental Impact Assessment (EIA). In the case of energy-efficient retrofitting, it should allow through a standardised procedure the setting of savings targets, depending on the level of cultural significance. The following section discusses the main aspects of cultural heritage values and how to assess them. In order to convey the value of a building or, more precisely, the set of values for all stakeholders involved in the planning process, 3ENCULT investigated to what extent the cultural heritage context can be accounted for in a quantitative way and, if so, whether doing this is desirable.

3.1.1 Cultural significance and cultural value

Every work on a monument has to start with a definition of the monument itself and its associated cultural significance. [Hubel, 2006, p. 138] At the end of the nineteenth century, state protection for monuments was initiated in the German states, with robust discussion concerning the values of cultural heritage. The negotiated 'classical' value, like historical, artistic, scientific, or urban value, became part of the cultural heritage legislation of several countries as well as in international charters. [Burra Charter, 1999] These values are usually the basis for monuments to be entered into the lists of protected buildings. The development of social changes in the late twentieth century saw the emergence of a new discussion about values. This is not limited to cultural heritage but to society as a whole. With reference to the subject of built heritage, professionals today discuss the values of identification and education, or even the value of dispute, to name but a few. [Meier; Scheurmann; Sonne, 2013]

Fig. 3.1: The range of listed monuments, examples from Germany

a) Cathedral and Old Court, Bamberg
b) Synagogue, Allersheim
c) BMW administration centre, Munich
d) Willy Sachs sports campus, Schweinfurt

e) Wilhelminian style building, Dresden
f) Historic centre, Bamberg
g) Remains of Buchenwald concentration camp, Weimar
h) Railway bridge, Rottendorf

i) Exhibition pavilion and gatehouse, Münsterschwarzach Monastery

Listed buildings and protected monuments are no longer limited to the classical hierarchy of heritage values, such as churches, castles, town halls and prestigious bourgeois houses. Today, the lists include industrial buildings and monuments such as the remains of Nazi concentration camps. In fact the need of protection for a building is dependent neither on its age nor its function (see Fig. 3.1).

The assignment of cultural values is a negotiation process within a community, brokered and even influenced by cultural heritage experts. Time- and context-sensitive value judgments are therefore not only valid for the present; rather they are intended to be handed down to future generations. Once the value of a monument is perceived, it can provide the basis for a protection by law and thereby also by the community.

The complexity of cultural values has been recognised as essential for cultural heritage. It is discussed on an international level, as indicated in recent charters and policy papers of the International Council on Monuments and Sites (ICOMOS), UNESCO, and the Council of Europe. In practice, the steady shift of values assigned to monuments can only lead to the outcome that the task is not so much the preservation of values but rather the care for the objects those values are associated with. [Meier, 2013] This care includes preservation of the material substance to which these values are bound, as well as the formal qualities, the aesthetic appearance of the building, and including the traces of history. Focusing preservation on the objects themselves helps to avoid the ranking of different values that are – and should be left – subject to each generation's own judgement.

As rewarding as a professional discussion about cultural heritage values might be, it is difficult to disseminate the complex issues to the general public. Cultural heritage preservation, however, is reliant on a broad acceptance within society. After all, when it comes to refurbishment of protected buildings, conservators must provide information about multiple layers of significance and the subsequent practical consequences. Planners need clear advice as to what is to be preserved and what can be changed. For dealing with protected buildings the definition of cultural values should at least provide a point of reference for setting priorities in a restoration project.

3.1.2 Assessment of values

The 3ENCULT project considered two concepts ideal for investigation, the InterSAVE (Denmark) and the DuMo-Index (Netherlands). [3ENCULT, D2.3/D3.2] Analysing the detail further, the two approaches differ. Broadly speaking, the difference is that the SAVE architecture and energy refurbishment concept (see also Section 4.1) is a qualitative and quantitative assessment of the cultural significance of the building and its surroundings, while the changeability index rates how far the building, or parts of it, can be changed without losing its cultural heritage value. The transdisciplinary and international discussion gave no clear-cut answers; but it resulted in a clear view on the advantages and disadvantages of its benchmarking concept:

→ The main advantage is the triggering of communication, making an informed discussion possible among experts with different backgrounds. Furthermore, there is the chance of gaining negotiation space for non-listed buildings.
→ The main disadvantage of the global rating on the building level is that a judgment of measures on the detail level is impossible. There is also fear that such a rating will be used eventually in legal contexts and consequently it will be difficult to respond to amendments. Classification of buildings according to their cultural value also gives the impression that a high cultural value will result in low energy efficiency. To draw such an inference is a problem because there is normally no interrelation between the cultural significance of a building and its structural characteristics.

For the sake of completeness another concept of rating the value should be mentioned which is worth discussing. The research report *Assessing the Values of Cultural Heritage* by the Getty Conservation Institute, Los Angeles, focuses on 'the lack of recognized and widely accepted methodologies for the assessment of cultural values, as well as the difficulties of comparing the results of economic and cultural values assessments'. [De la Torre, 2002] For the assessment of cultural heritage values, the study opens the view on anthropological and ethnographical methods and considers approaches from the environmental and economics fields. The environmental economists Susana Mourato and Massimiliano Mazzanti examine the application of cost-benefit analysis to cultural heritage preservation. [Mourato; Mazzanti, 2002] It is hoped that economic methods will facilitate a quantitative evaluation of cultural heritage value and consequently the scope of possible interventions. Among the authors of the Getty paper, however, conservation expert Randall Mason is not the only one to call attention to the different character of quantitative-economic and qualitative-cultural values. [Mason, 2002] Initial attempts at a solution for weighing these different aims on the basis of a heuristic approach were presented by the architect and conservator Thomas Will in his contribution to the International Congress on Interior Insulation in Dresden. [Will, 2011]

All concepts mentioned, however, are aimed at estimating potential energy savings or defining a realistic scope of measures, and may not achieve the best solution for energy-efficiency refurbishment of a listed building. The objective of correspondence between cultural values and physical attributes that emerged during the discussion among the 3ENCULT project partners is different, however. In this case the defined cultural heritage values are not bound to the building as a whole but to certain 'untouchable' elements. Other parts of the buildings are, in consequence, 'tradable', which is how it is complied with in practice. By considering certain construction elements, planning can be tailored to specific cases and takes the individuality of monuments into account. With this in mind the attention should focus on the EnerPHit building certification and on the 3ENCULT Historic Building Information System, two methods which take this into account in different ways. (see Section 4.3)

3.1.3 Classification according to technical aspects

As has been mentioned, the targeted energy savings potential of a building does not depend on heritage values. Typological and physical parameters, however, such as climate, orientation, amount of external walls, thermal conductivity, and moisture properties affect energy consumption. Therefore a classification based on specific factors like structure and building materials is helpful in finding solutions. Several recent studies and guidelines on the energy efficiency of building stock apply to this principle. [Grunewald; Will, 2010; RMIT 2013; TABULA 2009–2012] In general the established classifications include buildings and functions based on similar construction types, and in some cases the age of the structures, and are mostly combined with the building typology and identification of frequently used construction systems. It is reasonable to consider urban typologies, thereby distinguishing between different means of attachment to neighbouring buildings. Certain climate zones are usually respected by the geographically limited validity of guidelines and studies.

3.1.4 Dissemination without classification

The measures developed by 3ENCULT are available for other projects; therefore the transferability of 3ENCULT case study experiences to other buildings in an urban context was investigated. [3ENCULT, D2.1 2011] The placement of the various study cases in a building classification was proven by the investigation. A classification according to heritage values was refused for the previously mentioned reasons, but classification of the buildings based on specific factors also causes problems. Among the case studies there are examples like the house in Appenzell, which may be considered typically representative of a certain type of residential construction (see Case Study 8), and there are buildings like the Palazzo d'Accursio in Bologna, which may be unique in their appearance. When classifying buildings as a whole, the individuality of the monuments was not taken into account by the project, and the application of solutions developed by 3ENCULT was not limited to one class of building. Instead, it is necessary to ascertain the impact of certain measures on various construction types.

3.1.5 Conclusion

Classification of buildings for refurbishment can only be useful in finding solutions where a significant number of buildings with similar characteristics exist. Most monuments, however, are listed because they have specific individual characteristics. Some of the case study subjects of 3ENCULT have a significant history and cannot be assigned to any typological class. Indeed, every building needs an individual analysis and an individual conservation strategy. Building classification supplemented with a range of solutions and impact assessments (see Section 4.2) can provide guidance for choosing the most compatible measures. With the establishment of such a holistic approach, a helpful tool will be developed for conservators, architects, and all other stakeholders of planning processes.

Finally it must be clearly stressed: there are monuments so rich in their appearance, so rare in material characteristics, so singular in their building typology that the task is not to balance cultural heritage values and energy saving potential, but to preserve them unaltered to maintain their significance.

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3.2 INTERDISCIPLINARY APPROACH

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3.2.1 Common documentation of the building state

Only a profound documentation and understanding of the building, its material, its structure and its history, as well as the significance of its parts allow energy efficient solutions to be planned according to the specific demands of a particular building. This task requires different skills to be brought together – and the challenge is to enable dialogue between the building owner, architect, project planner, conservation officer, energy consultant, and maybe other stakeholders.

3ENCULT has shown that the best-tailored solutions were found where a constructive and open dialogue was possible, where specialised diagnosis results were documented together, exchanged and mutually explained so that joint conclusions could be drawn. In the following chapters, we describe the approach for interdisciplinary analysis as experienced and as recommended – first in principle and then as implemented in a practical prototype tool.

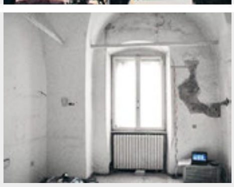
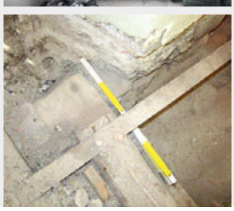
3.2.2 The 'Raumbuch' concept extended to energy aspects

The 'Raumbuch' principle described here, which is a cousin of the schedule of accommodation that is well established in German conservation circles and occurs in related forms in various European countries, is adapted to provide the framework for a comprehensive presentation of a building, including text information, pictures and drawings. The data is structured on different levels of detail, be they the urban aspects, the building as a whole, or an individual room with its structural elements. The main feature is the link between information and its accurate positioning in the building, usually via references to two-dimensional plans (see Fig. 3.2).

Fig. 3.2: Typical 'as-built' survey of one room in a 'Raumbuch', as practiced in Case Study 8

Comprehensive diagnosis and documentation is, however, important not only with regard to conservation aspects – energy retrofit planning also requires preliminary investigation of the building's state. The logical consequence thereof is that conservation and energy experts collect and document information together – especially as conservation and energy issues might overlap, for instance when examining damp and salt-contaminated walls. Table 3.1 shows the structure of conservation and energy related aspects in parallel at different levels of detail. Documenting them in this way gives all stakeholders access to a holistic building information system that contains descriptions, plans, photographs, drawings of details, the results of non-destructive or minimally destructive testing and monitoring data, as well as calculation results and models. It allows the architect, the conservation officer and the engineer to 'move' through the building on different levels of detail, with the relevant information for constructive discussion always available.

Tab. 3.1: Documentation content: aspects related to conservation (left) and energy (right)

General information name / company of surveyor, location, name of building, legal investigation, present function, original function, date of completion, architect / artists / other people, construction method, brief description (location, measurements, storeys, orientation, structure, roof, bays, balconies etc.)		
Urban context location, access, orientation, historical context		**Urban context** Position of building in built context, origin and location of overshadowing from trees or other buildings; availability of space for and sources of energy production, local climatic data, environmental conditions
Building type, shape / dimension, levels / axes, internal circulation / floor plan, function, building history / historical background **Facades / Roof** appearance, design elements, decoration, structure, roof and wall construction		**Building** actual energy performance, state regarding structural problems, fire prevention, seismic safety, composition and type of building services; particular architectural solutions related to the original use of the building, constraints due to preservation requirements **Facades / Roof** Analysis of the construction of the elements of the thermal envelope, identification of thermal bridges
Room / structural elements Comprehensive description of the design, including structure and layout, material properties associated with appearance such as colour and texture, all features that indicate an existing or previously existing structural system, design or function, all characteristics that indicate interruptions of these earlier systems, description of space-defining elements such as flooring, walls and ceilings in terms of their construction, surface fixed components (windows, doors), movable elements, installations etc.	 	**Room / structural elements** Construction of the external walls, windows, internal partitions and basement, identification of materials, type and dimensions. Technical data of materials: density, conductivity, specific heat capacity, water vapour diffusion resistance index, long-term water absorption etc., state of preservation / deterioration of building components, opportunities for passive use of solar energy and use of daylight, analysis of technical systems / building services, availability of space for building services, technical installations and distribution systems

It is important to note that the 'Raumbuch' version of an 'as-built' or condition survey does not compete with other methods of documentation, such as a restoration survey, but it offers the possibility of bringing the reports together on a common platform. The result is a systematic documentation of the building and a comprehensive assessment from different perspectives, all in a common tool.

3.2.3 Practical implementation in a prototype: hBIS^{ec}

In view of the above, a 'historic Building Information System covering aspects of energy and culture' (hBIS^{ec}) has been developed in 3ENCULT. The web-based database draws on the 'Denkmalinformationssystem' (Monument Information System) developed by ProDenkmal.

The user interface is divided into different sections (see Figs. 3.3 and 3.4): the *Navigation* panel at the upper left takes the user to a specific location within the building – the structure and level of detail can be tailored to that particular building's needs. The central panel displays *Main information* for the selected location, with the corresponding *Picture view* to its right. On the lower left *Associated documents* are available for the different types listed and these can be previewed in the *Document preview* window opposite it on the right of the screen. This version of the user interface design has been tested by ProDenkmal using certain project databases.

Conservation and energy aspects are deliberately presented in parallel, with colour codes to identify them and allow the user to take in many different aspects at a glance.

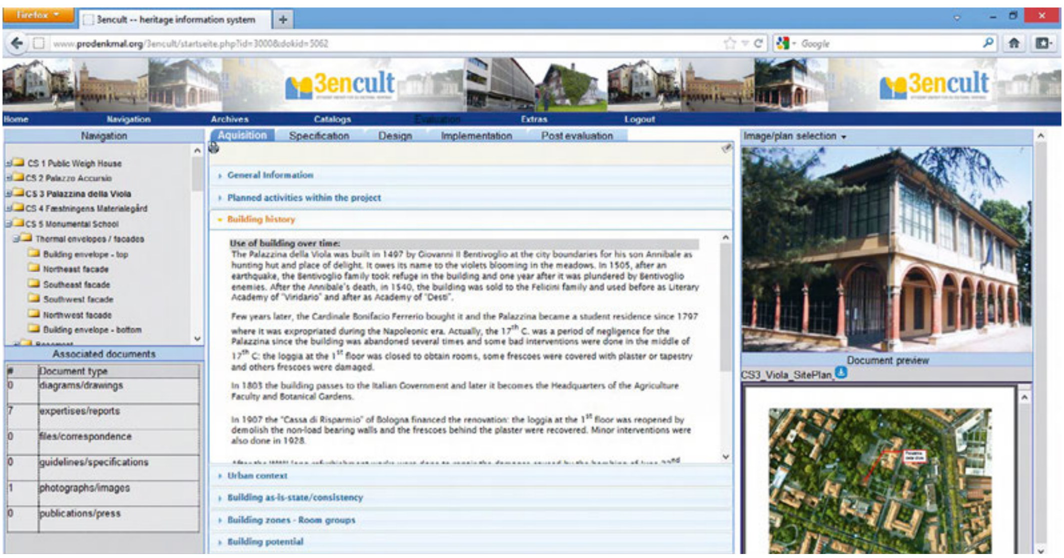


Fig. 3.3: User interface of the 3ENCULT database

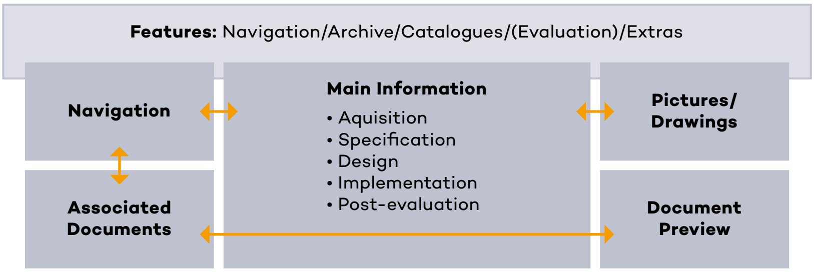


Fig. 3.4: Scheme of user interface

1. NAVIGATION

The navigation tree visualises the structure of the building (and can therefore be adapted specifically). The user navigates from layer to layer, moving deeper and deeper into the building, starting with the building as a whole and zooming in through building parts and building zones to more detailed levels such as individual storeys and rooms with their elements (e.g. outer and interior walls) and components (e.g. windows). Additionally, the 'thermal envelope' with the facades, foundations and roof is integrated at the same level as individual storeys. When information is entered in the main text box, or documents are attached, these are assigned to the corresponding levels. Conversely, when the user is searching for information regarding a particular door, for example, he can navigate through the building to that component. This structure also works like a filter: with every level deeper into the building, the information gets more detailed.

2. MAIN INFORMATION

In the central part of the user interface, data is deposited directly in the database. Horizontal tabs differentiate the stages of project planning **Acquisition, Specification, Monitoring / Simulation, Design, Implementation** and **Post evaluation.** Every section is divided vertically into subsections, so as to keep the structure clear. The Acquisition phase for example, on the Building level, consists of General information, Building history, Urban context and Building as-is-state / composition, among other headings. Guiding the user from level to level with **specific questions,** the database also works like an analysis tool.

3. PICTURE VIEW

This part of the user interface provides orientation while the user is navigating through the building: for example, clicking on the 'room' level calls up the ground plan of the related storey, on which this room is indicated with its room number. Additional images can be shown as well.

4. ASSOCIATED DOCUMENTS

The database allows documents to be uploaded and correlated with the layer concerned. Under Associated Documents, the user sees a list of documents linked to the active navigation layer. These associated documents are categorised under the headings: diagrams / drawings, expertise / reports, files / correspondence, guidelines / specifications, photographs / images and publications / press.

5. DOCUMENT PREVIEW

Pictures and documents uploaded under Associated Documents are displayed in parallel with the associated information shown in the middle part of the interface. From here they can easily be opened in a separate window and/or downloaded.

Tab. 3.2: Brief description of the database components

External documents, such as pictures, reports and plans, can be uploaded and managed under the *Archives* feature and can be viewed under *Associated documents.* The files can be uploaded to the database and directly linked to the relevant layers in the navigation structure, where they should then appear.

The *catalogues* are the key to an efficient workflow, because any repeated element, such as construction details, material, windows and doors (see Tab. 3.3), has to be described only once and then just linked to the respective room and/or facade. All general information is given in the catalogue, while information that changes depending on the element concerned (e.g. the exact width, height and depth of a window, its specific state of preservation and the installation Psi-value describing the thermal bridge) are documented on facade level or room level.

Tab. 3.3: Four catalogues and their main information

BUILDING COMPONENTS CATALOGUE
Name, total thickness and U-value (calculated or measured). Additionally, a detail drawing and photos can be uploaded. In a separate table, the stratigraphy of the element is documented by choosing the constituent materials from the material catalogue/database and assigning a thickness to each.
MATERIAL CATALOGUE
The properties of a named material, such as thermal conductivity, density, thermal heat capacity, water diffusion resistance and porosity can be entered, as well as information on its permeability to air, vapour and water. Additionally the data source can be named and a photo uploaded.
WINDOW CATALOGUE
The window catalogue comprises information on: (I) **window characteristics** e.g. typology (single, box-type, coupled and so on), number of sashes and sash bars, accompanied by a drawing and/or photo, (II) **frame** e.g. type, material, profile dimensions and thermal transmittance (Uf-value), (III) **glazing** e.g. type, spacer Psi-value, thermal transmittance (Ug-value), solar energy transmittance (g-value) and visible light transmission, (IV) **shading** e.g. typology, position and operability, description of material properties, and a photo or drawing, (V) **architectural shading parameters** e.g. overhang depth, height of shading component, horizontal distance etc.
DOOR CATALOGUE
After identifying the door label and the decision between internal or external type (from drop-down list), the user enters a general description of the door casing and leaf types (both from drop-down list) as well as the U-value and a drawing and photo of the door.

3.2.4 Potential of the tool

The potential of the hBIS^{ec} tool presented here goes far beyond diagnosis, because the development of solutions, the comparison of options and, finally, the selection of the one best-suited to the building concerned can profit from the structured presentation and simultaneous view of both conservation and energy aspects, not only on an aggregate level, but right down to the level of a single room.

Fig. 3.5: Use in the planning process on projects of a certain size or complexity

There is also a variety of application options. Since the database makes it possible for every stakeholder involved in an energy-efficient refurbishment to be properly informed, it is an essential tool for any holistic design approach, such as the Integrated Design Process (see Case Study 4). This is particularly important in the planning process for projects of a certain size and complexity (see Fig. 3.5).

The usefulness of the tool is not, however, limited to support during a single energy retrofit as illustrated above. Well documented case studies, where the reasons for any decision can be followed, make it possible to apply particular solutions to smaller or more simple projects where it would not be feasible to apply the whole process (see Fig. 3.6).

Finally, the comprehensive documentation of the as-built state and all interventions, together with explanations and reasons for them, creates a body of knowledge that can be handed down to future generations – of restorers and users of a specific building – as the basis for the sustainable maintenance and long-term preservation of that piece of built heritage (see Fig. 3.7).

The database can be accessed at the project's website www.3encult.eu.

Fig. 3.6: As a guideline for intervention in smaller projects with well documented case studies

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Fig. 3.7: Documentation of measures, their history and the reasons for them

3.3 HISTORICAL ANALYSIS

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3.3.1 Objectives

Historical analysis is part of preliminary investigations. Each professional renovation plan for an existing building of historical value requires a precise knowledge of it. In addition to technical aspects, which are of primary importance in terms of structural and physical building issues, this 'information collection' also relates to an accurate knowledge of the development of the construction. On the urban scale, the nationwide inventory of objects and ensembles worth being protected is essential for the preparation of design statutes according to the historic character of towns and villages. On the basis of the historical analysis it is possible to define the heritage value of monuments. The genesis of a building, usually represented in the various stages of construction, provides guidance for the appropriate planning of a correct and respectful maintenance or rehabilitation intervention. It is not the objective of such interventions to render or to reconstruct a fictional original state. Indeed, the generally accepted principle should be the preservation of the building fabric, including more recent additions and traces of history, as already demanded in the Venice Charter (Article 11): 'The valid contributions of all periods to the building of a monument must be respected, since unity of style is not the aim of a restoration.'

The level of detail and nature of the investigation depends on the respective quality of structure, the available primary and secondary sources, and the available financial resources. The various methods of analysis and documentation are to be adapted to the character of the building and the terms of reference. In many practical examples, it has been shown that a good preliminary investigation helps to lower costs as changes to planning are avoided. A professional historical preliminary investigation is also the best basis for a constructive dialogue with the conservation authorities. In order to set these standards different conservation departments published guidelines. [for example the one in Sachsen-Anhalt/Germany: Haseley 2011]

3.3.2 Building survey (List of protected buildings)

The inventory of monuments serves as a basis for conservation for the acquisition, exploration, and documentation of historic buildings. All information necessary for a justification of cultural significance is collected, and the results are communicated to the public in the form of texts, images and maps in order to arouse public interest in conservation beyond the state institutions. As a first step, general information about the historic building stock is made available, as agreed in the ICOMOS Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage (2003):

'2.2 Data and information should first be processed approximately, to establish a more comprehensive plan of activities in proportion to the real problems of the structures.'

A comparative overview of objects is obtained for a locally limited region. In most European countries inventory work is carried out by the heritage authorities and is the basis for registration of buildings in the official list of monuments. The requirement to maintain registers of protected buildings is also enshrined in European Charters, as in the Granada Convention 1985:

'*Article 2:* For the purpose of precise identification of the monuments, groups of buildings and sites to be protected, each Party undertakes to maintain inventories and in the event of threats to the properties concerned, to prepare appropriate documentation at the earliest opportunity.' [Granada Convention, 1985]

The scope of data provided by the inventory can be very different: from the simple compilation of a monument to the comprehensive presentation of cultural significance. The data are collected during a building survey partly in combination with archive information. A closer inspection of the building fabric is not part of inventory work. The lists of protected monuments are usually available to the public.

3.3.3 Building related acquisition

In contrast to the inventory, an in-depth analysis of individual objects in heritage conservation practice is done, for example, in advance of upcoming renovation and repair measures or expected demolitions. The nature and scope of historical analysis follows certain construction related issues, mostly resulting from the current conservation projects. The study allows a specification of monument evaluation and therefore planning tailored to the specific needs of cultural heritage.

In general, the aim is to read and interpret the building as a record of history. In this regard, historic and art historic aspects, as well as building technology and construction aspects are of interest. The documentation is usually started with a graphic survey of the exact measurements of the building, carried out either by traditional or advanced 3D methodologies. This is supplemented by observations on the object, archival research, and in some cases accompanying scientific and archaeological investigations. The task is complex, and requires trans-disciplinary collaboration, involving archaeologists, building researchers, conservators, art historians, historians, and architects, depending on need.

The task is not only to collect the findings, but also to try to clarify their assignment within the historical context. The compilation of results is required in the form of texts, pictures, and drawings in line with the assessment. The documents and sources used must be cited according to scientific standards.

A report should include the following points:

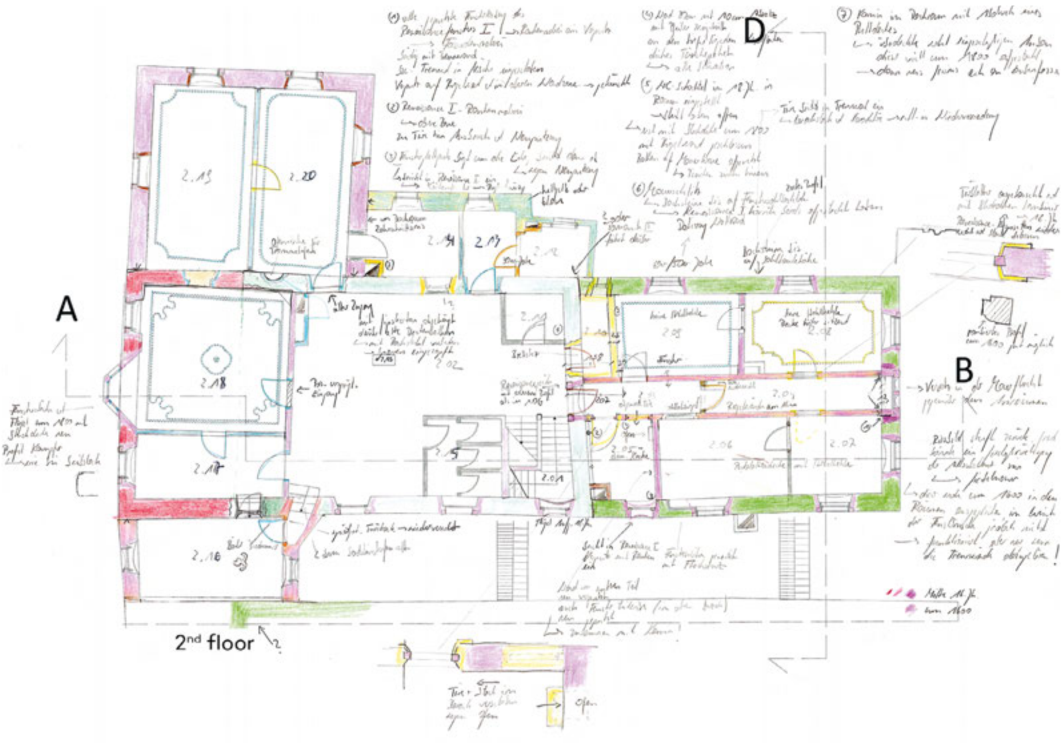
1. Orientation plans
   a. Excerpt from the cadastral map or site plan
   b. Building floor plans
2. Written report on findings acquisition
   a. Description and an evaluation summarising the object
   b. Description of current state
   c. List of sources
3. Photographic documentation
4. Building geometric surveys
5. Reports on accompanying surveys and analysis
   a. Restoration investigation
   b. Building archaeology
   c. Wood treatment expertise
   d. Structural scheme
6. Laboratory reports of material analysis

The results of these studies are taken into account for the preparation of plans showing the construction phases. This approach has been proved to give a comprehensible overview of structural changes. Based on the findings it is possible to create reconstructive drawings of different historical stages.

3.3.3.1 Building geometric measurement

Each upcoming refurbishment measure requires precise knowledge of the building fabric. The first step of an accurate inventory is an accurate building geometric measurement which may also contain additional information on materials, deformations, and constructions. This survey is the basis for all further investigations. A good building plan usually already contains information about the original construction process, the delimitation of different time phases, and constructional features. Because experienced professionals in building surveys prefer to work on-site, direct observation of the construction will result in additional valuable information. Interpretations will then flow from observation directly into the drawing. The methods of building survey are applicable regardless of the age of the building, but the level of detail of such a building survey depends on the nature of the building and on the condition of the assignment. For younger buildings, usually of the twentieth century, good floor plans are often obtainable in the archives. These, however, must always be checked against the current state of the building.

The technical implementation of a survey can range from a pure manual work, to a tachymetre supported measurement, to 3D scanning including its post-processing. This will initially depend on needs and logistical conditions. For example, areas largely covered by dense vegetation or neighbouring buildings are sometimes not detectable with technical devices; large rooms with high ceilings can exclude manual work. The measurements may be complemented by photogrammetric surveys. These represent the actual situation,



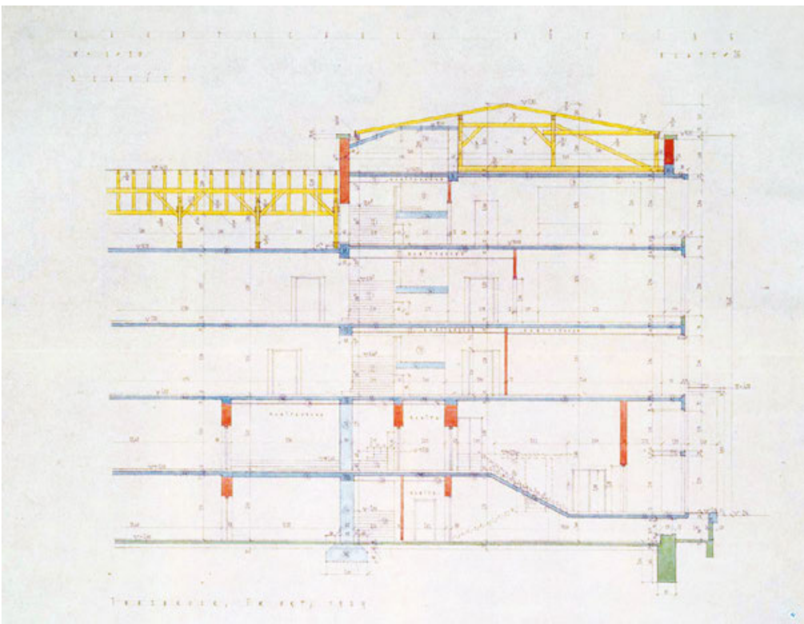


Fig. 3.8: Plan showing the different construction phases of the Bolzano Waaghaus (CS1)

Fig. 3.9: Original construction plan of the Hötting Secondary School, Innsbruck (CS5)

but can also be created on the basis of contemporary photographs. Just like the scan, a photogrammetric recording must be evaluated in order to make the results usable for further research and planning. Nevertheless there is a major difference to drawings where the author has to make decisions on what to show and how to interpret that. The analysis is not usually done on-site, so that post-processing of the data is necessary.

Existing gaps in the as-built plans, for example in the case of not directly visible areas, can be complemented by technical methods, such as endoscopic inspection, ultrasound velocity measurement, ground penetrating radar, and active infrared (thermography). In some cases, core samples are required, but preference should always be given to the non-destructive methods.

3.3.3.2 The building as a source

The challenge is to read the building as a source. For documentation of large or complex projects, the use of the 'Raumbuch' has proved successful (see Section 3.2). The 'Raumbuch' room by room inventory covers the material texture and the structure of walls, ceilings, and floors. Features like construction process, technology, and material procurement can also be taken into account. Designs and construction methods can be evaluated by referring to the architectural history and thus they may indicate the construction time. For most buildings, an investigation of design elements and decoration is also essential. With such analysis, architects and art historians can provide further information about time of origin as well as statements on the artistic and technical quality, and sometimes even about the artisans and masons. The observational studies are occasionally supplemented by stratigraphic investigations, which allow not only statements about the visible layers but also about covered design phases. Proper execution of such invasive activities should preferably be carried out by restorers. The knowledge about previous buildings can be complemented by archaeological excavations. The results of all investigations, inspections, and analyses require methodical and comprehensive interpretation.

3.3.3.3 Study of historical sources

To get an overview of the history of a building, its built environment, or its artistic evaluation, the study of scientific secondary literature is useful. This covers texts regarding the building itself, and scientific contributions to the building type, the local construction history, and specific phenomena in the construction, such as roof structures or ornaments.

Clearly distinguished from the study of literature is the research of primary sources, i.e. texts, objects, and artefacts from which information about the past can be gained. In individual cases, these are:

→ Pictorial sources such as artistic representations, plans, maps
→ Text sources such as letters, documents, newspapers
→ Material sources such as buildings, works of art, coins
→ Abstract sources such as festivals

The critical evaluation and interpretation is done by an expert, usually a historian or art historian. The expert must judge the authenticity and validity of the sources, taking into account the conditions of origin as well as the credibility of the source content. Often the reading of the ancient texts requires extensive experience.

Most sources are combined into a structure in a specific location. Depending on the age and purpose of the deposit, the information today may be found in various archives:

→ building administration;
→ libraries;
→ city, municipal and state archives;
→ church archives;
→ company and private archives;
→ cultural heritage authorities;
→ cadastral offices;
→ museums.

The findings from the sources complement the results of the building survey and inventory and may explain different findings. Plans of the construction phases can, for example, provide information about the causes of joints between various parts of the building, and a comparison with existing construction documents or deeds of ownership sometimes makes dating possible. Contemporary pictures show the design of the facades. The often diverse information from archival sources needs to be verified against the findings on the building.

3.3.3.4 Accompanying scientific research

Through applied scientific methods, further information can be added to the construction history. Some of these lead to concrete dating, but it is still necessary to check the credibility of results in their construction context.

Using dendrochronology it is possible to determine the date the trees from which the timber was sourced were felled, based on locally valid reference curves, where available. Statements about the age of the buildings, however, are only possible in combination with a detailed analysis of the timber structure and construction. Specialised professionals may further investigate if the dated timber part was reused or to which construction phase it belongs within the building, and whether the wood was stored prior to installation. More absolute dating is provided by the C14 method, especially for organic materials, or the thermo-luminescence method for determining the age of fired ceramic objects, but the results of these dating methods are usually not accurate enough for determining the building's history.

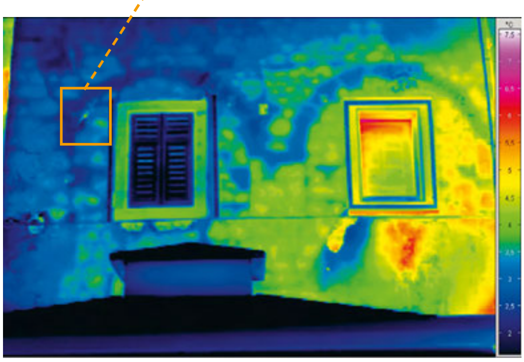
By comparing different objects, the relative dating methods allow the age of objects to be assessed against each other. For example, with comparative analysis, mortars can be assigned to a particular construction phase, but a relative chronology only comes from the stratigraphic investigation or building age analysis.

3.3.4 Documentation and results

The historical analysis is summarised in a report with the appropriate appendices. A report must be archived correctly so that it is accessible for future use. In order to future proof the documents, the materials used, such as printing and photographic paper, and file formats must meet the necessary durability requirements. The archives are responsible for the care of data and materials. Significant findings should be published to make them accessible to a wide audience.

The complete historical analysis enables the owner, architect, planner, and conservator to evaluate the heritage values. The assessment of different building parts leads to an evaluation of the whole building. With the overall documentation, precise planning of intervention measures and assessment of their impact is possible, and should avoid significant harm to the construction. Furthermore, documentation of the historical analysis preserves the information for future generations.

Fig. 3.10: Masonry arch documented by IRT and break opening as part of the construction history of the Waaghaus



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3.4 STRUCTURAL ANALYSIS

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3.4.1 Introduction

Structural analysis is quite a demanding task, especially in the case of historical buildings where centuries of (often) un-documented interventions make it almost impossible to get to an appropriate pre-intervention level of knowledge without a complex investigative phase that involves both documentary research and multilevel visual inspections together with physical / chemical / non-destructive / mechanical testing. This problem has been addressed in different ways in different European countries. In this chapter the Italian approach is presented, because it is quite systematic and has already been tested successfully on many occasions, often after some natural disaster has made emergency measures necessary. One important aspect of structural analysis is the necessity of using *destructive* (or *semi-destructive*) testing: at present it is impossible to obtain reliable quantitative measurements of the parameters needed for structural analysis without recourse to sampling, thus inevitably damaging the building. In order to limit the number and size of samples as much as possible, *non-destructive* testing – NDT – may be used. NDT may also allow the operator to select the most effective areas for later sampling and may allow the results of destructive testing to be augmented outside the sampling areas. Although NDT is no substitute for destructive tests (the Italian standards clearly state that destructive testing is mandatory), it is a very efficient way of obtaining a good level of knowledge of the building without causing excessive damage. NDT is discussed in Section 3.6, while some information on destructive and semi-destructive is given in the last paragraph of this chapter, together with useful internet links.

3.4.2 Diagnosis approach for structural investigation

3.4.2.1 Legislation

In Italy, listed historic buildings fall under the control of the Ministry of Cultural Heritage and must be treated in compliance with the *Cultural Heritage Code* (Codice dei Beni Culturali, D. Lgs. N° 42 of 22 January 2004). This code imposes considerable limitations on the types of alteration and refurbishment of this class of buildings. Each intervention requires the approval of the government department responsible for monuments and artistic treasures *(Soprintendenza per i Beni Architettonici).* Furthermore, structural diagnosis is affected by the limitations laid down by the Code, which requires the number of destructive investigations to be reduced to a minimum and carried out in limited parts of the building. The guidelines for their application to cultural architecture – laid down in the technical legislation (decree 3274/2003, ordinanza P.C.M. 3274/2003) first published in 2005 and updated a number of times since then[1] – mention the methods, tools and subject areas that should be taken into consideration when performing the structural analysis of a building. These guidelines have been published with the aim of providing an assessment procedure related to the seismic risk for historic buildings, mainly masonry structures, but they can be also utilised to guide the process of structural analysis with the goal of obtaining sufficient knowledge before deciding for the necessity of a possible intervention.

1 Latest revision: 'Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale – allineamento alle nuove Norme tecniche per le costruzioni', January 2011.

3.4.2.2 Investigation path and knowledge levels

The guidelines set out an interdisciplinary and multi-step approach, consisting of a number of fundamental modules for the analyses leading to a structural assessment. These main modules are integrated and mutually complementary, and they can be continually updated as the investigations and work progress. They include (not necessarily in this sequence) as in Table 3.4:

1) identify building;
2) survey construction geometry and crack pattern;
3) trace historic development of the building;
4) identify structurally load-bearing components;
5) determine physical and mechanical properties of components;
6) analyse soil and foundations.

Identify building The building has to be studied in relation to its location and to adjacent buildings. It is important to identify the building complex and the various structures that comprise it. In addition, it is important to locate both the building under study and the building complex on the site and on the land register maps. When dealing with architectural structures, it is useful to determine the position of valuable elements with the dual aim of protecting cultural heritage and being able to decide where to carry out possible destructive or semi-destructive tests without damaging its cultural value.

Survey construction geometry and crack pattern The aim of this module is to obtain a stereometric description of the building, which is a geometric representation both of the spaces and of the volumes occupied by partition elements, enclosure elements and connection elements, as well as all of the spaces that are not directly accessible, such as those above false ceilings. The results of surveys should be presented in the form of floor plans, elevations, sections and drawings of construction details. This necessitates measuring the dimensions of the various construction elements, both visible (beams, columns, walls) and concealed (components of ceilings, thickness of layers, build-up of walls and voids). The connections between structural elements need to be examined as well as the type of foundation, so as to evaluate the structural design. In order to obtain all the necessary information for a complete depiction of the building, different investigation techniques are utilised, depending on the type and volume of the object under study. To evaluate the geometry of the open spaces, *laser 3-D technology* can be used, which allows extremely precise 3-D models of the volume to be produced. For inac-

PHASE	OBJECTIVE	TOOLS
Identify the building	Locate and define the architectural complex and the buildings that it comprises; evaluate the context of the buildings of interest.	Land register planimetry, visual survey, building designs, soil maps.
Geometric survey and cracks pattern	3D geometric survey: plans, elevation, section, facades, design of construction details, crack distribution (causes and possible development).	Laser scanner, visual survey, GPR, IR thermography, endoscopy.
Building history research and evaluation of valuable aspects	Retrace the construction history of the building, including traumatic events and their effect and any strengthening measures. Reveal points and aspects of cultural importance.	Written and pictorial historical evidence, analysis of cracks. Specific visual and instrumented inspections.
Building materials survey and technological aspects	Identify load-bearing structural parts, quality and state of preservation of materials.	NDT, endoscopy, limited destructive test, draw inferences from the history of the building technology.
Tests for mechanical parameters and physical properties	Define strength parameters (compression, tension, shear) and physical properties (Young's modulus E, shear modulus G) of the masonry elements, establish wall composition.	Non-destructive, micro-destructive and destructive in-situ tests as well as laboratory mechanical tests on samples extracted on site; if meaningful, apply parameters of similar structures (by analogy), draw inferences from the history of the building and its technology.
Foundations and geotechnical survey	Soil stratigraphy, detect groundwater, estimate mechanical parameters of soil layers, ascertain and estimate shape and mechanical parameters of foundations.	Continuous penetration tests, bole holes, destructive in-situ and laboratory tests on samples taken, historical comparisons, borings test trenches, perforations, GPR, sonic tomography.

Tab. 3.4: Investigation path of the diagnostic approach to structural investigation

cessible spaces, if permission is granted, semi-destructive techniques such as *endoscopy* can be employed which, thanks to minimal drilling or boring allow valuable images to be collected. Otherwise, completely non destructive techniques can be applied, such as *infrared thermography, GPR (ground-penetrating radar), sonic and ultrasonic tests, sonic tomography and GPR tomography.* The mentioned Italian guidelines also cover the survey and mapping of the crack pattern present on the building (including the inclination and depth of cracks) through visual inspection. In addition to ascertaining the development of cracks, the inspector has to propose mechanisms that may have led to the present situation and predict likely behaviour in future. The mechanisms that may lead to collapse have to be identified.

Trace historic development of the building In many cases, a historic structure was not initially 'designed' and built with all the parts and shapes and materials that are visible in its present state. It is more common to encounter buildings that have undergone expansion, reconstruction and modification in the course of time. It is important to establish the time-line of these interventions and to determine their extent and the type of materials used, as well as the way in which the modified building parts are related and are connected with the previous part(s) of the building. This is necessary in order to understand whether inhomogeneities or discontinuities exist in the structure, of the kind that constitute points of weakness in the building or create new ratios between the stiffness of elements and thus a new and unforeseen distribution of loads within the structure. Information should also be collected about any extraordinary events that may have affected the building, such as soil settlement, earthquakes, or fire, as well as ordinary loads applied in the past in relation to the chronology of the building's destination of use. This historical analysis of the causal evidence of forces and exposure endured by the building provides qualitative indications about the building's response to determined stress classes. It is important to state that these are qualitative estimates only, as the present structure has been modified and probably weakened by the events to which it has been exposed. Thus it might no longer be in a state to withstand a new event of similar intensity to the past ones.

Identify materials and load bearing components The survey of materials and construction details comprises a detailed analysis of the construction elements which make up the building. The materials used, their quality and state of preservation need to be defined. The tests available are either non-destructive, semi-destructive, or destructive. For architectural objects, the number of destructive tests, such as excavation tests or plaster stripping, must be kept to a minimum and they must always be carried out in marginal positions, away from elements of value. In contrast, it is permitted to undertake NDT tests, using methods such as *sonics, ultrasonics, infrared, GPR and tomography,* on a broad scale to verify the integrity and structural homogeneity of the building as a whole. In any case, the analysis of the historic building should take into account the generally accepted construction principles and practices that were current when the building was erected, and locate the object geographically, so as to compile – by analogy and comparison – information about materials, workmanship and construction details. The fundamental parameters for evaluating the quality and safety of a masonry construction are: the materials' quality and state of preservation, the masonry layout, the thickness of the walls, the quality and type of connections between the walls, and connections of the walls with other structural elements.

Determine physical and mechanical properties of components The objective of this analysis is to ascertain, in numerical and quantitative terms, the physical and mechanical parameters characterising the various structural components. These parameters are necessary for carrying out the numerical assessment. Measuring them often requires destructive or semi-destructive tests instead of the non-destructive ones, but used with restraint regarding their number and extent. The masonry and the constituents of the masonry walls – units of bricks or stone and mortar – may undergo mechanical tests, in order to ascertain the moduli of elasticity, and the shear, compression and tensile strengths. The parameters measured for single constituents may permit the calculation of parameters for the wall as a whole if the masonry has a regular layout and units and is of good workmanship. Otherwise, it is opportune to determine a masonry wall's mechanical parameters by direct tests carried out on site, or by resorting to data banks with information about masonry of the same materials and of a similar age, quality and type to the one under study.

Analyse soil and foundations This analysis consists of two sections: one is a geotechnical analysis of the soil, the other an analysis of the form and characteristics of the structural foundations. The aim of the first is to study the soil strata, to detect ground water, if any, and measure the water table, and to supply mechanical information related to the material present in the various layers. In order to obtain a detailed study of strata, the survey is carried out via a number of *vertical borings,* from which the probe removes materials for subsequent analysis. The procedure for the foundations is first to inspect any available drawings or documents that could provide clues or factual information, and then to carry out a series of direct investigations. Pits or trenches are excavated, starting from the basement of the building, or from outside it, until the base of the foundations is reached; continuous borings are then cored through foundation walls, limiting the extent of destructive sampling as much as possible; non-destructive techniques, such as *sonic reflection methods,* are employed for obtaining information related to the layout and integrity of foundation structures.

Knowledge levels Once the various phases of analysis are completed and information of sufficient quality and quantity has been gathered, an assessment can be made. The guidelines for its application to cultural heritage constructions, as laid down in decree 3274, distinguish between three knowledge levels, as described in Table 3.5.

Tab. 3.5: Levels of knowledge in terms of the information gathered

KNOWLEDGE LEVELS	GEOMETRIC SURVEY	BUILDING MATERIAL SURVEY	MECHANICAL PARAMETERS AND PHYSICAL PROPERTIES	FOUNDATIONS AND GEOTECHNICAL SURVEY
LC1 - limited knowledge	Complete	Limited	Calculated, no survey	Limited investigation
LC2 - adequate knowledge	Complete + cracks and deformation survey	Extensive	Extensive investigation	Limited investigation
LC3 - accurate knowledge	Complete + cracks and deformation survey	Extensive	Extensive investigation	Extensive or complete investigation

Further information on destructive and semi-destructive investigation techniques

General course for the structural analysis of historic structures

http://ocw.mit.edu/courses/architecture/4-448-analysis-of-historic-structures-fall-2004/

Core sampling

http://en.wikipedia.org/wiki/Core_sample

http://theconstructor.org/practical-guide/compressive-strength-test-on-concrete-core/7581/

Flat-jack testing

http://www.iitk.ac.in/nicee/wcee/article/WCEE2012_2438.pdf

http://www.masonrysociety.org/masonry%20lab/Lab%206/Lab-6-flatjack.html

http://www.reluis.it/images/stories/Specifiche_esecutive_per_%20prova_con_martinetto_piatto_doppio.pdf (in Italian)

3.5 BUILDING INHERENT HISTORIC ENERGY CONCEPT AND ENERGY MANAGEMENT

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Fig. 3.11: Strickbau Appenzell (CS8), wood fired stove in the kitchen, backed by a tiled stove on the other side of the shared wall. Heating takes a central position in the building.

Energy use in a building has never been for free. To heat rooms and cook, people always had to organise and transport energy sources or fuels. Lighting in the building also competed with the temperature control of the rooms. Buildings and city housing were built to avoid unwanted heating in hot regions. Traditionally, expenditure and efforts to ensure a comfortable climate in a building have always been limited simply for economic reasons. Heat produced by cooking was therefore exploited to heat the kitchen or other rooms in the building, and use of the rooms was organised in a way that heat loss was kept to a minimum. In a castle, for example, it was never possible to keep all rooms to comfortable temperatures. Room division was organised so that there was maximum use of the heat, and in the mediaeval period, many cottages had their cattle livestock at the ground level and the living rooms above them. In early town planning the construction and orientation of houses were positioned according to the surroundings. Dahl [2009] draws a conclusive correlation on how the architecture corresponds to the climate. Traditional architecture was, on the one hand, dependant on the local building material available; on the other hand the main driving factor for the development of regional architecture has always been the reaction to the local

Fig. 3.12: Palazzina della Viola (CS3), Bologna, Italy, unused old fireplace

Fig. 3.13: Traditional blinds used for shade, Palazzo d'Accursio (CS2), Bologna, Italy. The red manually height-adjustable blinds significantly mark the townscape.

Fig. 3.14: Windows in Bolzano, Italy: Wooden shutters for shading in summer are exchangable with winter windows. Their small frames allow optimal light access to the building. Shutters can be partly open for ventilation and light, but ensure also minimum ventilation and light through wood slats.

environment. The local conditions of hot and cold temperatures, humidity and precipitation, wind and ventilation, and light and shadow were the unavoidable controlling forces in typical traditional building construction. Thus the regional traditional architectural solutions ensured human comfort by creating energy efficient constructions.

Exner and Lucchi [2014a; 2014b] show in an example how by the serial repetition of one building type a constant structure in a city is formed, interrupted only by a system of atria that provide daylight and fresh air to the dwellings. The surface-to-volume ratio, the dimensions of the courtyards, the presence of internal shadowing, the thermal inertia of walls and cellars, and the colour of the surface finishing have a positive influence on the heating and cooling demand of the buildings.

As an important part of the pre-intervention analysis of the building, its original energy concept has to be investigated and described and the details and findings documented. Depending on the concept of preservation, the details of the historic energy management of the building are important information from the past and dominant features of a building. From the building conservation point of view adequate treatment and presentation of the historic energy related constructions and concepts are indispensable. This is especially true in periods when energy consumption is a prominent and intensely debated topic in communities.

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Fig. 3.15: Atrium, enabling subdued light and ventilation for the internal rooms, Bolzano, Italy

3.6 NON-DESTRUCTIVE TESTING – NDT-METHODOLOGIES

Enrico Esposito, Antonio del Conte, Artemis Srl / Camilla Colla, Elena Gabrielli, University of Bologna

3.6.1 Non-Destructive Testing – NDT

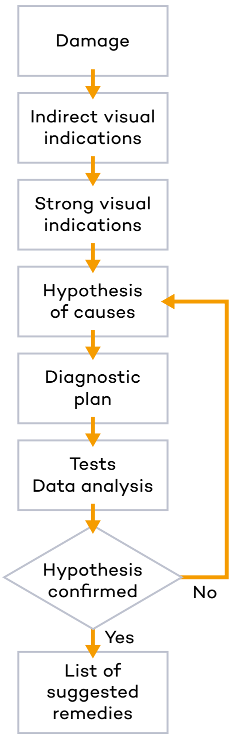

Fig. 3.16: Different stages of analysing damage to a heritage monument

Although the diagnostics included in 3ENCULT mainly focus on energy-related issues, reliable understanding of a building's state of preservation also needs to be obtained, so as to undertake all subsequent interventions safely. For this reason, a full diagnosis of the building must be made before any other work is started. Diagnoses are usually conducted to understand the reasons for some damage that has occurred and/or to augment the knowledge of the building's structure. The diagnostic process should always follow a logical path, starting from visual indications and aiming to understand the causes of damage so that remedies can be implemented (see Fig. 3.16).

The diagnostic plan would usually respond to the necessity of taking samples from the object under examination, ranging from micro-sampling for chemical analysis to cutting out sections of a wall for structural examination in a laboratory. Such invasive, destructive procedures should be kept to a minimum, so it is highly important to manage the sampling phase: for this purpose, a long series of *Non-Destructive Testing (NDT) techniques* exists that requires neither sampling nor destruction. These allow the operator to select the areas more suitable for sampling and also to extrapolate local results to broader areas of the object. NDT techniques may also be used to visualise hidden structures and structural defects, characterise surfaces and in general allow the operator to obtain a complete view of the object's state of preservation. However, it is very important to remember that NDT techniques are mainly *qualitative* and do not allow some important characteristics of materials and objects, such as strength or residual stress, to be evaluated directly; in such cases destructive testing is mandatory and national regulations are quite strict in this respect. Moreover, NDT techniques usually require *specialised personnel* who must be able to interpret the results, not just to collect them. It is impossible to describe here, even briefly, all the NDT techniques commonly utilised for the diagnosis of cultural heritage monuments. So, we will restrict the focus of this chapter to some of the NDT techniques employed in evaluating the energy efficiency of historic buildings.

3.6.2 NDT tools for the diagnosis of energy efficiency

With regard to evaluating the energy efficiency of buildings, a number of methods and non-destructive testing (NDT) techniques are presently available. It is possible to detect thermal bridges in the structure, assess the U-values of walls, windows and doors, gauge the level of air tightness, analyse the build-up of architectural components and gain indications of air quality inside the building (IEQ).

The main non-destructive investigation techniques used for evaluating the energy efficiency of buildings are:
1) measurement of heat flow;
2) thermography;
3) ultrasound and sonic testing;
4) blower door test;
5) ground-penetrating radar – GPR;
6) video endoscopy.

Of course this list is not exhaustive and we must also remember the most important NDT technique, which is *visual analysis by experienced operators.* In the following section, we give more details of some of the above mentioned techniques as well as Internet links to other sources of information.

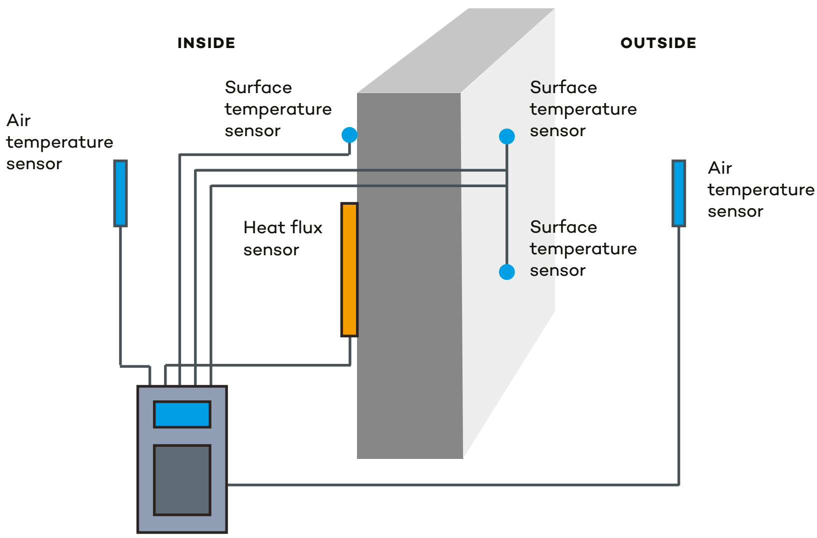

Fig. 3.17: Experimental set-up for U-value measurements

3.6.2.1 Heat flow

The measurement of heat flow allows the evaluation of the *thermal transmittance* of building elements, the *U-value,* which is commonly used to describe the thermal performance of building elements, and consequently the overall energy performance of a building. Generally, U-values are calculated with readily available software programmes, rather than measured *in situ.* However, U-value calculation programs were developed with non-traditional, present-day building materials and construction techniques in mind, rather than traditional buildings. Also, historic buildings are characterised by very thick masonry walls, which offer good thermal insulation and high thermal inertia: both features that, if properly exploited, contribute significant benefits to the energy balance of the building. For these reasons, measurements of the U-value should be taken, and the most common instrument set-up is shown in Figure 3.17. Here are some practical hints on performing U-value measurements:

→ Generally, a great wall thickness, combined with building materials of high thermal resistance, result in a lower U-value. However, care should be taken to establish the actual build-up of the building element, as defective areas, structural irregularities and ventilated cavities, among other things, may have a significant impact on the heat flow measurement. For these reasons, it is highly advisable to check the area with an IR camera, so as to avoid placing the sensors on thermal bridges or other discontinuities: the U-value measurements should always be taken on an area that can be considered representative of the 'average' behaviour of the wall.

→ Usually, sensors are placed against the walls and kept in place by adhesive tape, placing them in a layer of conductive paste to ensure an unobstructed heat flow; if the wall is of historic/artistic value, this approach is not possible and special solutions must be found. In the case of the Palazzo d'Accursio, Artemis and UNIBO designed and produced *ad hoc* steel frames to hold the sensors in place against the walls (see Fig. 3.18). Instead of using standard thermal paste, a thin (1.5 mm) thermo-conductive foil was employed.

Fig. 3.18: Steel bracket to hold sensors in place and thermo-conductive foil pad for U-value measurement

3.6.2.2 Infrared thermography

Infrared thermography (IRT) is a two-dimensional, non-contact technique for the measurement of radiant heat flow; owing to the physical link between this flow and the surface temperature, IRT is commonly referred to as a technique for the non-contact mapping of the temperature distribution on a surface. Basically, an infrared camera (IR camera) detects the electromagnetic energy radiated by an object and converts it into an electronic signal that, via digital/analogue encoding, is usually presented as a video image and stored in a non-volatile memory attachment. Radiant heat flow is influenced by many material characteristics and by the environment surrounding the structural component under examination. Generally speaking, differences in recorded thermograms may depend on:

1) Surface characteristics (e.g. smoothness/roughness, presence of humidity)
2) Surface materials
3) Substrate materials
4) Presence of discontinuities in the substrate (structural defects, voids, etc).

Fig. 3.19: IR camera for field use

These characteristics may be present simultaneously, so IRT investigation is not simple, especially in the data analysis phase. Different sequences of images of the same sample should be acquired in different thermal situations, e.g. with a cold surface, an irradiated surface and a cooling surface, so as to be able to separate all of the aforementioned influences. For example, when looking at an apparently uniform plaster surface, an area of different plaster will show up even at an ambient temperature, while a defect will generally appear only after thermal excitation of the surface. So taking measurements with and without thermal excitation may help to understand which type of inhomogeneity we are observing. In general, heat will flow from warm areas to cold ones and will accumulate in the presence of a local increase in thermal resistance, so that a local increase in temperature will be recorded; this behaviour will be immediately observable by IRT and thermograms may be used to distinguish both structural characteristics and defects. However, great attention must be paid to surface characteristics, especially surface colour, that directly influence surface emissivity; i.e. the efficiency with which an object emits / absorbs infrared radiation. For this reason, observations should be made of homogeneous parts of the surface, or where local *emissivity* correction is possible.

In Figure 3.19, a modern IR camera equipped with a bolometric array of sensors is shown; cameras of this type are very light (≈ 800 g) and may be used for a full day before batteries need to be recharged. In Figure 3.20, we show some examples of the IR inspection of buildings; this type of testing is useful for both the structural and the energy assessment of constructions.

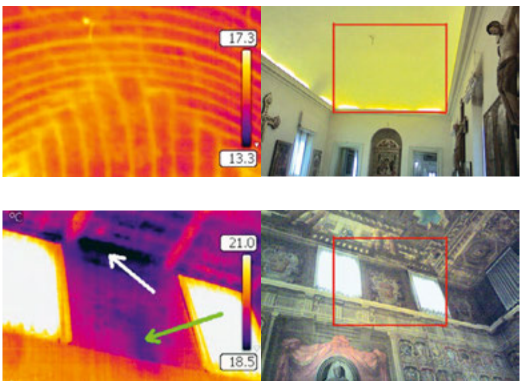

Fig. 3.20: Examples of IR thermography testing

3.6.2.3 Ultrasound and sonic testing

Sonics and ultrasound testing are acoustic tests. While sonics use low frequency acoustic signals, ultrasonic testing (UT) uses high frequency (> 20 kHz) sound energy to conduct examinations and take measurements. Sonics and ultrasonic inspections can be used for flaw detection and evaluation, dimensional measurements, material characterisation and more, such as solder joints characterisation. Some of the advantages of these inspections include:

- → Sensitiveness to both surface and subsurface discontinuities.
- → Depth of penetration for flaw detection is superior to other NDT methods.
- → Single-sided access is possible.
- → Electronic equipment provides instantaneous results although data analysis requires a skilled operator.

Fig. 3.21: Sonic test on masonry wall (top), ultrasound testing of a concrete block (bottom)

As with all NDT methods, ultrasonic inspection has its limitations, which include:
→ Part preparation is required, for example plaster has to be removed from walls.
→ It normally requires a *coupling medium* to transfer acoustic energy into the examined material, and this represents a serious drawback with works of art.
→ Materials that are rough, irregular in shape, very small, exceptionally thin, or not homogeneous are difficult to inspect.
→ Cast iron and other coarse-grained materials, a condition that often happens with artworks, are generally difficult to inspect owing to low sound transmission and high signal noise.
→ Defects oriented parallel to the sound beam may go undetected.

Due to lower operative frequencies, sonic testing is less prone of ultrasounds to material irregularities, and it can be used on greater distances and thicknesses, although it cannot supply as detailed results as the latter. A typical ultrasound inspection system consists of different functional units, such as the *pulser/receiver, transducer(s), and display devices.* A pulser/receiver is a device that can produce (and receive and decode) high voltage electrical pulses and transform them into micro mechanical motion and vice versa: once activated, the pulser generates high-frequency ultrasonic energy that is introduced into the material and propagates in the form of waves. In the case of sonics, an *instrumented hammer* is used to generate the signals, instead of a transmitting transducer, and an *accelerometer* as the receiving sensor. In both cases, when there is a discontinuity (such as a crack or a void) in the wave path, part of the energy will be reflected, back transformed into an electrical signal by the receiver and displayed on a screen. The operator can read signal travel time directly on the screen and, knowing the propagation velocity, the position of the defect may be calculated. Both methods are also used for the characterisation of materials because the pulse velocity (Vl) is dependent on the material properties.

In brief, wave velocity is generally considered to obtain an estimate of the material strength property, while wave attenuation will give indications about the presence and seriousness of defects. In Figure 3.21 we show an example of ultrasound testing of a concrete block using 52 kHz, 50 mm probes and of sonic testing of a masonry wall using an impact hammer.

3.6.2.4 Blower door test

The aim of the test is to investigate the level of air tightness of the external envelope of the building, which means how permeable a building is to air infiltration (see Fig. 3.22, left and middle). To perform this evaluation, the building is subjected to controlled differences of pressure and temperature; blower door tests yield general values for the building/part of the building under investigation. Air exchange between the inside and outside has an impact on temperature and humidity and thus on energy consumption, while

Fig. 3.22: BDT equipment and fan mounted on historic window (left), BDT testing with fan installed in door (middle). BDT test: checking air infiltration with a hot-wire anemometer (right)

air movement and air flow are also highly relevant for comfort. As a further consequence of heat exchange, the air movement is altered; this has to be controlled using smoke tests and/or the air velocity determined with an anemometer (see Fig. 3.22, right).

3.6.2.5 GPR (Ground Penetrating Radar)

The aim of GPR (Ground Penetrating Radar) technology is to investigate walls or structural elements in depth, by using electromagnetic waves. This technique was developed in the 1950s in the geophysical field for specific tasks concerning soil investigation. In the construction industry, GPR is particularly suitable for the structural diagnosis of existing historic buildings on which the use of invasive inspection techniques or coring is forbidden. GPR makes it possible to investigate ceiling structures, the arrangement of beams, columns, the presence of metal reinforcement within walls, as well as to evaluate the thickness of the construction elements and layers and detect the presence of cavities, defects or inhomogeneities. For the purposes of energy efficiency, radar allows us to obtain information on the thickness and layering of walls and ceilings (see Fig. 3.23). GPR is also a very efficient way to identify moisture in walls and foundation structures, thus providing much more detailed and in-depth information than a purely visual analysis would deliver; it not only highlights the saturated areas in the walls, but also distinguishes between the visible level of capillary rise and dry areas.

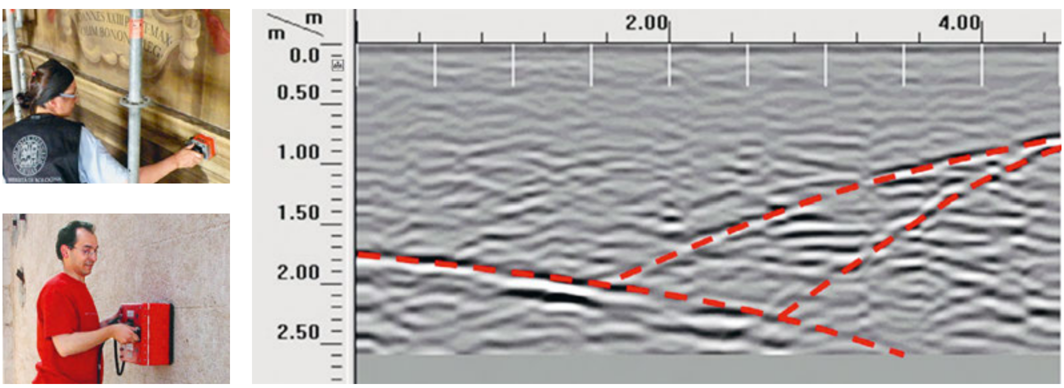

Fig. 3.23: High-resolution GPR test on frescoed wall (top left), GPR investigation that allows the profile of the vaults to be determined (bottom left, right)

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The single most appreciated website for NDT is probably NDT.net, http://www.ndt.net/index.php.

Also of great interest is the following website: http://www.ndt-ed.org/

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Heat transfer

http://en.wikipedia.org/wiki/Heat_flux_sensor

3.7 SIMULATION OF ENVIRONMENTAL CONDITIONS, HAZARDS, AND CRITICAL POINTS

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Numerical simulation and computer modelling is currently developing quickly in all areas. Complex phenomena of everyday life, like the weather or highly specific subjects of the societal, scientific or economic world, are being simulated and modelled for study purposes. From the computational point of view the limits are pushed day by day. The intention of simulation is a better understanding and to find improved solutions to problems. The less the limits are constrained by computer power, the more they are given by the input data and numeric process description. A particular advantage of numerical simulation seems to be that it requires relatively little work and less time in comparison to field experiments or real world investigations.

Numerical simulation has, moreover, the advantage of being non invasive. This makes it of significant use in the field of cultural heritage. Simulation of natural hazards can diminish heritage losses, as shown in Drdácký et al. [2011], which illustrates the outcome of another EU-funded project. Modern software tools originally designed for conventional buildings and modern construction elements have been adjusted and applied to the challenges of preserving heritage buildings as this field becomes more and more important. The tools continually evolve to cover different aspects of the building. As part of the 3ENCULT project, a simulation was run replicating energy balances, efficiency of energy performance solutions, airtightness, moisture in the thermal envelope, moisture transport, thermal bridges, light distribution and artificial lighting comfort measurement, and user comfort. Most of those aspects are interlinked and a clear distinction between efficiency improvement and risk assessment cannot be drawn. With regard to energy efficiency measures on buildings, however, all of them – by intention – change the building climate conditions, which is why building climate and its simulation take a central role. Building climate simulations can be part of the risk assessment for heritage buildings, and guidelines on energy efficiency measures in cultural heritage demand modelling to supply evidence of damage free installations [BDA 2011]. The first step is to depict the actual climate conditions within the structure, which is a simplified representation. The importance of the parameters must be ranked to decide which to include in the model. By depicting the actual climate conditions and simulating typical cycles of, for example, temperature and moisture changes, critical elements in danger of deterioration and damage triggers are identified. By changing the installation models ideal solutions are identified without further risks to the building. Experimenting with the model is done by entering different parameters into the software and studying the outcome. It should be noted, however, that any result is a mathematical function of the parameters and the algorithms. The better the parameters are known and the better the real processes are expressed mathematically, the more accurate will be the result. Nevertheless, parameters have to be measureable with the given tools, and processes fully understood before either are properly modelled.

Within heritage buildings we find quite different conditions in terms of type of building and materials used. Heritage buildings sometimes represent elaborate stories of modifications, reconstructions, decay, rehabilitation, and repair. This is clearly demonstrated by the study of the building history of the Waaghaus in Bolzano, Italy, Case Study 1 of 3ENCULT (see Case Study 1). The building is mainly constructed from local cobble stones (Bozen quartz pophyry) in a rough stone masonry type. The thickness of the masonry varies throughout the building, as does the external and internal plaster. The material data of the hard and dense Bozen quartz pophyry is well known and can be measured with high precision. Less well known is the data of the historical mortar, assumed to transport moisture, which changes the properties of the mortar and the entire wall. The mortar to stone ratio as a determining factor influencing the masonry is less resolved. Old masonry regularly exhibits small and large air pockets, and the stone/joint ratio may vary from 1:2.5 to 1:8. As this data is not always available, assumptions may have to be inserted into the model to achieve a calculation, but this should be kept to a minimum. Prior to modeling, all necessary data has to be collected and the pre-intervention analysis adjusted to suit the model.

Fig. 3.24: A four-metre drill core through the masonry of a historic building, showing a heterogeneous material formation with complex reproduction properties

The first thing to note is that monitoring is equally important for both modeling and simulation (see Section 6.2.). Comparing the model with real data facilitates the advancement of the model which is evaluated and calibrated accordingly. Data gathered from monitoring has to be meaningful for modeling; it must test the soundness of the model, and is needed for input into the simulation. Firstly, recent and current actual conditions have to be demonstrated by the simulation. This first step may be used to recreate recent problems. In the second step, future developments are simulated, which should indicate likely future challenges to be addressed by adapted measures. It should be noted that most of the simulations work in a 2D or 3D space, bringing the available selected data into a wider context.

Within the modelling, the future conditions in a heritage building are under study, for example the building climate in specific or in all rooms, the temperature, moisture, or salt distribution at a specific location like beam ends (see Case Studies 5 and 6) or window-frame zones (see Case Study 1). This reinforces the message that is important to define precisely what the team wants to model, and the importance of a clear description of what is possible and feasible to model given the available resources.

Following the compilation of input data, for example, for hygrothermal simulation, a calibration with measured data is carried out. In 3ENCULT, monitoring in the buildings was designed so that the data was useful for computer modelling. It has to be taken into account that this is not easy. As described (see Chapter 6), the design and set up of the monitoring system require cooperation between all persons involved in data-acquisition and use.

Conclusion Computer modelling and simulation of environmental conditions and hazards are helpful tools to determine critical points in the construction which arise from the measures taken in the construction. Nevertheless there is still huge potential in the development and adjustment of the available software to depict the conditions in heritage buildings. To date, modelling is not a substitute for real investigations, but can be a meaningful additional tool to interpret the data.

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4 PLANNING OF INTERVENTIONS

4.1 THE 3ENCULT METHODOLOGY FOR THE ENERGY RETROFIT OF CULTURAL HERITAGE

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4.1.1 Environmental assessment of historic buildings

There is a general need for development of a methodology for energy efficiency interventions in historic buildings – a methodology which comprises comprehensive analysis and diagnosis of the building, its history and cultural heritage as well as monitoring and simulation of energy consumption.

The EU has adopted and supported the development of environmental assessment methods for major environmental projects. These existing environmental assessment methods and procedures such as Environmental Impact Assessment (EIA) Strategic Environmental Assessment (SEA) and Sustainable Development of Urban Historical Areas Through an Active Integration Within Towns (SUIT) may have some relevance for and be applied to energy retrofit projects for historic buildings.

At the same time these methods could involve a risk of including too much, or of being an overkill, for a single energy retrofit project as the methods are normally used for large public infrastructure projects or environmental projects. It is therefore desirable to develop a methodology which is better suited to facilitate the processes and identify the problems connected to projects in most heritage buildings in urban areas of Europe.

Generally, the main objective is to bridge the gap between conservation of historic buildings and climate protection.

4.1.1.1 EIA, SEA, and SUIT

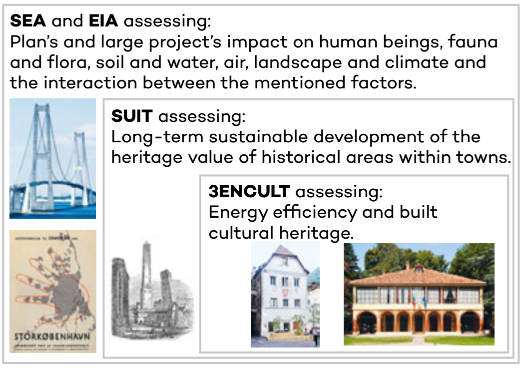
EIA and SEA are used worldwide as assessment procedures and are sources for European directives concerning environmental policy. EIA addresses industrial and infrastructure projects and requires an environmental assessment to be carried out by a nationally recognised authority. This must be done for projects which are likely to have significant effects on the environment by virtue of their nature, size, or location, amongst other things, before development consent is given. The projects may be proposed by a public or private entity.

SEA addresses plans and programmes. Its objective is to provide a high level of protection for the environment, and requires integration of environmental considerations into the preparation and adoption of plans and programmes. This encourages the promotion of sustainable development by ensuring that, in accordance with this directive, an environmental assessment is carried out on plans and programmes which are likely to have significant effects on the environment.

SUIT addresses urban historic areas. The main objective of the SUIT project was to make more effective use of EIA and SEA procedures in order to foster long-term active conservation of urban fragments.

Conservation of urban heritage requires a different approach to that used for built heritage. Conservation and changes in urban historic areas have to take the vibe of the city, the evolving culture of its population, its infrastructure, and its socioeconomic development into consideration, which means involving third parties such as members of the public and special interest groups.

Fig. 4.1: Scale relation between EIA / SEA, SUIT, and the 3ENCULT assessments



There is at present no specific assessment procedure related to historic buildings, cultural heritage, and energy retrofit.

SEA, EIA, and SUIT are assessment methodologies for plans, programmes and projects on a higher planning level and are more comprehensive than the energy retrofit of a single listed building and its surroundings. Despite the environmental focus in these assessment methods, there is no special focus on energy efficiency in supply and consumption, which is the main focus area in developing a methodology for energy retrofitting of buildings with high cultural value.

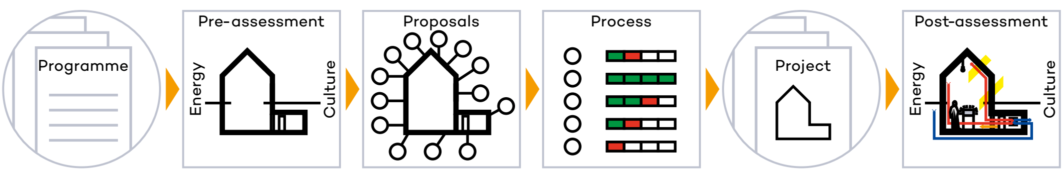
4.1.2 The 3ENCULT methodology

The aim of the 3ENCULT methodology is to provide an approach and a process that makes it possible to identify and integrate values of culture and energy in the conservation of built heritage.

Throughout the survey, assessment, and decision-making, the 3ENCULT methodology is a guiding methodology that identifies and balances culture and energy values, referring to cultural charters and conventions as well as to energy standards and directives.

The identified values are integrated into scenarios and models to support the inclusive process, public hearings, and decision making. Scenarios will include passive and active energy retrofit solutions and are evaluated in a multidisciplinary decision forum.

Fig. 4.2: The 3ENCULT Methodology



4.1.2.1 Programme

The building owner or client will normally have a concept for interventions in a historic building. This concept is the foundation of a more detailed building programme, which is a coordinated brief of the needs and preferences of the building owner for the project.

In the context of an energy retrofit of historic buildings, this programme will include goals for decreasing the energy consumption of the building as well as for the conservation of essential cultural and architectural values.

4.1.2.2 Pre-assessment of energy and culture

A precondition for evaluating the possibilities for appropriate interventions is a careful and comprehensive assessment of existing energy conditions and consumption as well as a thorough assessment of existing heritage condition values, including environmental, historic, and architectural values.

Energy assessment Both new and historic buildings are guided by European Directive 2010/31/EU on the energy performance of buildings (EPBD).

For the time being, EPBD allows member states to decide that buildings officially protected or worthy of conservation because of their special architectural or historical merit need not apply the requirements stated in the directive.

According to EPBD every member state or region is obliged to apply a calculation methodology for energy simulation.

The Passive House Planning Package (PHPP) has been developed for use as a tool for calculation and certification of refurbishment projects and will be specifically adapted to the requirements of historic buildings. The national or regional applied calculation methodology, however, may substitute the use of PHPP. [EPBD, Article 3].

In principle the energy assessment may be done both before and after intervention; and in both cases the consumption may be measured as well as simulated by use of appropriate simulation tools.

Cultural assessment It is important that the cultural assessment process concentrates on the identification of essential conservation values for a single building in an urban context, thus creating possibilities and room for interventions without harming these values.

In the context of energy retrofit of historic buildings in urban areas, the national assessment methods for cultural and architectural values should be applied.

Urban context The Danish heritage registration and evaluation system known as the Survey of Architectural Values in the Environment (SAVE) method has been an important tool for the designation of landmark buildings and urban environments.

SAVE addresses the complete heritage register of the built environment in a municipality for the purpose of producing a municipal preservation plan. It could also be applied to the registration and survey of a group of buildings or a single building and its surroundings.

Further description of the system can be found in the International Survey of Architectural Values in the Environment (InterSAVE) booklet by the Danish Ministry of Environment and Energy (see References).

Building level For a comprehensive and thorough analysis of architectural and cultural values in a single building a detailed investigation system is needed.

An example is the Danish guidelines for evaluating heritage values, which may have many similar editions in European countries. The methodology was developed by the Danish Agency for Culture, an agency of the Danish Ministry of Culture, as a tool for a thorough examination of all Danish listed buildings in order to describe and evaluate heritage values.

In order to describe the building from the most important points of view, the assessment is based on the following criteria:
→ basic information;
→ building description;
→ building history;
→ environmental value;
→ cultural value;
→ architectural value;
→ essential conservation values.

The environmental, cultural, historical, and architectural evaluation must be knowledge-based and have a cogent argument. As far as possible, the overall impact should be assessed rather than structural details.

4.1.2.3 Energy intervention – proposals

Energy saving measures are proposed, listed, and assessed to find possible measures and interventions for energy savings in historic buildings.

Initially a comprehensive list of energy saving interventions can be produced, including windows and shading, insulation and airtightness, ventilation and heat recovery, passive and active heating, cooling and hot water, daylight and artificial lighting, electricity, and integration of renewable energy systems.

Depending on the specific case, the list can include more radical architectural and technical interventions.

In order to avoid exclusion of possible interventions and solutions, the list of proposals can be prepared without reference to the building's architectural and conservation value. The list of proposals for possible interventions should be made as broadly as possible.

The proposal list can then be subject to a series of processes where the stakeholders in the project discuss the arguments for and against the proposals.

Arguments can be qualified by parallel simulation of a single intervention's impact on energy consumption as well as by argumentations for the impact on cultural values. The output of the process can be integrated in the final report and project.

The authors of the Saxon Study emphasise the dependence of a building's energy demands on shape, size and construction elements as well as the particular conditions of use and location. [Grunewald; Will, 2010] To reduce the energy demand it is essential to optimise all or, in some cases, several of the mentioned variable facts such as use and construction (see Fig. 4.3). The study distinguishes five different types of residential buildings in the specified region, and the regional characteristics of these building classifications are highlighted. Other studies have come to similar conclusions.

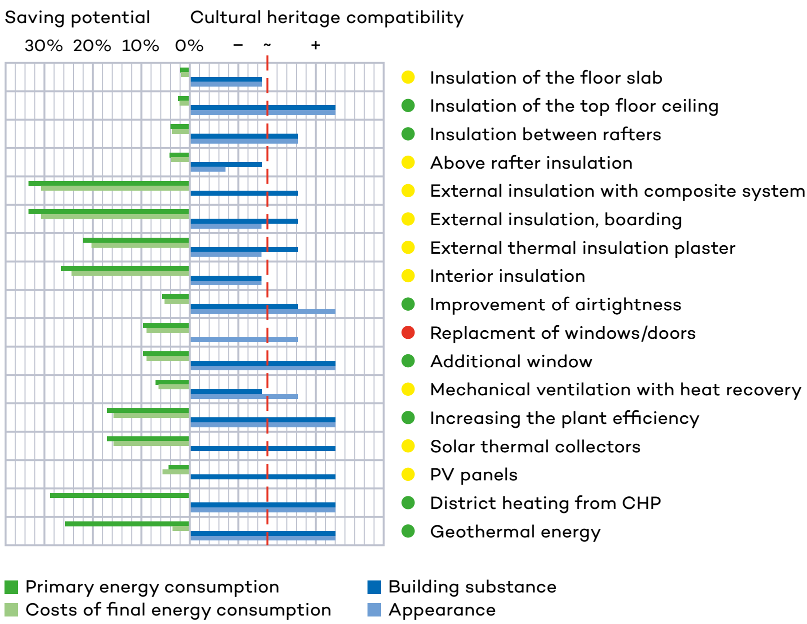


Fig. 4.3: Saving potential and cultural heritage compatibility, case study group C.2

4.1.2.4 Multidisciplinary process – evaluation and report

To meet requests and demands raised by the energy retrofit of historic buildings, it is appropriate to involve a broad forum of cultural and technical competencies in the evaluation and decision process (see Tab. 4.1).

Tab. 4.1: The list of proposals is negotiated in a series of meetings, where pros and cons are considered for exclusion or further investigation, and documented for the next meeting.

Heating, cooling, water

	Possible intervention	Multidisciplinary meetings 1	2	3	4	Objections
16	Mechanical recirculated cooling					
17	Passive cooling by chilled ceiling or wall					Incompatible with heritage values
18	Cooling by transferring surplus heat to outside					
19	Cooling by tubes in earth					Cooling capacity insufficient
20	Cooling by heatpump from earth/seawater					Cooling capacity insufficient
21	Heating by radiator					Only to be placed in rooms without cooling
22	Heated floor					New floor construction impossible
23	Centralized supply of domestic water					
24	Decentralized supply of domestic water					Not cost effective
28	Rainwater harvesting					Limited reuse of water

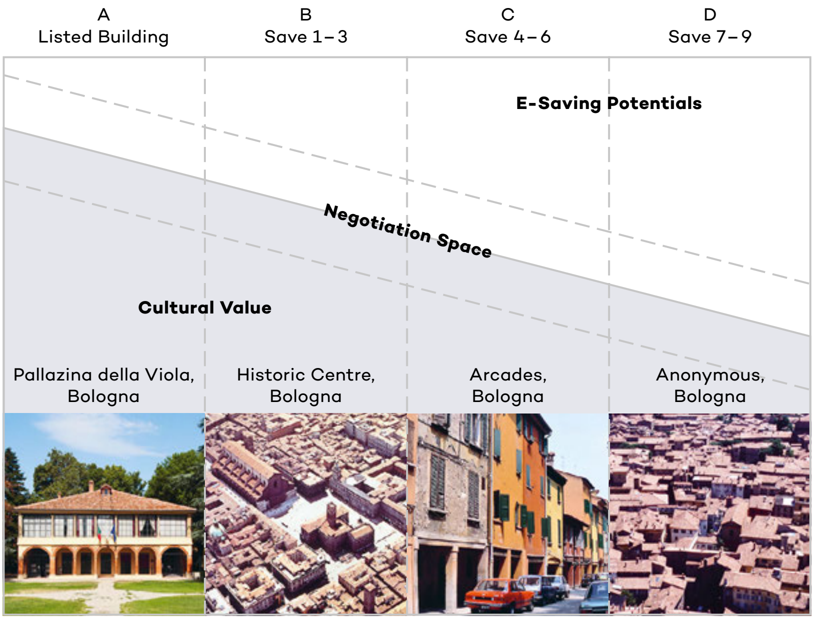


Fig. 4.4: Four classes of cultural value based on the SAVE categories 1–9 with different options for saving energy.

In heritage buildings and groups of building in urban areas that have significant public interest, a public hearing is relevant and desirable. The Aarhus Convention recognises that the quality of decisions can be improved through the active involvement of the general public. This calls for the development of a multidisciplinary process, which ensures that decisions are made on a broad range of opinions and relevant facts among stakeholders, experts, and the public.

In Figure 4.4, four categories of cultural and architectural value are defined from listed buildings, through SAVE category 1–3, to SAVE category 4–6, to SAVE category 7–9.

All of these categories have cultural value as well as potential for E-savings, but to a variable degree from A to D. This categorisation also has room for negotiation between the building authority and the building owner, indicating that special and/or local conditions may be taken into consideration regarding the degree of energy efficient interventions.

4.1.2.5 The Project

The project summarises the process from the plans and decisions made, to the completion of the construction. The project reflects the results of the methodology from programme to decision making and thus it illustrates the particular energy interventions selected with respect to the architectural or historic values of the building.

The project should also display outcomes negotiated with the local building authority concerning compliance with building codes and energy regulations in balance with the cultural values of the building.

4.1.2.6 Post intervention evaluation

Post intervention evaluation for energy retrofit in heritage buildings must assess the architectural and cultural impact of the project's interventions as well as the reductions achieved in energy consumption. At the same time it is convenient for controlling the building's physical parameters such as temperature, humidity, airflows, and daylight.

4.1.3 Perspectives

The proposed methodology, related to historic buildings, cultural heritage, and energy retrofit describes a process which embraces a sequence of profitable activities to ensure comprehensive multidisciplinary decisions.

The methodology has a specific focus on single buildings in an urban context and is developed for listed or highly valued built cultural heritage, but it may also be appropriate for buildings which represent a more generic building culture.

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4.2 CRITERIA FOR CONSERVATION COMPATIBILITY OF ENERGY EFFICIENCY MEASURES

Christoph Franzen, Institut für Diagnostik und Konservierung an Denkmalen in Sachsen und Sachsen-Anhalt e.V.

The conservation compatibility criteria for energy efficiency measures and integration of renewable energy sources are the same as for all measures with regard to built heritage and result in an impact evaluation. Preservation is desirable for conservation of the historic building stock and its appearance. Where changes are necessary to the existing structure, the measures and the structure's condition after the measures are completed are to be documented as per preservation standards. The aim of an energy efficient retrofit is not based on specific guidelines like the standardised Energy Performance Certificate, but must consider current use and user behaviour of the structure. Necessary amendments to energy efficiency improvements take into account existing materials, and should be fault tolerant, repairable, and reversible.

The 3ENCULT project developed a catalogue of technical solutions to be used to guide and support decision making, considering consequences for cultural heritage as well as for structural and energy efficiency issues. It demonstrates how to optimise the single elements of a building and the impact on the building as a whole. For monuments and built heritage, it is only possible to choose measures suitable for construction and appearance if information about materials, techniques, practices, and effects are already available. To provide the required information, classification according to specific details can give a point of reference. Thus architects and other stakeholders can be informed about the adaptability of certain measures, the advantages and disadvantages as well as the effects of implementations and accompanying measures that need to be taken.

The following list of questions – developed and used within 3ENCULT[1] – can be helpful for the evaluation of the conservation compatibility of a measure for a specific building:

1 Franziska Haas, Technische Universität Dresden [based on 3ENCULT, D2.1, 2011].

THE MOST IMPORTANT FEATURES:

Impact on monuments and built heritage:
- → To what extent will the historic building structure be damaged or affected?
- → What parts of the surface will be at risk of damage or alteration?
- → Is the measure reversible, or will future reversal potentially cause damage? *e.g. penetration of adhesive and chemicals into the surface*
- → Will the energy system be altered? *e.g. change from a warm to a cold roof structure, implementation of air tightness to historic windows*

Constructional compatibility
- → For which category / type of building are the measures applicable / not applicable? *e.g. residential buildings, exhibition buildings, detached farmhouses*

- → For what type of construction, in particular outer walls, are the measures applicable / not applicable? *e.g. natural stone masonry, timber framed walls, single glazed windows*
- → Are there existing constructions / materials which the measures are not compatible with?
- → What are typical problems of implementation, how serious are they, and how often do they occur? How error-prone is the workmanship?
- → What are the existing experiences of the measures? What long-term experiences are documented?

Saving potential
- → What are the expected costs and the economic effect?
- → What is the economic and environmental result of the expected energy retrofit and CO_2 reduction?
- → Which alternative measures could have similar effects? *e.g. sealing and repair of historic windows instead of installing new windows, internal instead of external insulation*
- → How durable are the proposed measures and what could influence their effectiveness?

Accompanying measures
- → Is the new surface compatible with the historic surface?
- → What problems exist with the sourcing of new material and disposing of the used material?
- → Which accompanying measures and preliminary investigations may be essential? *e.g. for the external insulation of the basement an archaeological excavation may be necessary*
- → What other measures are not compatible? What other measures are recommended in combination?

The ten basic rules proposed by the Austrian guideline [BDA 2011] *Energieeffizienz am Baudenkmal* describe and define the conservation principles to be applied to the assessment of energy refurbishment measures, and should guide every intervention project. Their translation into English (as below) was made available by 3ENCULT for application in its case studies.

1. Original The primary objective of conservation is the unchanged preservation of the historic stock and its appearance as far as possible. In the case of necessary changes the pre-existing state, the measures, and the state after the measures are to be documented under preservation standards.
2. Analysis Most built heritage exhibit quite a heterogeneous constitution grown in time. In the course of the planning a complete knowledge of the stock both with respect to structure and building physics is essential.
3. Overall project Measures should be based on holistic planning and not focus on single actions. The achievement of single U-values or theoretical demands on thermal heat is not adequate. The aim is to reach a sensible improvement of the total energy budget of the building.
4. User behaviour and need The aim of the energetic conservation should not be based on specified guidelines like the standardised Energy Performance Certificate, but has to refer to practical use and the behaviour of the user in the specified object.

5. Individual Historic buildings need individual solutions instead of standard formulations. This requires all parties involved to accept the probability of increased planning efforts, an improved quality assurance and intensified communication with and between expert, owner, investor, and heritage authorities until the termination of the measures.
6. Conservation The first step is to look for sources of errors on the monument, to do repairs and reactivate original functions to promote the historic ideas. Not until the options of restoration have been exploited, one may decide on amendments or exchanges.
7. Material accordant Necessary amendments in the course of energetic improvements have to be accordant to the existing materials.
8. Fault tolerant Given the fact that both in production and in use there are never ideal conditions, fault tolerant, repairable and reversible constructions are preferred.
9. Risk free A long standing damage freeness is to be guaranteed. For this often the participation of experts on building physics with major experience in monument conservation is necessary. Innovations and experiments on monuments are solely justifiable if they are included in serious scientific projects. In other respects it is imperative: better less and safe – than much and risky.
10. Perspective Measures on a monument are lined up in the stepwise development of the former centuries. Preservation forces all participants to have a vision beyond the liability of time and depreciation.

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4.3 ENERGY EFFICIENCY LEVELS AND CERTIFICATION

Zeno Bastian, Passive House Institute, Marleen Spiekman, TNO

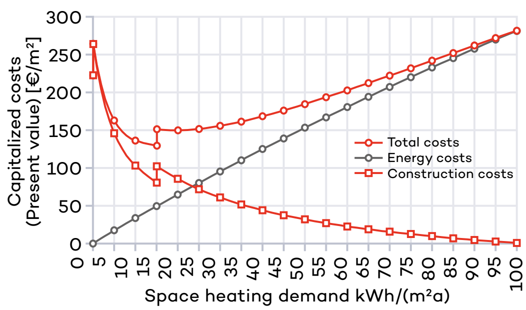
When a historic building is to be retrofitted, the opportunity to investigate whether the energy efficiency of the building can be improved at the same time should not be missed. The people involved in the planning of the retrofit measures face the question of which level of energy efficiency, e.g. which insulation thickness, is reasonable for their specific building. The following chapter gives some advice regarding this question, mainly based on economic considerations – starting off with an explanation of the situation in new buildings and leading over to the differences in general retrofits. Finally, the EnerPHit standard is described, which gives recommendations for quality levels of energy efficiency measures in building retrofits. The chapter closes with a description of the EnerPHit approach to the energy retrofitting of historic buildings.

4.3.1 Which level of efficiency makes sense in building energy retrofits?

4.3.1.1 Efficiency levels in new buildings

For new buildings, a highly efficient energy standard such as the Passive House standard [PHI 2013] is essential for reducing CO_2 emissions in the building sector to a sustainable level. At the same time, an analysis of the full life cycle costs shows the Passive House standard to be economically very profitable. In Figure 4.5, a drop in the total costs curve can be observed at 15 kWh/(m²a), which is caused by the simplification of the heating system, once the radiators can be omitted and the remaining heating demand can be covered by the ventilation system. This drop adds further to the profitability of the Passive House standard (which has 15 kWh/(m²a) as a main criterion). However, trying to go even further and save the remaining kilowatt-hours in order to reach a building with zero heating demand leads to disproportionately high construction costs, which cannot be compensated for by the savings thus generated.

Fig. 4.5: Cost diagram: Additional construction costs for energy-efficiency measures (starting at a base case of 100 kWh/m²a) heating demand), energy costs and total costs

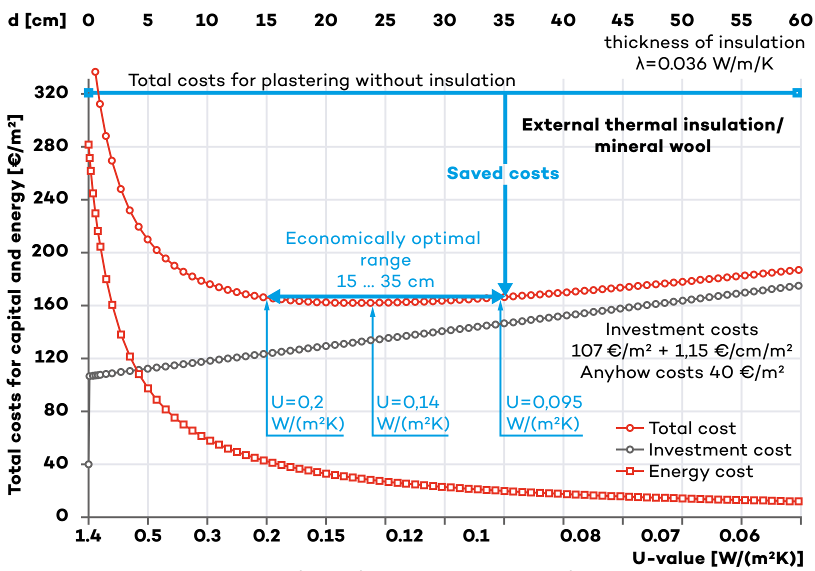


2013 Lifecycle 50a / no subsidies
2.5% Real interest rate
Energy price 9 Cent/kWh
© PHI

4.3.1.2 Economically optimal efficiency levels for standard energy retrofits

In the case of energy retrofits, the situation is quite different from new constructions. For one thing, reaching very high efficiency standards such as the Passive House standard frequently requires a much greater effort, caused by typical difficulties such as remaining thermal bridges at the basement walls. For another, existing radiators can sometimes stay in use, meaning that investment costs cannot be reduced by installing supply air heating. As a result the Passive House standard is often not the economically optimal solution for retrofit projects.

A more suitable approach is to try to achieve the economic optimum for each specific renovation measure, instead of aiming at a given energy standard for the whole building. The economic optimum is the efficiency level at which the sum of investment costs for that energy saving measure, the energy costs, and the maintenance costs over the life cycle of the measure are lowest (see Section 2.2). If we take, for example, thermal insulation for an external wall, the cost curve is quite flat at the optimum level, leading to a rather wide range of optimal insulation thicknesses between 15 and 35 cm for which the life cycle costs are almost equal (see Fig. 4.6). It is generally advisable to aim for the higher insulation thicknesses in this range. This way the financial risks of unforeseeable future energy price hikes are lowered and the CO_2 emissions are further reduced. As a rule, doubling the insulation thickness cuts the heating costs and CO_2 emissions caused by heat losses through an external wall almost by half.



Real interest rate 2.50% p.a., Av. future fuel price 9.0 ct/kWh, Life cycle 40

Fig. 4.6: Investment costs, energy costs and total costs for mineral wool external wall insulation in relation to the insulation thickness and the U-value (for Central European climate).
Top left and upper blue line: costs (without insulation) of new external plaster with no energy savings. The difference between this and the blue total costs curve (with circles) represents the cost savings over the life-cycle of the insulation measure. The insulation is profitable whenever its total costs curve is lower than the total costs without insulation.

In the context of the 3ENCULT project and based on earlier research on passive houses in different climate zones [Schnieders et al., 2012] a study was carried out to determine cost-optimal quality levels for energy-saving measures such as wall, roof, and floor slab insulation, glazing, and ventilation systems. Calculations were carried out for each location in a grid of climatic data sets covering all of Europe, with the aim of finding the set of component qualities with the lowest lifecycle costs for a typical building. Two hundred combinations of different ventilation, window and shading qualities were combined with different insulatio levels of the opaque building envelope.

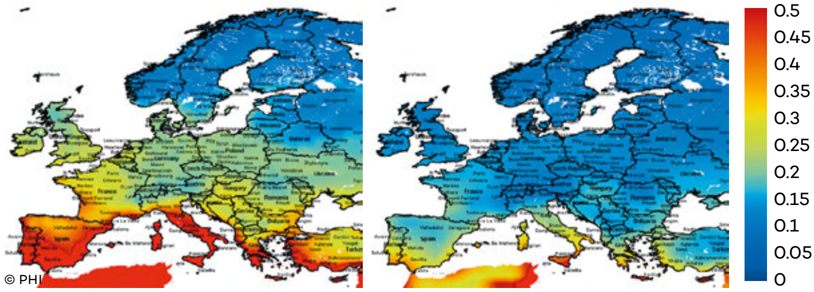


Fig. 4.7: Cost optimal U-values for basement ceiling insulation: In the historic building with only partial refurbishment (right), the economic optimum is achieved at a higher insulation thickness than in the new building (left).

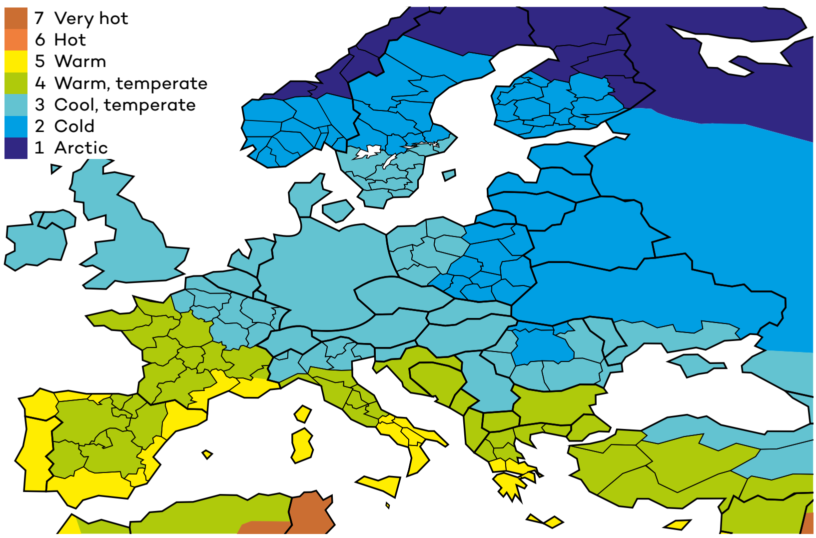


Fig. 4.8: Cost optimal component qualities: table (bottom) and climate zone map (top)

Climate zone			Arctic	Cold	Cool-temperate	Warm-temperate	Warm
Building component inclination							
Window		$U_{w,\ installed}$ [W/(m²K)]≤	0,45 / 0,50 / 0,60 / —	0,65 / 0,70 / 0,80 / —	0,85 / 0,90 / 1,00 / —	0,85 / 0,90 / 1,00 / —	1,30 / 1,35 / 1,45 / —
		If active heating present	$U_g - g*0.7 \le 0$	$U_g - g*1.0 \le 0$	$U_g - g*1.6 \le 0$	$U_g - g*2.8 \le -1$	$U_g - g*5.2 \le -2.3$
		Solar load during cooling period [kWh/m^2_{window}a]				≤ 100	
Door		U_D [W/(m²K)] (without installation thermal bridge)	≤ 0.35	≤ 0.55	≤ 0.75	≤0.75	≤ 1.20
Opaque envelope against	ambient air	Exterior insulation [W/(m²K)]	≤ 0.09	≤ 0.12	≤ 0.15	≤ 0.25	≤ 0.50
		Interior insulation [W/(m²K)]	≤ 0.25	≤ 0.30	≤ 0.35	≤ 0.45	≤ 0.75
		Exterior paint	—	—	—	—	—
	ground		Determined in PHPP from project specific heating and cooling degree days against ground.				
Ventilation		Heat recovery	≥ 80%	≥ 80%	≥ 75%	≥ 75%	—
		Humidity recovery	Yes	Yes	—	—	—

© PHI

The combination of components leading to the lowest sum of investment and energy costs was determined using the net present value method. Some building components were considered for the study that are not, or not widely, available (e.g. quadruple glazing). These may currently be expensive due to low production numbers. Estimated investment costs for these products under mass production conditions were used for the study.

The cost-optimal component set for the typical end-of-terrace house (new-build) used initially in the studies resulted in a functional passive house[1] at almost all locations. At the same time, the minimum requirements for thermal comfort and the prevention of moisture accumulation were easily met. In order to test the suitability of these component qualities for refurbishments, the method was also applied to several variations of another building, a typical three-storey Wilhelminian-style residential building in a historic city quarter. For this building, a full refurbishment with Passive House components (including remaining thermal bridges, which cannot be removed) was analysed, as was refurbishment with interior insulation. In additional studies only one component was refurbished, as this could potentially be the case in step-by-step renovations, or if selected measures are not possible due to cultural heritage restrictions. The resulting cost-optimal component qualities were often even better than for the typical new building (see Fig. 4.7, note for the historic building with only partial refurbishment the colour shifts towards blue which stands for lower optimal U-value, i.e. thicker insulation). One explanation for this is the longer heating period in less efficient buildings. Thus an individually improved building component can save more energy over the course of a year in such buildings than in a passive house, making it even more profitable to invest in better quality. Figure 4.8 shows cost-optimal energy efficiency levels for energy retrofits for all European climate zones (without taking into account the effect of even better cost-optimal component qualities in partial refurbishments, described above).

1 A functional Passive House can be air-conditioned simply by heating or cooling the amount of fresh air already required for hygiene.

4.3.2 Historic buildings and the Energy Performance of Buildings Directive (EPBD)

Legislation is a tried-and-tested tool that can help meet energy targets. The Energy Performance of Buildings Directive (EPBD) is such a tool. It operates on a European level and influences legislation in all member states with regard to energy use in the built environment. It is often perceived that the EPBD does not take historic buildings into account, however this is not strictly true. Member states may exempt listed historic buildings from some of the requirements, but not from all. A global overview of the EPBD requirements for existing buildings and the specific rules for listed historic buildings is given in Table 4.2. Note that the content of the table is an interpretation of the EPBD made by the author, and the national interpretation of the details may differ in the member states.

Tab. 4.2: Main requirements set by the (recast) EPBD for existing buildings and exemptions for historic buildings.

MAIN EPBD REQUIREMENTS FOR EXISTING BUILDINGS	EXEMPTION FOR LISTED HISTORIC BUILDINGS?
When existing buildings undergo major renovation, the renovated building or the building part has to meet national minimum energy performance requirements. In addition or as an alternative, requirements may be set for the renovated building elements.	Yes, member states may decide not to set or apply these requirements to officially protected buildings if compliance with certain requirements would unreasonably alter the appearance of the building.
If a significant part of a building envelope is retrofitted or replaced, the energy performance of this building element needs to meet national minimum energy performance requirements.	Idem, as above
Energy performance certificates are required when a building is constructed, sold or rented out to a new tenant and for all buildings bigger than 500 m² which are occupied by a public authority and frequently visited by the public (in the latter case, the certificate also needs to be displayed).	Idem, as above
If building systems (heating systems, hot water systems, air-conditioning systems, large ventilation systems) are installed, replaced or upgraded, national system requirements must be met.	No. System requirements must be applied, but only in so far as they are technically, economically and functionally feasible.
Large heating, ventilation and air-conditioning systems need to be inspected regularly.	No exemptions

4.3.3 EnerPHit: a voluntary standard for advanced energy retrofit

While the EPBD and its national adaptations set mandatory requirements for the energy demand of new buildings and renovations, there are also a number of additional voluntary energy schemes. Some exist only on a local or regional level, e.g. for municipal funding programmes, whereas other standards are valid nationally, throughout the whole of Europe or even worldwide. The Passive House standard was defined in the 1990s by the Passive House Institute in Germany. It is now widely applied to buildings all over the globe, from the mild climate of Portugal to hot and humid Shanghai or Minnesota's freezing cold winters. For all locations, the Passive House standard combines very high energy efficiency with excellent user comfort at minimal life-cycle costs.

In many European countries, the building renovation market has gained the main market share in the recent past. As stated above, when old buildings are renovated, it is often difficult to achieve the Passive House standard. Typical reasons for this are unavoidable thermal bridges as well as the general design of buildings, which was not originally optimised for energy efficiency. For such buildings, the Passive House Institute (PHI) introduced the [EnerPHit] standard in 2010. The basic principle is to modernise all energy-relevant elements of the building with Passive House components. This way almost all advantages of the Passive House standard can be gained in retrofits, even if the heating demand is not reduced all the way to the Passive House limit of 15 kWh/(m²a).

Fig. 4.9: EnerPHit seal

Typical Passive House components, which are required for EnerPHit retrofits in cool, temperate climates like Central Europe, include an efficient heat-recovery ventilation system, windows with triple glazing and insulated frames, more than 200 mm of thermal insulation and very good airtightness levels. Thermal bridge effects should be mitigated as best as possible, within reason.

The benefits of these measures for the building owner and occupants include:

→ Warm indoor surface temperatures, preventing condensation and mould and ensuring a much more even temperature distribution inside, contributing to optimal thermal comfort.
→ Improving airtightness prevents structural damage caused by the permeation of exterior building components by humid indoor air. Uncomfortable drafts caused by the inflow of cold outdoor air are also avoided.
→ Comfort ventilation with heat recovery tangibly improves air quality with positive health effects and helps reduce mould by removing moisture reliably.
→ Using Passive House components in modernisation can reduce heat demand by more than 90 percent. Carbon emissions for building heating are reduced to the same extent, if not more.
→ The sum of all energy-saving measures results in a yearly financial profit for owners and residents.

4.3.4 EnerPHit certification for historic buildings

An energy retrofit for a historic building is always a challenge, as great care has to be exercised to preserve the integrity of the historic substance and its characteristic appearance. Obviously not all energy saving measures that make sense for a standard retrofit of, for example, a post-war apartment building can be applied to a historic building. A historic facade with lavish ornamentation should not be covered with an exterior wall insulation system. Sometimes even interior insulation is not possible, because of wall paintings or other interior design elements worth preserving.

However this should not lead to the conclusion that no energy-saving measures can be implemented at all. In most historic buildings there are some parts with little or no heritage value, and in such cases full renovation with Passive House components is possible. A typical example would be town houses with ornamented street facades and unornamented rear facades. Interior insulation can be applied to the street facade, while the rear facade can be equipped with full exterior insulation and Passive House windows. If there are historic windows worth preserving in the street facade, these could be complemented by an additional interior layer of triple-glazed windows that takes over the thermal insulation function, while the exterior views are not compromised. In addition, a minimised low-impact heat-recovery ventilation system is possible in many historic buildings, if the designer carefully adapts it to the special characteristics of the building.

Fig. 4.10: Historic town house after renovation with interior insulation on the street facade and exterior insulation on the rear facade (amongst other measures). The heating demand could be lowered by approx. 80 % while preserving the appearance of the building.

Such an approach is also taken for the EnerPHit requirements. All construction components without heritage preservation restrictions should be retrofitted to the full efficiency level of the EnerPHit component requirements. For construction elements with historic value, energy efficiency enhancement is only required as far as it is compatible with the heritage preservation requirements. Such a component-based approach ensures that the maximum possible energy efficiency is achieved wherever possible, while maintaining the historic value of the building.

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4.4 ENERGY BALANCE CALCULATION

Zeno Bastian, Passive House Institute

4.4.1 What is an energy balance calculation?

4.4.1.1 Measured energy consumption and calculated energy demand

One of the most important purposes of buildings is to provide a comfortable indoor climate, which will differ most of the time from the frequently changing weather conditions outside. Ensuring that indoor temperature and relative humidity stay within certain comfort limits will normally require some energy input. In times of climate change and rising energy prices most owners are interested in knowing just how much energy their building needs for heating and cooling.

The easiest way is to measure the actual consumption of a building with, for example, a gas or electricity meter, which is installed by the energy provider for billing. However the figures obtained this way will not yield an accurate picture of the actual quality of the building. The reason for this is that there are a lot of non-building related factors that influence the heating and cooling energy consumption of a specific building during a specific period of time. These include:

- → weather (temperature, solar irradiation, wind, air humidity)
- → indoor temperature set by the occupants
- → amount of air change through windows or with a mechanical ventilation system
- → internal heat generation by electric appliances and body heat.

As a result of these factors, a building may have an energy consumption three or four times higher than that of a second otherwise identical building.

There are many occasions for which more suitable figures for describing the thermal properties of a building are needed:

- → for targeting a certain energy standard during the planning of the building
- → as evidence that legally required energy standards are met
- → for determining figures for legally required building energy labels
- → as evidence that voluntary energy performance standards are met, for example to obtain Passive House certification or government funding.

For all of the above an energy balance calculation is needed which will use standard assumptions for non-building related factors. The result is an energy demand, i.e. the energy that will be required in the modelled building under standard conditions in order to maintain comfortable indoor conditions. These figures are much more suitable for describing the actual quality of the building. They can also be used for comparison of two or several buildings in terms of their energy efficiency level. An energy demand calculation that predicts the building's performance is an essential tool for optimising its properties during the planning stage.

As a matter of principle the results of the energy balance calculation will in most cases differ from the measured energy consumption. In old buildings with low efficiency standards the calculated energy demand will usually be higher than the measured values. The reason for this is that the energy balance calculation is based on certain assumptions, for example an air exchange rate and indoor temperature considered healthy and comfortable indoor conditions. In reality, however, the occupants of old buildings with a high energy demand often live in unhealthy and uncomfortable conditions as this saves significant heating and cooling costs.

4.4.1.2 Principles of an energy balance according to the European standard EN 13790

EN 13790 uses a method that determines the heating demand based on an energy balance of heat losses and heat gains. As a rule the heat gains (including heating) must always equal the heat losses.

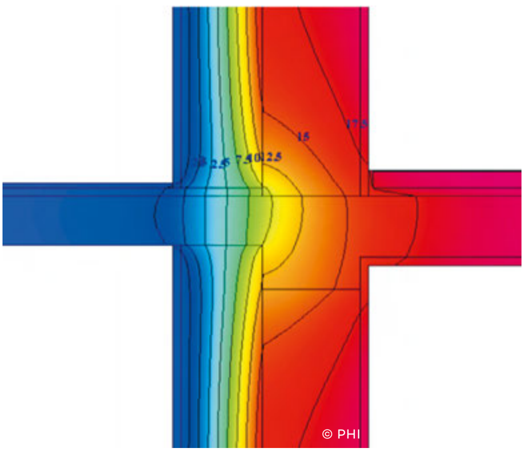


Fig. 4.11: Results of a two dimensional thermal bridge calculation. As the isotherms indicate, heat flowing through thermal bridges adds to the transmission heat losses.

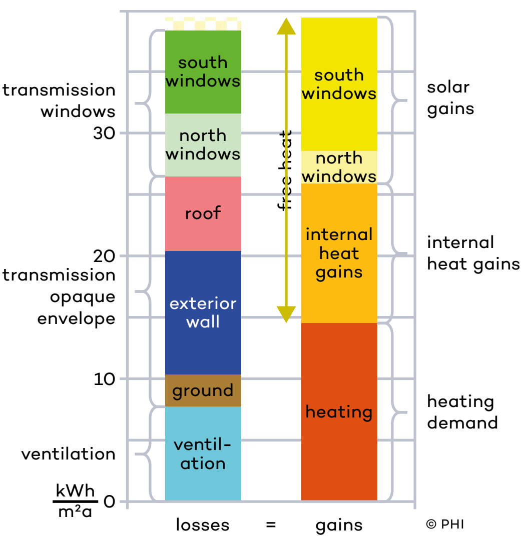


Fig. 4.12: Space heating balance with heat losses and heat gains in kWh / (m²a)

The heat losses include:

→ transmission heat losses (heat flow through the building fabric of roofs, exterior walls, basement ceilings / floor slabs, and windows); the transmission heat losses are composed of the losses through regular building components plus the thermal bridge losses at building component junctions;
→ ventilation losses (air exchange by intentional ventilation through windows or a mechanical ventilation system plus unwanted air exchange through leaks in the building envelope).

The heat gains are composed of:

→ the internal heat gains (by electrical appliances and body heat of the occupants);
→ heat gains by solar irradiation mainly through windows.

Not all of the heat gains are usable since they may occur at times when the indoor temperature is already above the set point.

The basic principle of an energy balance calculation is to subtract the usable energy gains from the energy losses. The remaining difference in the energy flows has to be provided by the heating system, i.e. the difference is the heating demand of the building.

As a basis for the calculation an energy balance boundary has to be defined. This is a theoretical boundary separating the conditioned indoor climate from the outdoor climate. It encloses all rooms of the building which are heated or cooled. Only the heat that flows through this boundary is taken into account for the calculation. Unconditioned rooms, such as basements, are generally not included in the balance boundary.

The calculations can either be carried out for each month or for the whole heating period. The monthly method is somewhat more precise and also yields information about the length of the heating period. However, comparisons have shown that the annual method is accurate enough for most purposes (see [AkkP 13]).

4.4.1.3 Dynamic building simulation vs. stationary energy balances

Dynamic methods, in contrast to stationary methods like EN 13790, calculate a dynamic model of the building. This means that for every point of time, energy flows, temperatures etc. are determined, whereas EN 13790 only yields total for one month or for the whole heating period. Dynamic calculation allows for a more detailed consideration of temporary effects like, for example scheduled ventilation and the thermal storage effects of the building. It is also suitable for building models with several temperature zones. The main applications of dynamic simulations are scientific research and the design of special use buildings.

However, setting up a dynamic simulation model is quite time-consuming and complicated, which results in a relatively high risk of undetected errors. For a simple terraced house, more than 2,000 separate data entries may be required, not including climate data. This makes it less suitable for the routine work of architects, engineers, and energy consultants. For this target group, software based on a stationary method like EN 13790 is much more efficient. It is simpler to use and yields instant and robust results without excessive computing time.

4.4.2 The Passive House Planning Package (PHPP)

The Passive House Planning Package (PHPP) is an integrated tool for stationary energy balance calculations, including all energy flows within the system boundary. The programme is based in large part on European and international standards (including EN ISO 13790). It was originally developed as a design tool for buildings with very low energy demand (such as passive houses).

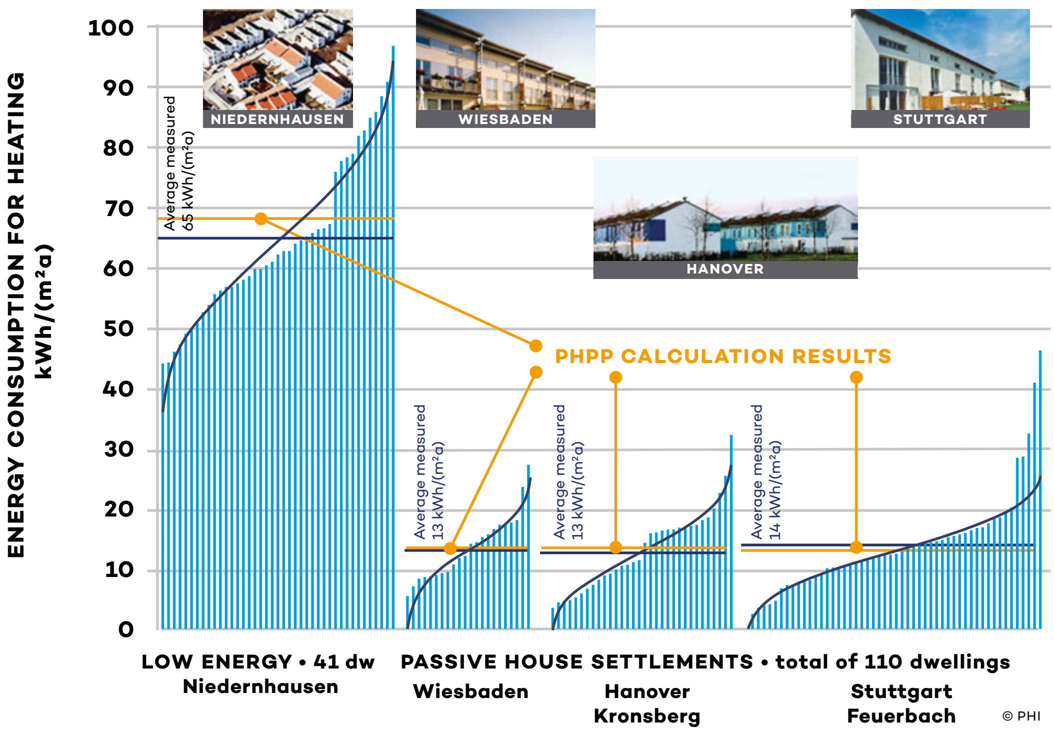
PHPP was presented for the first time in 1998 (see [AkkP13]) by the Passive House Institute (PHI) and has since been continuously developed. The package is based on MS Excel and includes worksheets for heating and cooling energy balances, heat distribution and supply, electricity demand and primary energy demand. New design modules have been added successively, for example calculation of window parameters, shading, heating load, and summer performance.

The calculations are instantaneous, i.e. after changing an entry the user can immediately see the effect on the energy balance of the building. This makes it easy to compare components of different qualities and thus optimise processes for a specific construction project – whether a new construction or a refurbishment – in a step by step manner. Typical monthly climatic conditions for the building location are selected as the underlying boundary conditions (particularly temperature and solar radiation), and the PHPP calculates a monthly heating or cooling demand for the relevant building. The PHPP can thus be used for different climatic regions around the world. The PHPP forms the basis for PHI's system of quality assurance and certification of a building as a passive house or an energy retrofit with Passive House components (EnerPHit).

The PHPP is continuously validated and refined based on measurements and new research results. As part of accompanying scientific research studies, measurements from more than 300 projects have so far been compared with calculation results.

The PHPP energy balance module was shown to depict the thermal building characteristics of passive houses as well as buildings with poorer energy standards very accurately.

Fig. 4.13: Comparison of PHPP calculation with consumption measurements in housing developments with low energy and passive houses



The diagram in Figure 4.13 shows the results of a comparison between measurements and PHPP calculations for different houses at different locations. It is interesting to note that in all cases, irrespective of the thermal insulation standard of the buildings, there is high relative scatter due to user behaviour, but the calculations matched the average measurement results very accurately.

4.4.2.1 Application of PHPP in historic buildings

Even though PHPP was originally developed for low energy and passive houses, it also works well for old or historic buildings. Accurate results can be expected for space heating and cooling, primary energy, and domestic hot water and electricity demands.

In very low-efficiency buildings stationary software like PHPP, however, is typically not completely reliable for heating and cooling load calculations, which are necessary for dimensioning technical systems, because of the highly volatile energy flows in such buildings. Also, the summer comfort calculation (the frequency of overheating in summer in buildings without active cooling systems) will be less accurate for buildings with low insulation levels. PHI plans to solve these issues in an upcoming PHPP version.

4.4.2.2 New PHPP features for building renovations developed in the 3ENCULT project (3ENCULT)

The PHPP has been applied to all 3ENCULT case study buildings for calculating energy demand before and after the interventions. PHPP was further developed in 3ENCULT in order to enhance its usefulness for building renovations.

Verification for retrofit certification Former versions of PHPP could only be used for Passive House verification and certification. A new feature allows designers to verify the energy demand in modernised historic buildings or other refurbishment projects. A dropdown menu in the 'Verification' worksheet offers the options 'Passive House' or 'EnerPHit'. The energy performance of the building in question is subsequently rated according to the corresponding certification criteria.

Variant calculation When new houses are built, there is generally one consistent planning design, which is implemented without major interruption during a limited time span. In refurbishments of historic buildings there are at least two options that have to be considered, which are the state of the building before and after refurbishment. Frequently, refurbishments are not carried out as a complete renovation all at once. Instead, the different energy saving measures are carried out step by step at the time when the component in question needs to be replaced. An important PHPP improvement is that it is possible to calculate in parallel each stage of the refurbishment process with the corresponding energy demand.

Select active variants >>>		Active: 3-Renovation with Passive House components	Existing	Moderate thermal insulation	Renovation with Passive House components
Results	**Units**	3	1	2	3
Annual heating demand	kwh/(m²a)	**15,1**	419,9	62,6	15,1
Heating load	W/m²	**10,7**	175,3	36,3	10,7
Overall specific space cooling demand	kwh/(m²a)	**0,6**	7,0	1,5	0,6
Cooling load	W/m²	**7,8**	34,5	14,0	7,8
Frequency of overheating	%				
Total primary energy demand	kwh/(m²a)	**62,3**	552,7	118,8	62,3
Certifiable as Passive House?	yes/no	**yes**	no	no	yes
User defined	Units	Link	Link	Link	Link

Tab. 4.3: Screenshot from PHPP 'Variants' worksheet

For this a new 'Variants' worksheet has been created. The worksheet allows for the representation of different refurbishment stages or different variants of the same stage. A variant can be chosen and activated; i.e. the values of this variant are used in the other PHPP worksheets. At the top of the worksheet the calculation results for annual heating demand and other demands are shown for each variant. In the rows below the specific values for each variant and component can be entered, for example the wall insulation thickness.

Economic efficiency evaluation of energy saving measures In the new PHPP 'Comparison' worksheet it is possible to calculate the economics of energy retrofit measures. The calculation is based on the input of the building properties in the 'Variants' worksheet. The results include the calculation of the yearly net profit generated by the measure as well as the cost per kWh of energy saved. The maximum investment sum at which the energy saving measure will still be profitable is also given.

PHPP also shows the calculated energy savings as usable energy, total energy, primary energy and the corresponding CO_2 emissions.

The results calculated for interior surface temperatures help the user to evaluate whether a construction fulfils minimum requirements regarding thermal comfort and prevention of mould growth.

References

EN 13790 EN ISO 13790:2008, *Thermal performance of buildings – Calculation of energy use for space heating and cooling.*

AkkP13 *Energiebilanzen mit dem Passivhaus Projektierungspaket,* Arbeitskreis kostengünstige Passivhäuser, Protokollband Nr. 13, Passive House Institute, Darmstadt, Germany, 1998.

PHPP *Passive House Planning Package (PHPP),* Passive House Institute, Darmstadt, Germany, 1998–2014, available at www.passivehouse.com

4.5 HYGROTHERMAL SIMULATION

Ayman Bishara, Ulrich Ruisinger, Rudolf Plagge, Dresden University of Technology

4.5.1 Introduction

Different assessment and simulation methods are available for the hygrothermal analysis of wall and roof constructions. While the assessment methods proceed on the assumption of constant climate conditions, the simulation methods usually use real climate data. This clarifies the different objectives of these methods: With the assessment method, reality is deliberately not being depicted, but rather a typical or extreme case is being assessed. In contrast to that, the simulation method tries to calculate as closely to reality as possible without neglecting an appropriate margin of safety.

There are several hygrothermal assessment methods:

→ the method of determining the minimum requirements for thermal protection according to DIN 4108-2 (German Standard 4108-part 2);
→ the Glaser method according to DIN 4108-3 (German Standard 4108, part 3);
→ the monthly balance method according to DIN EN ISO 13788 (European Standard), which is essentially based on the Glaser method; and
→ the COND method being developed by Dresden University of Technology.

A lot of hygrothermal simulation methods are available, using software programs such as WUFI (Fraunhofer Institute for Building Physics) and DELPHIN (Dresden University of Technology). It can be assumed that more than two dozen simulation methods with differing ease of use have been developed in this field worldwide. The majority of them, however, originated in the context of research projects or dissertations and were therefore often not developed further afterwards, which means that they can no longer be used.

This article aims at offering practitioners new approaches to the hygrothermal assessment of wall and roof structures. It is divided into three main parts: the first part gives an overview of available calculation methods. The numeric hygrothermal program DELPHIN is also introduced in greater detail. The second part illustrates evaluation criteria for hygrothermal simulation processes as well as the evaluation of simulation results, using an example taken from practice (old brick masonry, TUD Case Study). The third part summarises the results of the calculation process and draws conclusions.

4.5.2 Overview of methods used

The COND method, the simulation program DELPHIN and the DIN-method were selected from available methods for the purpose of conducting comparable calculations with reference to a construction catalogue. Table 4.4 gives an overview of the transport and storage processes of the selected methods, to be discussed in the following sections. The requirements and limitations are of interest, as well as the incoming parameters.

	DIN (GERMAN-STANDARD)	COND	DELPHIN
thermal conduction (latent heat)	constant thermal conductivity (latent heat not considered)	thermal conductivity depends on humidity (latent heat not considered)	thermal conductivity depends on humidity (latent heat considered)
thermal storage	not considered	not considered	considered
vapour diffusion	constant vapour diffusion	constant vapour diffusion	vapour diffusion depends on humidity
capillary liquid water transport	not considered	linear increase of liquid water transport, diffusion model	liquid water transport depends on humidity, capillary pressure model and diffusion model as alternative
moisture storage	not considered	approximated, linear moisture storage	measured hygroscopic and over-hygroscopic moisture storage
air flux	not considered	not considered	air pressure profile calculation, convective air flux through air pressure gradient and buoancy
climate boundary conditions	constant according to DIN 4108	constant (DIN) or other reasonable constant values	constant or transient, e.g. hourly, 'real' climate data

Tab. 4.4: Overview of the methods: considered transport and storage processes

4.5.2.1 Simulation programme DELPHIN

The modelling of physical processes and the development of modern calculation technology allow quantitative information on the hygrothermal performance of buildings to be obtained under natural climate conditions by software simulations of heat and moisture transport processes.

What DELPHIN calculates The programme uses the model of coupled heat, humidity and air transport in capillary porous building materials. This means that the following transport processes are numerically analysed by means of balance equations:

- → *Heat transport* through building components and construction details (e.g. wall constructions, thermal bridges, connection details);
- → *Moisture transport* (liquid and vapour transport) as well as *Moisture storage* in constructions as an indicator of longevity (prevention of moisture damage etc.);
- → *Air transport* (fluxes of moist and warm air through open porous building materials and leaks, condensation in cooler zones).

The calculations can be made one-dimensionally (e.g. for the analysis of an undisturbed wall cross-section), while two-dimensional sections through details of construction can also be reviewed. Thereby the effects of thermal bridges on the moisture behaviour of window connections, for example, can be evaluated. Real climate conditions are provided in detailed data sets, which means that the climate components

→ temperature, relative humidity,
→ solar radiation (light and thermal radiation) and
→ precipitation, wind direction and wind velocity

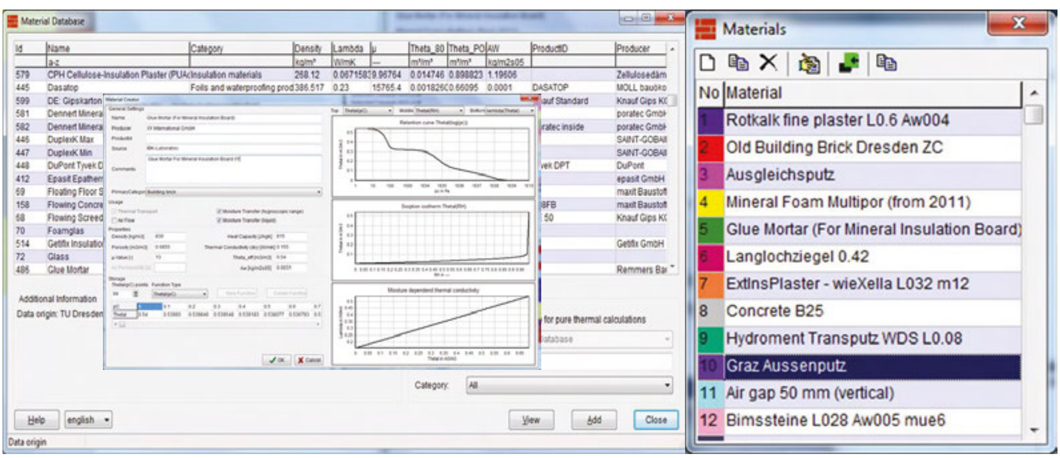
are applied as year-long sequences on an hourly basis. Users can take reference conditions from German DIN standards, or define their own.

Programme components The DELPHIN programme package consists of a user interface (input interface), a solver (calculation module) and a post-processing tool for the visualisation of the result data. Databases for air and material data sets are connected. The interactive project creation enables a quick generation of the construction to be calculated and a definition, as well as the assignment of data sets for boundary conditions and materials. Climate data sets and material data sets can be imported from the databases.

The graphic output allows the presentation of the results with natural, illustrative functions such as two-dimensional coloured image and contour plots, location and time cuts and the post processing or further processing of data. Physical units, axis scales, and any choice of display section are integrated. It is also possible for a time-resolved representation in the form of a film or exported graphic formats to be embedded in other programmes (word processing etc.). The graphic analysis of the results can be done both during the calculation and afterwards.

The material properties are taken into account as material functions. The material database contains data that has been measured by the physical building research and development laboratory (see Fig. 4.14).

Fig. 4.14: DELPHIN material database



4.5.3 Evaluation criteria for hygrothermal simulation processes

The illustrated evaluation criteria method is demonstrated here with reference to a practical application (see Case Study 6). Under investigation was the old brick masonry of a building, plastered on both sides, which was insulated on the inside with calcium silicate boards of different thicknesses. The calcium silicate boards show high capillary liquid water conductivity and are agglutinated all-over (see Fig. 4.15). A thin layer of interior plaster has been added as finishing layer. The interior insulation is vapour permeable, so condensate due to vapour flux can be expected in regions below the dew point. Table 4.5 below presents characteristic material parameters of the exemplary wall construction being used in the DIN- and COND-process.

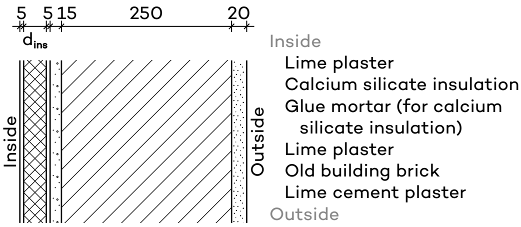


Fig. 4.15: Exemplary wall construction for the demonstration of the evaluation criteria

Tab. 4.5: Material parameters of the exemplary wall construction

Material	ρ	λ	μ	w_{80}	w_{eff}	A_w
	kg/m³	W/mK	-	Vol%	Vol%	kg/m²s$^{0.5}$
lime plaster	1600	0,75	11	5,4	34,4	0,081
calcium silicate	270	0,065	3,9	0,5	90,0	1,172
bounding mortar	1520	1,00	32	7,9	32,9	0,020
lime plaster (hist.)	1800	0,82	12	1,1	28,5	0,127
existing building brick	1710	0,80	8,3	0,5	31,9	0,333
lime cement plaster	1900	0,80	15	4,9	22,0	0,033

4.5.3.1 Condensation and drying cycle

Capillary condensation The pore system of capillary-porous building-materials stores water in absorbed liquid form at nearly any degree of relative humidity. The percentage of moisture storage in terms of water vapour, however, is negligibly small. The causal mechanisms that lead to storage in liquid form are referred to as ‘vapour pressure lowering’ and ‘capillary condensation’. In pores of building materials that contain water, the vapour pressure above the meniscus (the curved surface of the water) will be lower than the saturation vapour pressure. Therefore the relative air humidity in the air-filled pores of a capillary porous building material is usually less than 100 %, even though liquid water is present. The process of capillary condensation starts at air humidity around 30 %.

Definition of the moisture range The variation of the coexistence of water-filled and air-filled pores over time, including the phase transformation processes (evaporation and condensation), is described by simulation programmes by means of a moisture storage model. This realistic modelling has a drawback, because it cannot regard all of the liquid water present as being condensate. Therefore the hygroscopic moisture range is defined between 1 % to 95 % relative humidity. The binding energies of the absorbed water at the lower limit of the hygroscopic humidity range lie in the magnitude of the thermal energy. The amount of capillary tension and thereby of binding energies is lower with increasing moisture content (and relative humidity). The decrease of binding energies accelerates disproportionally at relative humidity above 95 %, so it may be assumed that this water is now present almost as free-moving water (DIN 15148).

Moisture storage function Within the hygroscopic range, the moisture storage function is determined by exsiccators with salt, while above the hygroscopic range it is usually determined by means of pressure-plate equipment. The entire moisture storage function is therefore conveniently divided into the hygroscopic range, the sorption isotherm and the overhygroscopic range, the suction suspense curve. The latter is not derived from the relative humidity, but from the capillary pressure (see Fig. 4.16).

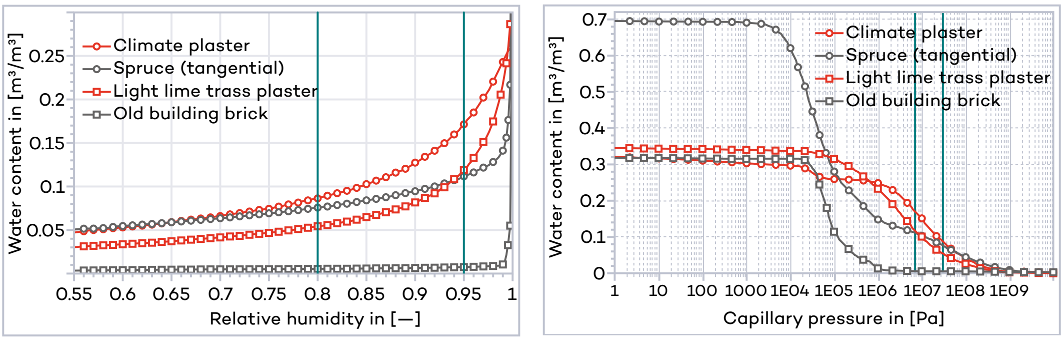


Fig. 4.16: Material functions of different materials in comparison. Left: sorption isotherms; right: moisture retention curves. The perpendicular green lines mark 80 % and 95 % air humidity. Together a sorption isotherm and a moisture retentioncurve describe the moisture storage function.

Chronological progress of the transport processes The evaluation of enclosing constructions depicts the chronological progress of the transport and accumulation processes regarding heat and moisture. These processes proceed under the influence of defined climate conditions that usually repeat cyclically. The definition of initial conditions is necessary for the simulations. In these simulations a relative humidity of 80 % and a temperature of 10° C were chosen. The initial moisture content of the materials then corresponds to the practical moisture content, in DELPHIN labeled as θ80.

Amount of condensate without driving rain Starting from the initial state, the DELPHIN output shows the variation of the integral moisture mass over time, as well as the annual condensation and drying cycles (see Fig. 4.17). The progress of the integral amount of moisture gives an idea of how fast a construction reacts to external influences. The transient condition is the time duration until e.g. the integral moisture mass does not change anymore from year to year. In the example below the settling time is reached in the third year. However, it is possible that even after 30 years this process is not

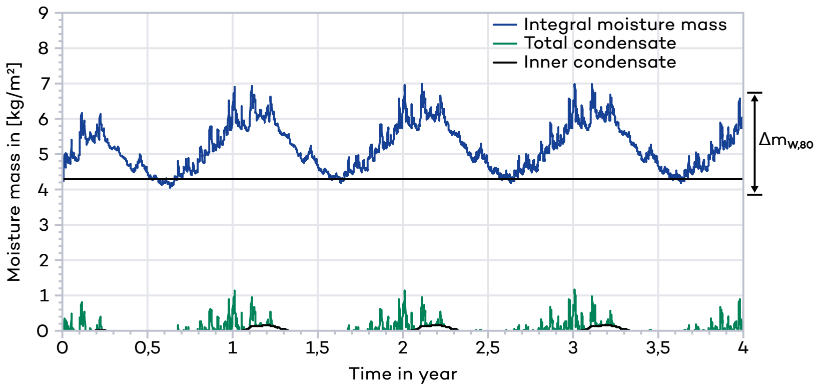


Fig. 4.17: Exemplary construction without driving rain (north-facing). Blue line: progress of integral moisture mass. Green line: integral condensate mass with 80 mm insulation. Black line: condensate in the inner layers (insulation, constituent plaster and inner brick or stone layer).

Without driving rain (north)	SYMBOL	UNIT	NON-REFURBISHED	30 MM	50 MM	80 MM
Difference between initial humidity (80 %) and maximum humidity	$\Delta m_{W,80}$	kg/m2	0.727	1.800	2.200	2.527
Maximum inner condensate	$\Delta m_{W,T,int}$	kg/m2	0.0	0.166	0.270	0.398

Tab. 4.6: Results for an exemplary wall construction (north-facing) without driving rain

complete. An average lower amount of moisture compared to its initial state indicates lower moisture stress. Only the study of the local distribution of moisture in combination with the material functions can clarify whether an uncritical situation can be assumed, though.

The difference between the amount of water at the beginning of the simulation and the maximum amount of water ($\Delta m_{W,80}$) occurring in the steady state is specified. These values can vary considerably in different constructions, mainly due to different storage behaviour of the materials concerned. The maximum internal condensate quantities are documented in Table 4.6. In simulations without driving rain, the quantity of internal condensate $\Delta m_{W,T,int}$ may be compared with the limit according to DIN 4108-3.

Amount of condensate with driving rain The amount of moisture in a west-facing facade exposed to heavy rain is displayed below (see Fig. 4.18). The traces are noticeably different from those showing progress without driving rain. The major part of the penetrating rain is stored in the outer layer. Higher humidity not only causes higher thermal conductivity, but also greater liquid water conductivity, allowing more driving rain to penetrate further and reach the inner part of the stone. The circumstance that, even in a non-refurbished construction, driving rain can advance very deep into the construction is taken into account here in the maximum values of the inner condensate.

The maximum value of condensate for the non-refurbished version and the maximum value of the refurbished version are entered in the table below. From Table 4.7 it can be noticed that the amount of moisture is much higher with exposure to driving rain. The integral moisture is briefly more than

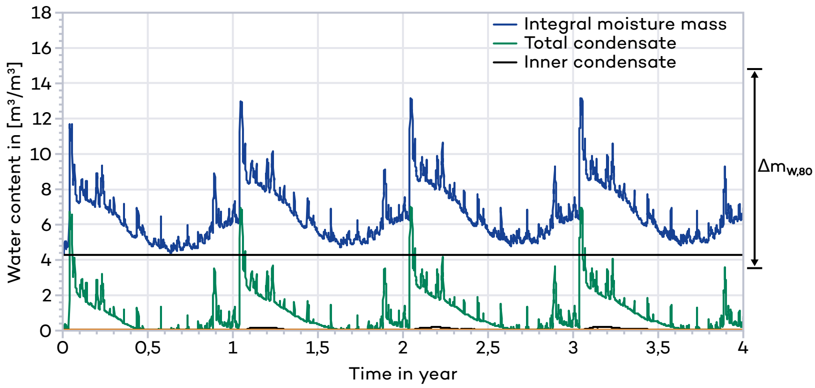


Fig. 4.18: Exemplary construction with driving rain (west-facing). Blue line: progress of integral moisture mass and inner condensate (black line) with 80 mm insulation. Orange line (near x-axis): maximum value of the non-refurbished construction, here 0.141 kg/m². The insulation system causes the difference of orange and black lines.

Exposed to driving rain (west)	SYMBOL	UNIT	NON-REFURBISHED	30 MM	50 MM	80 MM
Difference between initial humidity (80%) and maximum humidity	$\Delta m_{W,80}$	kg/m2	6.701	8.426	9.021	9.574
Maximum inner condensate	$\Delta m_{W,T,int}$	kg/m2	0.141	1.090	1.628	2.012

Tab. 4.7: Results for an exemplary wall construction in west orientation with driving rain

twice as high; the maximum total amount of condensate (turquoise line) adds up to 8 kg/m² and the maximum internal amount of condensate temporarily lies at 2.0 kg/m².

4.5.3.2 Heat loss through transmission

In order to gain a balanced value for the unsteady transmission of heat through the construction components, the heat flux density and the temperature difference between the inner and outer air are evaluated. The unsteady heat transfer coefficient can be defined according to Equation 1 as the quotient of the heat flux density q_{HP} through the inner surface and the difference between the inner and outside air temperatures $\theta_{i,HP} - \theta_{e,HP}$. In each case, the time-average values of the heating period (HP) are accounted for in the calculation.

$$U_{inst,HP} = \frac{q_{HP}}{\theta_{i,HP} - \theta_{e,HP}} = \frac{\int_{HP} q(t).dt}{\int_{HP} (\theta_i - \theta_e).dt}$$

The total of the heat transfer resistance (according to DIN 6946) and the thermal resistance corresponds to the reciprocal U-value. This gives the unsteady thermal insulation resistance $R_{inst,HP}$ during the heating season:

$$R_{inst,HP} = \frac{1}{U_{inst,HP}} - R_{si} - R_{se}$$

To determine a continuous heating period, the course of the outside temperature is first approximated with a cosine function (see Fig. 4.19). Analogous to the guidance contained in the German Energy Saving Ordinance of 2007 (EnEV), 10°C were determined as heating limit in the evaluation.

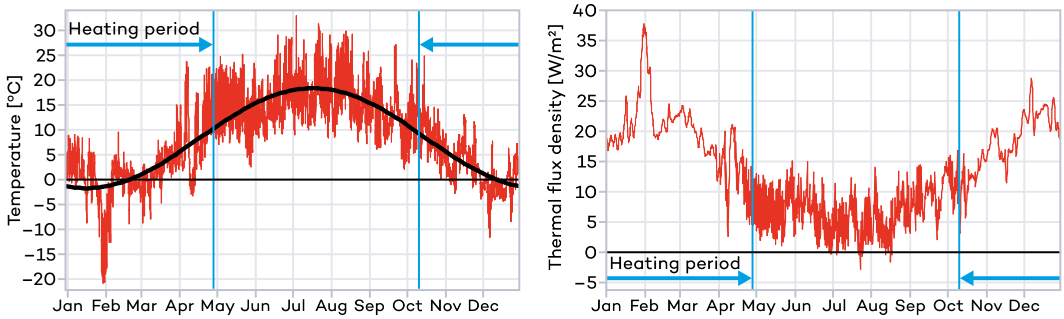


Fig. 4.19: Approximation of outside temperature with cosine function (left) and simulation of thermal flux density (right) for the calculation of unsteady U-value.

Besides the direct calculation of the U-value based on heat flux density, additional advantages of the unsteady process are apparent: even the long-wave radiation is considered, in addition to the relevant heat storage processes in solid walls, the moisture-dependent thermal conductivity and solar gains. Furthermore there is a possibility that climate data specific to a particular region can be considered. Unsteady U-values give more detailed information on the expected transmission heat losses.

Without driving rain (north)	SYMBOL	UNIT	NON-REFURBISHED	30 MM	50 MM	80 MM
Average heat flux density	q_{HP}	W/m²	34,90	18,73	14,41	10,68
Unsteady heat transfer coefficient	$U_{inst,\ HP}$	W/m²*K	1,98	1,06	0,82	0,61
Unsteady thermal insulation resistance	$R_{inst,\ HP}$	m²*K/W	0,34	0,77	1,05	1,48

Tab. 4.8: Results for an exemplary wall construction (north-facing) without driving rain

The values for the heat transfer coefficient and the thermal insulation resistance vary from the results of the simplified steady-state processes, while the percentage alteration with reference to the DIN values increases along with the thickness of the insulation layer. A direct comparison shows that, for an exemplary wall construction, increases in the U-value of 4.2 %, 6.0 %, 6.5 % and 7.0 % are registered for the non-refurbished construction and the 30/50/80 mm insulated alternatives respectively.

4.5.3.3 Microclimate on the inner wall surface

Temperature and humidity on wall surface The near-wall microclimate, meaning the progress over time of temperature and relative humidity on the inner wall surface, can be calculated by means of hygrothermal simulation. From the knowledge of the microclimate on the inner wall surface, the danger of mould growth can be deduced, because a ‘favourable’ microclimate is a necessary condition for mould growth.

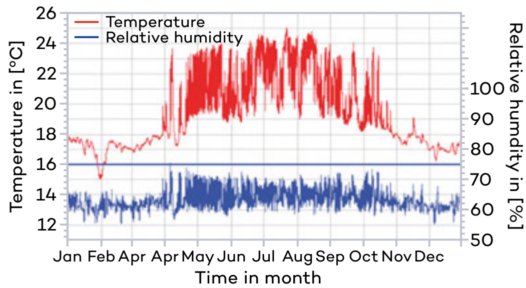


Fig. 4.20: Temperature and relative humidity on the inner surface of a wall with 30 mm insulation (horizontal line emphasizes 75% relative humidity). The curves allow a first estimate of thermal discomfort and mould growth.

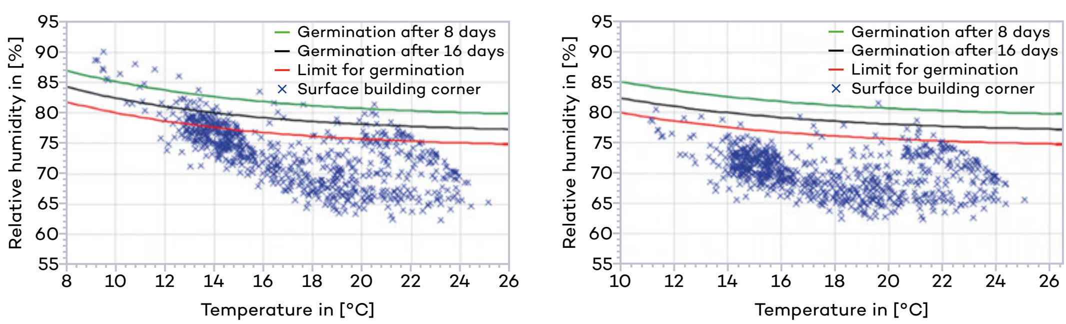
Influence of wall orientation The situation in building corners or other constructional details is generally considered to be more critical than in an uninterrupted area. Here the critical location is the north-west corner. The facade here receives the lowest solar radiation and has the highest exposure to driving rain. Mould spores could germinate inside the corner, owing to the low heat-flow resistance of only 30 mm insulation (see Fig. 4.21).

Not until the air humidity rises to $\psi_{si}=75\,\%$ (blue horizontal line in Fig. 4.22) can mould growth occur on common building materials (WTA-handout 6-3-05). For the evaluation of mould risk, it is initially sufficient to check the progress of the relative air humidity for violation of the 75 % limit. If that is not the case, the danger of mould can be excluded, under the assumed user conditions, but only for the surface or location examined.

Comparison with isopleths for mould fungus Temperature progress has to be included in the evaluation if the boundary value of $\psi_{si}=75\,\%$ is exceeded, because the germination and growth of mould depend strongly on the temperature. In this context, the annual course of the relative humidity over temperature is shown here (see Fig. 4.21). Each cross represents a twelve-hour-average-value of the paired values for air humidity and temperature. This time interval has been chosen because shorter violations of the limit for germination cannot cause mould growth. The solid lines, the isopleths, illustrate boundary values for germination. Isopleths are lines of same growth and represent an assessment of the probable germination of mould.

The limit of germination or LIM (= Lowest isopleth for mould growth) is indeed exceeded several times, although in the case of 50 mm insulation thickness the duration of this occurrence is not long enough for mould to germinate.

Fig. 4.21: Temperature and humidity values in north-west building corner with driving rain overlaid on isopleths. 30 mm insulation (left) is not enough to prevent mould growth, 50 mm insulation (right) is sufficient.



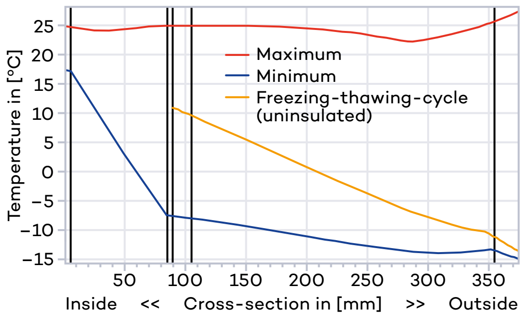


Fig. 4.22: Exemplary construction (80 mm insulation, northern side, without driving rain) minimum and maximum temperatures as well as the minimum temperature of the uninsulated wall (orange line)

4.5.3.4 Temperature and moisture profile, freezing-thawing-change

Besides the physical situation on inner wall surfaces, the distribution of humidity and temperature inside the wall (in cross-section) is of interest. Figures 4.22 and 4.23 with the temperature and humidity profiles show characteristic distributions over the course of one year. They include maximum, minimum and average profiles. The vertical black lines indicate the confines of the layers of the wall in the display of temperature and humidity profiles.

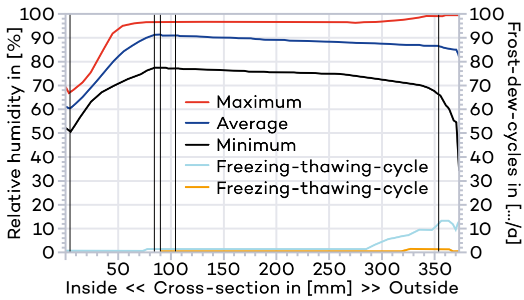
Temperature profiles The maximum and minimum temperature profiles are shown in Figure 4.22. The minimum temperature profile of the uninsulated construction is added in orange. Comparison of the minimum temperature profiles before and after the attachment of inner insulation makes clear the temperature increase for the new inner wall construction and the temperature decrease inside the existing wall construction. The cooling of the wall construction can lead to a prevention of the drying potential and thereby raise the danger of frost.

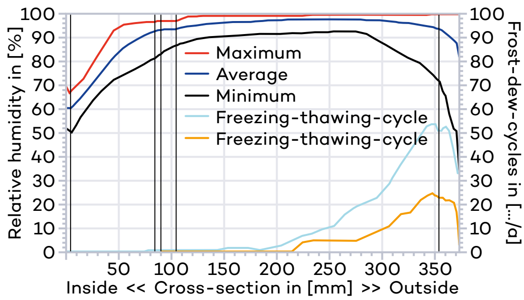
Only marginal differences in the temperature profiles can be detected between the simulations with and without the influence of driving rain, which is why with the chosen climate driving rain on north-facing walls hardly causes changes in the temperature behaviour.

Fig. 4.23: Exemplary construction (80 mm insulation, western side). Characteristic air humidity profile in the course of the year as well as the profile of the freezing-thawing-cycle. Left: without driving rain, Right: with driving rain

Relative humidity profiles Figure 4.23 displays the profiles of relative air humidity. The humidity profile is used to illustrate how far the humidity can approach the inner surface, which is generally referred to as 'breakdown'. The average profile provides an assessment of whether the relative humidity tends to follow the maximum or minimum profile.

The air humidity profile shows a distinct difference between the simulations with and without driving rain. From the comparison of the progress of the integral humidity masses over time, it was predictable (see Figs. 4.17 and





4.18) that the air humidity profiles with driving rain would be higher. Figure 4.23 shows that this situation, with very high driving-rain penetration of solid brick masonry leads to high moisture content of over 95 %. The humidity level decreases slightly towards the capillary-active inner insulation, while it increases steadily inside the inner insulation.

Freezing-Thawing-Cycle The profile with the values for the yearly Freezing-Thawing-Cycle (FTC) is also shown in the graph for the air humidity profiles. The annual FTC is calculated on the basis of the temperature and water content profiles resp. pore-size diameter. Very low quantities of ice forming and thawing, e.g. with an ice volume of 0.5 Vol- % in a material with a porosity of 28 Vol- %, count as one FTC as well. So, one FTC does not signify actual frost damages. Otherwise many facades would suffer from obvious frost *damages.* FTC profiles are suitable to compare different construction variants.

4.5.3.5. Evaluation of the simulation results

Minimum thermal protection, condensate The evaluation of the simulation takes place, as far as possible, analogously to proofs under steady-state calculations. As in steady-state calculations, identical boundary values are applied for exceeding the allowed amount of condensate and for the evaporation of the condensate, in respect of the minimum thermal protection, whereby evaporation refers solely to the drying of the inner condensate. Insulated west walls, exposed to driving rain (see Tab. 4.9) also contain high amounts of condensate. The inner condensate evaporates completely during the weather period, despite the high amount of condensate, even in west-facing structures (see Fig. 4.18).

Mould criteria The condition for the mould criteria differs from the requirements so far, because of the inclusion of temperature and the use of isopleths. An additional symbol is introduced for the mould criteria (see Tab. 4.9). The yellow circle signifies that although the condition $\psi_{si}(\theta)_{Co}$<LIM has not been met, the duration of the transgression of LIM is certainly not sufficient for mould growth.

4.5.4 Closing summary

A closing summary in the form of a matrix in Table 4.10 brings together the results of the calculation processes according to DIN, COND and DELPHIN for different insulation thicknesses. The COND process and the simulation results allow the option with 80 mm thick insulation. All other constructions do not satisfy the requirements for minimum thermal protection.

A green rectangle means that the tests discussed here have been passed in all respects using the chosen method. A red rectangle indicates that the essential requirements of each evaluation process have not been fulfilled and that under the given conditions this construction is not suitable for use. An orange rectangle indicates that under exposure to driving rain the requirements would not be fulfilled in a worst-case scenario. However, as this construction might in fact work anyway under unfavourable boundary conditions, it should not be ruled out completely.

Simulation with driving rain The matrix of simulations with driving rain (see Tab. 4.9) can be interpreted as follows. The large amount of penetrating rain is based on the assumption of some very unfavourable boundary conditions. That is why non-compliance with the maximum amount of inner condensate and the incomplete evaporation of the inner condensate only result in an orange warning. If, however, the amount of inner condensate is exceeded in the simulation without driving rain, or the evaporation of the condensate is not given, the construction will receive a negative assessment. The designer then has to search the building for construction details that need to be examined for potential defects and consider whether the design provides sufficient protection from driving rain to guarantee lasting freedom from moisture penetration. At this point, it should be noted again that basing the analyses on a different climate could lead to a different conclusion.

Tab. 4.9: Evaluation of the simulation results for an exemplary wall. Above: north-facing without driving rain. Below: west-facing with driving rain

Without driving rain (north)	CONDITION	NON-REFURBISHED	30 MM	50 MM	80 MM
Minimum thermal protection	$R_{inst} \geq 1.2$ m²*K/W	✗	✗	✗	✓
Allowed amount of condensate	$m_{W,T,\,int} \leq 1.0$ kg/m²	✓	✓	✓	✓
Evaporation of the condensate	$m_{W,T,\,int} \leq m_{W,V}$	✓	✓	✓	✓
Avoidance of mould	φ_{si} (θ) < LIM	✗	✓	✓	✓

With driving rain (west)	CONDITION	NON-REFURBISHED	30 MM	50 MM	80 MM
Minimum thermal protection	$R_{inst} \geq 1.2$ m²*K/W	✗	✗	✗	✓
Allowed amount of condensate	$m_{W,T,\,int} \leq 1.0$ kg/m²	✓	✗	✗	✗
Evaporation of the condensate	$m_{W,T,\,int} \leq m_{W,V}$	✓	✓	✓	✓
Avoidance of mould - wall	φ_{si} (θ) < LIM	✗	✓	✓	✓
- northwest corner	φ_{si} $(\theta)_{Co}$ < LIM	✗	✗	○	○

Tab. 4.10: Closing evaluation of the construction, separated according to evaluation methods and climate conditions

	NON-REFURBISHED	30 MM	50 MM	80 MM
DIN 4108	[red]	[red]	[red]	[red]
COND	[red]	[red]	[red]	[green]
DELPHIN without driving rain	[red]	[red]	[red]	[green]
DELPHIN driving rain exposed	[red]	[red]	[red]	[orange]

Conclusion One of the priorities in planning renovation work is the evaluation of moisture protection. It must be considered if the permanent success of an energy-efficient renovation is to be ensured. This means that every component of critical constructions must be examined and evaluated (e.g. condensation, driving rain load, ascending humidity, building moisture and thermal bridges). Another important aspect concerns the compatibility of the interior insulation and the substrate. The interior insulation should be dimensioned so as to avoid surface condensation and limit internal condensation, with the goal of maintaining the drying potential. Calculation and evaluation methods as mentioned above (e.g. COND, Standard 4108) and simulation programmes (e.g. DELPHIN) are currently available as planning tools. Their use requires knowledge of each required building material parameter.

The detailed evaluation of the hygrothermal situation (e.g. with internal insulation) requires the integration of moisture management into the planning phase. That means the hygrothermal simulation has to be performed using real climate conditions in order to evaluate complex construction details (e.g. for thermal bridges). The protection of the exterior walls from driving rain and the airtightness/convection inside the construction also need to be considered.

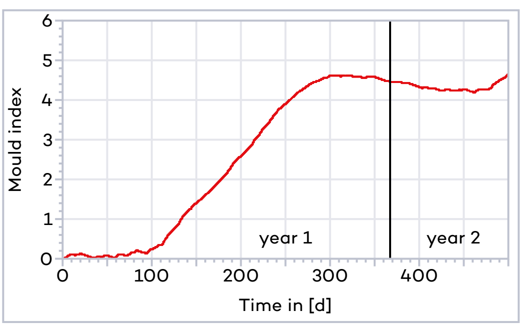
4.5.5 Outlook

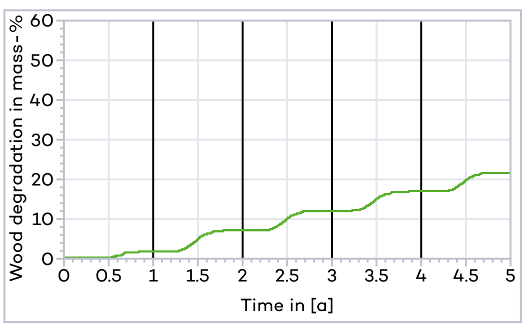
As knowledge about damage processes and the possibilities of damage modelling increase, evaluation criteria change or are replaced by others. Discussed but not yet implemented in guidelines are alternative models of mould growth evaluation as presented in [6] or the calculation of wood degradation in dependency of temperature, humidity and time [7].

The mould index [6] in Figure 4.24 (left) indicates the degree of mould growth on an internal wall surface. While '0' means no mould growth the maximal index of '6' means complete coverage with mould. On the right-hand side of Figure 4.24 the progress of wood degradation [7] within a time span of five years is depicted. In this case, after five years more than 20% of the wood mass have been destroyed by fungal growth.

Other approaches in assessing 'real' damage processes, as shown in the WTA handout 6–5 [9], at least now consider e.g. the saturation degree of materials, which is closer to the true phenomenon, frost-thaw change, than the overhygroscopic moisture mass.

Fig. 4.24: Example for the progress of the mould on a wall surface (left) and the degradation of a wooden beam (right)





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5 ENERGY EFFICIENCY SOLUTIONS

5.1 INTERIOR INSULATION

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An additional layer of insulation can increase the thermal performance of the walls of an existing building considerably. From the point of view of building physics, exterior insulation is generally preferred as a fail-safe option; in most cases it is also the least expensive and technically least demanding solution. Building professionals are highly familiar with it and therefore it is not dealt with in this book.

In this chapter, we present different systems for insulating walls from the interior, describe their peculiarities and propose best-practice solutions for design and implementation. The focus lies on capillary active systems, which have been analysed specifically in 3ENCULT.

5.1.1 Why interior insulation?

Insulating a wall – be it from the exterior or the interior – has a number of positive effects, ranging from energy savings, CO_2 reduction and the prevention of mould growth on cold surfaces, to better comfort and increased property value.

Even if – as outlined above – exterior insulation is usually the preferable solution, there are situations in which the insulation of a wall from the interior is justifiable and advisable:

- → Historic listed buildings with facades worthy of preservation, such as half-timbered facades, or stucco facades;
- → Buildings very close to the neighbouring one, where insufficient space is available for exterior insulation;
- → Not enough roof overhang present (or possible) for external insulation;
- → Apartment houses in which not all co-owners agree to energy-saving facade renovation;
- → Rooms only used occasionally, such as guest rooms and hobby rooms, or buildings only used intermittently, such as churches, community halls, clubhouses, and holiday homes.

At this point, it is important to note that insulating a wall from the interior does not just mean attaching insulation board, but carefully planning and installing a complete interior insulation system, including the right levelling mortar, adhesive, foil where needed, plaster, and, finally, paint. Usually manufacturers provide the whole system and can make specific recommendations.

Interior insulation systems require the integration of moisture management into the planning phase, as well as the careful design of details such as window reveals and internal wall connections.

5.1.2 Interior insulation systems (IIS)

With interior insulation, the existing wall will become much colder. This not only reduces its drying potential, but might also lead to condensation of water vapour, especially at the former interior surface, which is now covered by insulation.

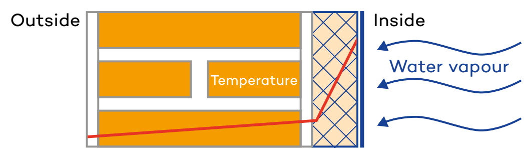
Moisture management is therefore a major task for the development of interior insulation systems. There are two principal ways of dealing with the moisture issue and preventing accumulation in the wall cross-section: (I) vapour-impermeable systems and (II) vapour-permeable, capillary-active systems.

Vapour-impermeable interior insulation systems Such systems hinder or prevent the water vapour flux into the wall – with vapour-retardant foils, dense interior plaster, or vapour-resistant insulating layers. The positive aspect is clear: the accumulation of condensate inside the wall is avoided. However, there is a possible negative impact: the construction cannot dry out towards the inside, which might be an issue if, for example, driving rain penetrates the wall. Moreover, in practice it might be very difficult to achieve the necessary quality in the design and on-site construction of connections, penetrations and deformations (as, for instance, at the beam ends of timber beam ceilings).

Vapour-retardant systems display similar properties. They reduce vapour diffusion from the inside to the outside, but at the same time the existing wall structure can still dry out towards the room to a certain extent.

There are also vapour-retardant systems where the vapour conductivity changes depending on the surrounding moisture level. They might be used where an existing roof with relatively high vapour-resistance in an outer layer has to be insulated from the interior. During winter the low relative humidity in the room causes the foil to have high resistance, so little vapour enters the construction; in summer water vapour transport shows a reversal process. Higher outside temperature causes water vapour transport towards the room, leading to an increase of the foil's moisture, and reduces its resistance, so that the construction can dry out.

Fig. 5.1: Operating principle of vapour-tight interior insulation



Vapour-permeable, capillary-active, interior insulation systems These systems allow vapour to diffuse into walls; they buffer the resulting moisture and remove the liquefied water from the condensation zone back towards the room [3, 4]. Thanks to the hygroscopic storage capacity of vapour-permeable, capillary-active interior insulation systems, humidity peaks in indoor air can be buffered and the indoor climate can be regulated. Their capillarity (liquid conductivity in over-hygroscopic range) ensures that moisture is distributed rapidly and widely inside the insulation layer. This accelerates the drying process and improves the insulating effect of the insulation. Crucial to the functioning and performance of the interior insulation is the interaction between moisture buffering, vapour and liquid water transport. An assessment of interior insulation types therefore requires exact knowledge of these variables and more sophisticated measurements than usual. The following figure shows the principle of capillary-active interior insulation.

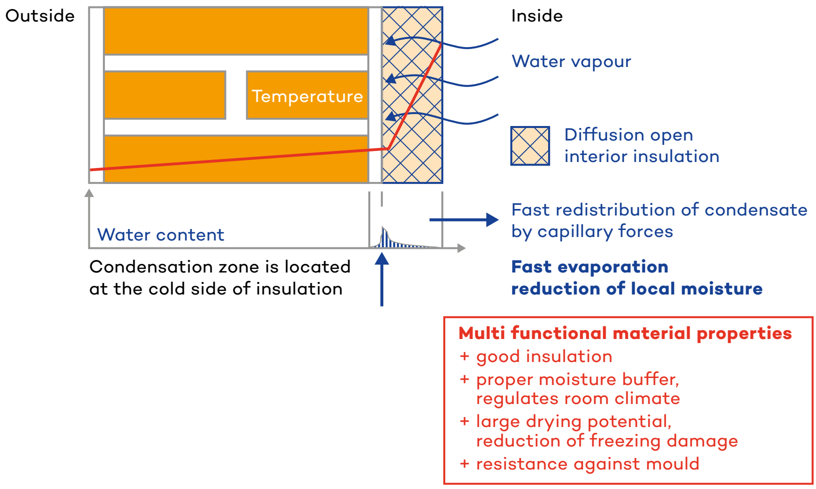
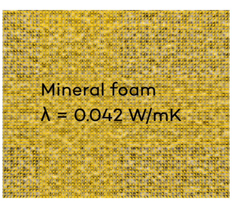


Fig. 5.2: Operating principle of capillary-active interior insulation: owing to the predominant winter temperature difference between inner and outer faces of the wall, water vapour diffuses into the construction. The condensate is mainly transported into the opposite direction back towards the room and evaporates.

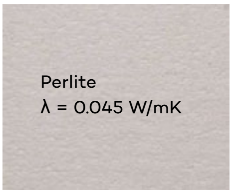
At the position where the dew point is reached, water vapour condenses and accumulates in the pores of the insulation material. The insulation material transports the condensate back towards the interior surface, because the vapour resistance and liquid conductivity of the insulation mortar is much lower than of the insulation material itself. Closer to the interior surface, the liquid water evaporates again.

5.1.3 Various materials used as interior insulation

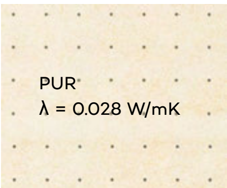
In the last twenty years, numerous insulation systems have been developed and optimised for use as interior insulation. A key advantage of vapour-permeable capillary-active systems is their multi-functionality: improvement of the insulation value, regulation of humidity, integration of fire protection, sound-proofing properties and the structural coupling to existing walls are all crucial for a construction. Because vapour-tight interior insulation systems lack robustness, many problems have been documented in the past. Vapour-permeable capillary-active interior insulation avoids most of them. In the following paragraphs, various vapour-permeable capillary-active interior insulation systems are described.



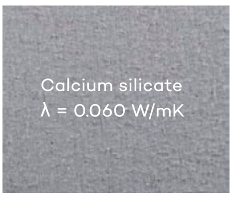
Mineral foam interior insulation system Mineral foam board is made from a material that is highly vapour-permeable, with good moisture storage and moderate moisture transport. The insulation board is easily workable. The system is non-combustible and offers a high degree of fire protection (German building material class A1). The measured thermal conductivity is $\lambda = 0.042$ W/mK.



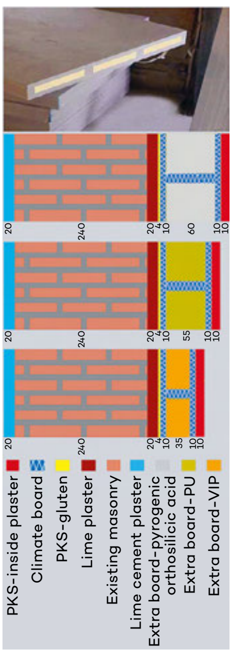
Perlite interior insulation system This product is capillary-active interior insulation based on natural expanded Perlite and a specific binder, with good moisture transport at high levels of humidity and moderate moisture storage. The board is lightweight, fibre-free and contains no toxic substances. The system is not combustible and offers a high degree of fire protection (German building material class A1). The product has a measured thermal conductivity of λ = 0.045 W/m·K.



PUR interior insulation system An optimal energy-saving option for interior insulation is PUR foam board with capillary pervasions. The product has a thermal conductivity of λ = 0.031 W/m·K. PUR has a better U-value than other interior insulation materials at the same thickness – or, to put it the other way round, less thickness is needed to achieve a certain U-value, which means that more usable space is left in the room. Since the board's vapour-diffusion resistance is several times higher than that of most other capillary-active systems, less condensate is formed. The system is capillary active owing to capillary pervasions. As the board is made from polyurethane, its resistance to fire (German building material class B2: normal flammable) and its sound insulation properties are poor.



Calcium silicate 'climate board' Calcium silicate climate board in combination with a moisture-regulating smooth lime plaster finish is an interior insulation system that has been known for a long time. It is sufficiently proven as a safe interior insulation system and can be considered an optimal solution with regard to vapour-permeability and room climate. Since the climate board has a thermal conductivity of λ = 0.06 W/m·K, it needs a greater insulation thickness than other such systems to obtain comparable insulation values. These climate boards are notable for effective moisture transport. The system is not combustible and offers a high degree of fire protection (German building material class A1). Acoustic protection is not impaired by the use of this inner insulation system



Calcium silicate 'Xtra climate board' Xtra climate board has all the positive characteristics of calcium silicate climate board, such as capillary-active moisture-regulation and fire-protection, as well as better insulating properties. Integrated into the climate board's structure is a high-performance thermal insulation core, which may consist either of pyrogenic orthosilicic acid (German building material class A1), vacuum insulation panels (VIP, class A1), or rigid polyurethane foam (PUR, class B1). This insulation system is compatible with all classic system components of calcium silicate climate board and is mounted similarly. The thermal conductivity depends on the thickness and the material of the insulation core. With a PUR core 3 cm thick, the measured thermal conductivity is λ = 0.0343 W/m·K.

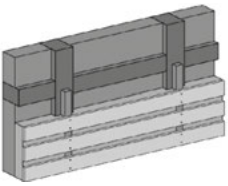


Fig. 5.3: Loam cork kieselguhr interior insulation

Loam cork kieselguhr interior insulation An ecologically friendly alternative to the aforementioned interior insulation systems in board form is the use of thermal insulation clay. This insulation system is a mixture of clay, expanded cork, kieselguhr (diatomaceous earth), and wood wool, which has slowly been compacted, and finally horizontal shuttering (as compaction boundary and plaster substrate). A layer of clay plaster is applied to the surface. Thermal insulation clay has a thermal conductivity of $\lambda = 0.075$ W/m·K and is therefore not as effective at saving energy as the other insulation materials examined here: at the same thickness, it achieves a less beneficial U-value. Owing to its smaller insulation effect and its higher resistance to vapour diffusion, less condensate is generated inside the wall construction. An increased moisture load is generated during installation, however, and drying-out might have to be accelerated by dedicated measures. One great advantage is that the system is very tolerant of subsequent building work and loads: radiators, services installations and domestic objects can be attached directly to the wooden construction. Furthermore, uneven surfaces or irregularities in the existing plaster do not have to be smoothed out extensively beforehand, thus avoiding the work of skimming with topcoat plaster, which is necessary for all other board systems. The effort involved in inserting the rammed clay mixture is nevertheless higher than that for attaching insulation materials in board form.

5.1.4 Regulation requirements for thermal protection

National regulations stipulate the mandatory requirements for thermal protection.

Moisture protection Moisture protection is particularly important in the planning of interior insulation: with interior insulation, the amount of heat transmitted through the walls is much lower and therefore the original building envelope is subject to greater temperature fluctuations. The standardised Glaser method is a simplified method of checking moisture protection and limited condensation in the construction. It accounts only for steady-state heat flow and vapour diffusion and is therefore not suitable for checking the moisture-protection of interior insulation if the effects of driving rain, building moisture and reverse diffusion in summer time, as well as moisture storage and liquid transport processes, are important functional mechanisms.

Fire protection, environmental protection, health and safety at work National and international building standards specify the requirements used in the building regulations and fire safety regulations. The manufacturers of the individual components of an interior insulation system must ensure that health hazards arise neither in the assembly nor in the use of that system. The regulations specific to that material and product-type must be observed. Any instructions given for assembly should state the necessary protective measures and precautions, as well as the possible dangers.

5.1.5 Guidance for the planning / use of an interior insulation system

A vapour-permeable and capillary-active insulation system should be dimensioned in a manner that surface condensation is avoided and inner condensate is limited. Moreover, with regard to driving rain, sufficient drying potential towards the inside is required, so as to avoid damage to the construction.

Analysis of the state of construction At the beginning of the planning process, it is necessary to conduct a thorough examination of the existing state of the property. This should include the examination of the following aspects in particular (including the system manufacturer's instructions for assembly and use):

1) Thermo-technical condition of the building such as: present U-value, building material, thermal bridges and building-component dimensioning;
2) Moisture condition of the building;
→ moisture content of the masonry wall;
→ salt loads;
→ possibility of removing moisture-sensitive material layers (e.g. gypsum plaster);
→ necessity and possibility of removing diffusion-impeding layers (e.g. oil paint);
3) User-induced moisture load;
4) Further noticeable damage, e.g. mould growth, crystallisation;
5) General physical state of the exterior building components.

Preparation of the surfaces With all insulation materials in board form, a leveling mortar can become necessary to create an even surface – if there is no full contact between insulation board and the surface of the existing historic wall, the capillary principle cannot work. This plaster is preferably applied as NHL plaster (natural hydraulic lime) or lime plaster with a low cement content, possessing a vapour diffusion resistance < 15; sufficient capillary activity (Aw > 1 $kg/(m^2h^{0.5})$ and high porosity (> 50 Vol %); this serves as the substrate for the inner insulation panels. The strength should average out at 3 – 4 N/mm^2. The base plaster must be even and bearing.

Outdoor and indoor climates The outdoor climate conditions for the calculation's 'boundary and transitional conditions' should be selected according to EN 15026. When assessing the usability of a particular interior insulation system, the real climate-data records of the city / region concerned should be used. Special attention should be paid to the direction of driving rain, which can differ from place to place.

As regards the indoor climate, ventilation systems have a positive effect on the room climate and reduce the moisture load in the whole construction.

Driving rain protection of the exterior wall With interior insulation, the old construction as a whole becomes much colder and this also changes the drying potential of the wall. Possible loads can be calculated with the help of EN ISO 15927-3. The possible driving rain strain has to be accounted for in many constructions at the design stage. If necessary, safeguarding the façade from driving rain has to be combined with the installation of the interior insulation system. The information from the manufacturer on the versatility of the interior insulation system in dependence of the driving rain strain class should be followed.

Air tightness and convection Moisture accumulation due to the convection of moist, warm room air behind the interior insulation system must be prevented at all costs – convection can transport one or two orders of magnitude more vapour than diffusion can! Make sure that the following construction measures have been taken (where applicable):

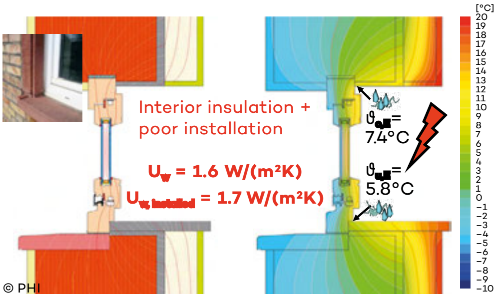
1) Full bonding of the insulation board onto the existing construction
   Note: Unevenness in the substrate can only be partly compensated by the bonding mortar. Greater substrate tolerances must be evened out with a suitable plaster before beginning the insulation work, so as to ensure continuous bonding of the diffusion-open and capillary-active system.
2) Full mechanical pressing of the system onto the subsurface
3) Continuous permanent airtight connection of the airtight layer/vapour-retardant foil to the adjacent building components. Particular attention needs to be paid to all penetrations, such as pipes, electrical systems, suspension, if they cannot be placed in a separate installation layer between airtight layer and room.

Detail planning In order to achieve certainty in planning, not only for the existing wall construction, but also for construction details, the system manufacturer should be contacted first for standard solutions that can be adapted to a specific object. Following this, the planner should assess critical or exceptional detail connections by means of further dimensional thermal or hygrothermal simulation (see Section 4.5).

In particular, the following points should be noted:

1) Since the original building envelope is subject to large temperature differences, the planning of an interior insulation measure needs to take account of any components, such as water pipes, that might be sensitive to frost.
2) In order to avoid thermal bridges, the interior insulation system should be continued into the window and door reveals.
3) Increased heat loss can occur especially via geometrical/structural thermal bridges, such as in corners and at connections to internal walls and ceilings. To counteract this, insulation wedges or other system-compliant detail solutions can be applied to adjacent interior walls, floors, or ceilings.

Not like this! Interior insulation **must** be contiunued to the window



The correct way: interior insulation must be continued to the window and the window sill should be shortened

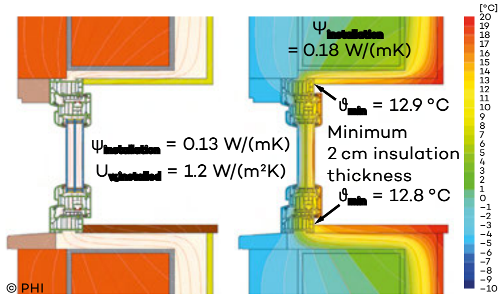
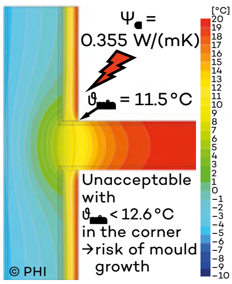
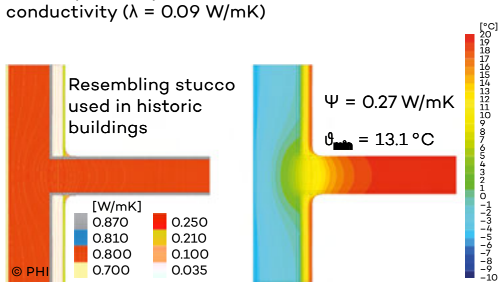


Fig. 5.4: Continuation of interior insulation to the window [7]

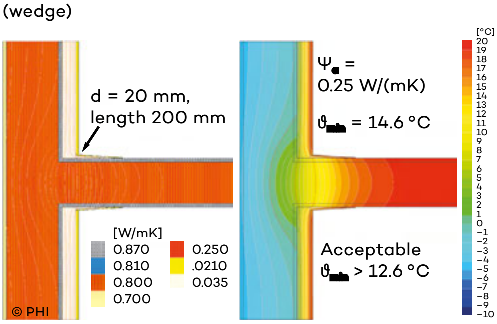
Fig. 5.5: Insulation wedges, curved plaster and metal sheets can solve the issue of critically low temperature at the connection to an internal wall or ceiling [7]



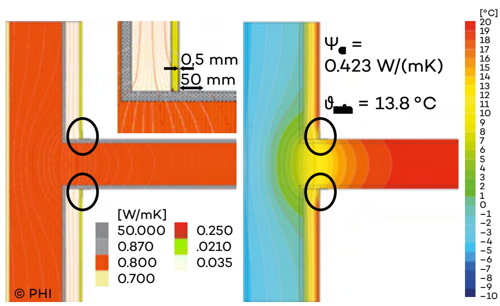
Curved piece of plaster with reduced thermal conductivity (λ = 0.09 W/mK)



Interior insulation with accompanying insulation (wedge)



Metal sheet as a passive heat collector in the corner



5.1.6 Summary and conclusion

For an interior insulation system to function properly, moisture management has to be integrated into the planning phase. That involves hygrothermal simulation using real climate conditions in order to evaluate complex construction details (e.g. thermal bridges). The driving rain protection of the exterior wall and the air tightness / convection must also be considered in the hygrothermal simulation and should be evaluated.

In general, the use of interior insulation has a lot of positive effects: energy saving and CO_2-reduction, with their concomitant environmental benefits; protection against condensate and mould growth in order to prevent damage to the construction as, for example, after window replacement (and / or with insufficient ventilation); the improvement of thermal comfort, which increases the value of rehabilitated building; the retention of brick masonry constructions as they are, and a short heating-up time for rooms in temporary use.

Capillary-active interior insulation, in particular, has numerous advantages: the regulation of moisture in the construction; the maintenance of a healthy room climate; vapour-permeable construction; the retention of the drying potential, and reduction of frost damage probability.

The energy-efficient upgrade of historic buildings requires special training and a detailed knowledge of various fields such as building materials, construction detailing, real climate conditions and hygrothermal simulation tools. Courses for architects, engineers and craftsmen in new subjects of this kind are available at university level and at graduate level.

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5.2 AIRTIGHTNESS AND MOISTURE PROTECTION AT BEAM ENDS

Søren Peper, Armin Bangert, Zeno Bastian, Passive House Institute / Michele Bianchi Janetti, Rainer Pfluger, Fabian Ochs, University of Innsbruck (Section 5.2.5)

5.2.1 Airtightness – how and why?

There are many disadvantages of air flowing in through joints and gaps in the building envelope. A large percentage of building damage is caused by leaks in the building envelope. Sound insulation is reduced, draughts cause discomfort for occupants and there are high heat losses.

That is why it has long been a requirement that the external envelopes of buildings must be airtight, as in the currently valid set of standards. The view to the contrary, which is still widespread, is nurtured by the mistaken assumption that building leaks ensure the air supply and ventilation of dwellings. However, air exchange is dependent to a very large degree on the current wind pressure and temperature uplift. There are substantial draughts in very leaky old buildings even at moderate wind speeds, but during periods of mild or calm weather, air exchange is inadequate. It is therefore not possible to ensure a sufficient rate of air change for the needs of hygiene and furthermore high ventilation heat losses are inevitable.

This applies just as much to new buildings as to old ones. In energy-efficient buildings an increased level of airtightness is particularly important. The hygienically essential rate of air change can be ensured by means of a ventilation system.

At best, ventilation through leaks causes discomfort and increases heat loss considerably, because heat recovery is ineffective in the case of air entering the building through leaks.

In particular, airtightness has the following advantages:

- prevention of moisture-related building damage;
- prevention of draughts and discomfort;
- prevention of high heat losses due to infiltration;
- improvement of sound insulation;
- improvement of indoor air quality (e.g. prevention of pollution with radon from the ground).

An adequate level of airtightness is the basis for:

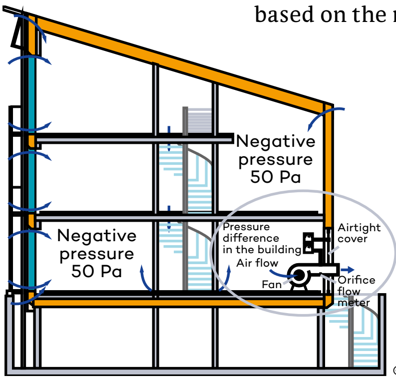
- the use of a variable demand-oriented ventilation system (functioning with directed air flows) and
- the effectiveness of the thermal insulation without air flowing through it.

It is necessary to use distinct terms here: the windtightness of a building component protects it from external air flowing in through the thermal insulation, which would otherwise impair the insulating effect and lead to increased energy consumption. This should not be confused with airtightness as discussed here, which refers to the movement of air through the building envelope, from the inside towards the outside or vice versa.

Windtightness is completely different from *airtightness,* which is an important function of energy-saving buildings.

5.2.1.1 Testing the airtightness

The airtightness of a building can be ascertained by means of a pressure test (airtightness measurement or 'blower door test') which determines the overall residual leakage of the building. A fan is built into a door or window, by means of which first depressurisation and then pressurisation is applied to the whole house. Using the measuring device of the blower, the volumetric air flow is measured at a pressure difference of between 10 and 70 Pa under depressurisation and then under pressurisation. The characteristic value of the volumetric air flow at a pressure difference of 50 Pa is then calculated based on the results [EN 13829].



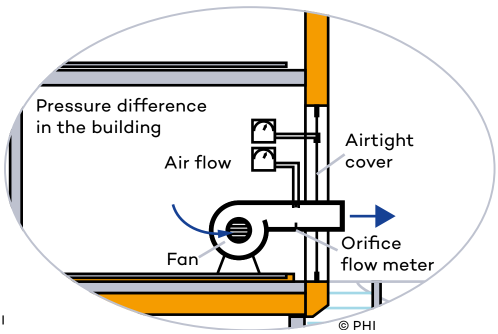


Fig. 5.6: Basic measurement setup for testing airtightness

Fig. 5.7: Detail of basic setup

5.2.1.2 Airtightness measurement in refurbishment projects

Depending on the refurbishment project (partial or complete refurbishment), the airtightness of the building can either be improved or completely re-planned. *In the case of complete refurbishments at least, it makes sense to ascertain the airtightness before and after the modernisation measures.* During the measurement before the start of modernisation work (initial or preliminary measurement), any problematic areas where airtightness may be inadequate can be checked or detected. These findings should then be incorporated into the planning for airtightness.

At the same time, the initial value of the project is documented, which can be used to ascertain the improvement after implementation of the modernisation measures. When taking the initial measurements for planning, the building components that will constitute the airtight layer must be specified. If specific areas prove to be airtight enough (e.g. intact interior plaster), they can be incorporated into the new concept.

5.2.2 Basic principles for planning airtightness

There are two planning fundamentals for achieving an airtight building envelope (based on [Feist, 2001]):

1) The *'pencil rule':* it must be possible to trace the airtight layer of the envelope on the drawings (for each part of the building) without lifting the pencil – except for any planned ventilation openings.
2) There must be *only one uninterrupted airtight layer.* Leaks CANNOT be remedied by another airtight layer before or after the first one (e.g. double-lip seals at windows, vestibule door behind the front door). To put it metaphorically: water won't stop leaking from a bucket with a leak if the bucket is placed inside another bucket with a leak.

Besides these basic principles, the following guidelines are helpful for successful planning of the airtightness – whether for a new construction or for a refurbishment of an old building (based on [Feist, 1995]):

- → *simplicity:* in order to reduce the likelihood of deficiencies in the workmanship, all construction details should be as simple to carry out as possible;
- → preferably *large uniform* areas with a simple basic construction;
- → choose reliable and proven basic construction techniques – no need to develop completely new or exceptional sealing systems;
- → *adhere to common principles* when planning different connections;
- → in principle, any *penetrations* of the sealing envelope should be avoided or minimised.

When planning an airtight building, three construction elements should be specified and taken into consideration:

1) construction techniques for airtightness in *standard constructions (areas of uniform construction);*
2) airtight *connections* of building components (along a 'line'); and
3) airtightness of *penetrations* through building components or at corners where more than two components meet (at a 'point').

5.2.3 Special features of modernisation

It has already been analysed in [AkkP 24] that reflecting on the requirements given above for the modernisation of old buildings quickly reveals the problems related to this: in old buildings there is hardly ever a continuous, easily accessible layer through all building components that can be used for creating the new airtight layer (see Fig. 5.9). In modernisations of old buildings, if there are interruptions in the airtight envelope, one can hardly expect the excellent results relating to the n_{50} values that are always achieved in the passive house. Therefore it should be considered how this objective can be achieved with old buildings. For old buildings, each case must be examined and determined individually. When deciding in favour of a concept, it is important to keep the whole building with all its aspects in mind. Some aspects will be examined in detail below.

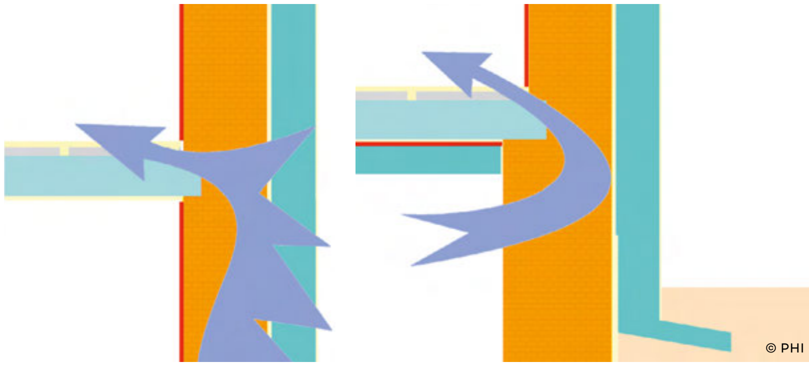


Fig. 5.8: Problematic area in an airtight layer on the inside: the wooden beam ceiling; subsequent sealing is only possible by removing the planks at the edge – with interior insulation this is vital.

Fig. 5.9: Absence of interior plaster in the depth of the wooden beam ceiling, exposed during modernisation work

In solid constructions requiring modernisation, there are often wooden beam ceilings that interrupt the airtight layer – which is usually the interior plaster. Figure 5.8 shows a leak from/to the outside near the wooden beam ceiling, with the airtight layer on the inside (left-hand diagram). With an unplastered masonry wall in the area of the floor construction, it can be expected that this will not be sufficiently airtight. The right-hand diagram shows a leak in the area of the wooden beam ceiling, towards the room below (e.g. basement), which is not located within the airtight volume. Figure 5.9 shows an unplastered area in an exposed floor construction.

During the complete refurbishment of a building built in the Wilhelminian style, some of the beam ends had to be replaced. For this reason the floor had to be opened up near the external walls of the rooms. In such cases, it is possible to create the uninterrupted airtight layer all along the inside of the exterior facade. In this case, interior insulation was attached. The airtight layer is only interrupted by the beam ends, each of which had to be joined to the airtight layer.

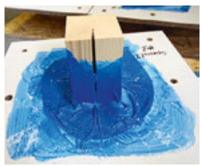
5.2.4 Integration of beams

On refurbishment projects with protected historic facades, the only option is usually the use of interior insulation. In refurbishments that demand a high level of energy efficiency, old and cracked wood beams represent a difficult challenge for designers and craftsmen. The conventional standards do not provide a solution for this problem. Even among experts there is no consensus on dealing with penetrations of the airtight layer by wooden beams. Inadequate integration of beam ends into the airtight layer of the building poses a risk. This will greatly increase the likelihood of structural damage due to convective moisture transport into the cold exterior wall area [AkkP 32]. Other penetrations of the airtight layer frequently occur in the roof area, particularly at the roof/wall connection to the eaves, the collar beam connection to rafters and where posts giving support to roof beams stand on the insulated top floor ceiling.

In particular, it is details such as the integration of cracked beam ends that are crucial to the level of airtightness achieved in a refurbished building. Deficient planning or execution can lead to an increased heating energy demand and structural damage. Frequently, old beams must be inspected at the point where they enter the wall in order to check the building substance (load-bearing structure) and determine any necessary work. Subject to the prerequisite that the wooden beam can be exposed completely (all around), the important issue is the execution of the airtight joint between the beam and the airtight layer of the wall with interior insulation.

Different methods of sealing the junction of the airtight layer with the beam have been scientifically tested [Peper; Bangert; Bastian, 2014]. A successful method always requires sealing of the cross-section of the crack in the beam. In contrast with simple sealing using tape, the leakage volume flow can be reduced significantly as soon as the crack is filled with (a suitable) material. In the case of larger cracks, if a channel is drilled for injecting sealant and subsequently filled in, this will result in extremely small leakage volume flow rates. Filling can be done using a suitable sealant or even a wooden dowel. This method of sealing cracks can then be combined with other methods of sealing between the beam and wall. However, the structural stability of the beam must be resolved prior to this, since drilling takes place.

Tab. 5.1: Overview of the different sealing methods which were carried out using sample beams.

			
Sealing tape	**Butyl rubber tape**	**Special solution (pure acrylic dispersion)**	**Plaster sealing tape**
			
Sealing membrane collar	**Drilled hole for injecting sealant**	**Thick bituminous coating**	**Poured gypsum** © PHI

© PHI

Fig. 5.10: Attempt to seal the joint of a beam with a wood panel using airtight adhesive tape

The crucial issue for successful sealing is that of whether the chosen technique succeeds in filling the crack or not. Special products must be used for creating the airtight joints following sealing of the cracks. The type of material of the special products chosen plays less of a role than the need to seal the crack to a large extent.

To some extent, the various materials differ considerably in use. Joining a beam to the airtight layer (vapour-retardant membrane, composite wood board, etc) is relatively quick if special sealing of the crack is not carried out.

In contrast, a qualitatively high standard of sealing – for which accessibility of the beam and thorough cleaning are prerequisites – requires more time and diligence. The material in each individual case must be selected in accordance with the respective boundary conditions.

The procedure for the successful sealing of beams can be reduced to the following steps:

→ expose the beam;
→ clean the area of the beam that is to be integrated;
→ fill cracks;
→ seal the junction of the beam and the wall face.

A prerequisite here is the use of suitable material (special products) throughout. The decision for or against a particular method of sealing wooden beam connections must always be reviewed case by case.

5.2.4.1 Procedure for exposing beams

As mentioned before, in order to achieve successful sealing of the beam, it is essential first to expose the beam and clean the relevant area. When applying interior insulation, some uninsulated spaces remain between the beams, where the temperature decreases on account of a lack of interior insulation. Problems with moisture may occur here if specific measures are not undertaken. Figure 5.10 shows how this problem can be solved by inserting vapour-impermeable insulation material between the wooden beams. K. H. Fingerling has published this method [Fingerling, 1995] and applied it to an existing building in Kassel, Germany.

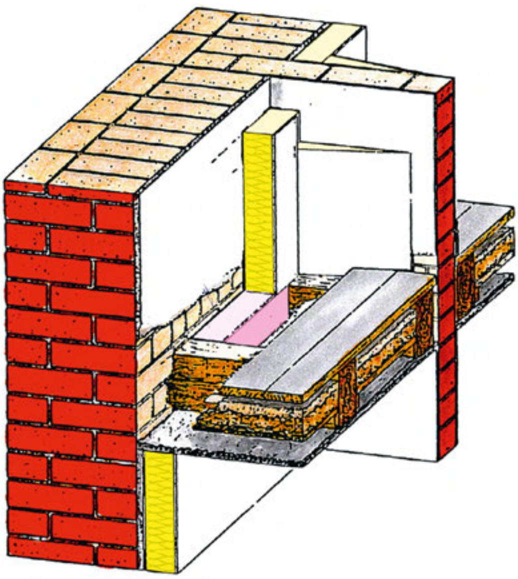


Fig. 5.11: Insulation and sealing of the spaces between the beams of a wooden beam ceiling in a solid masonry structure

A possible approach suggested by Fingerling is as follows:

→ Check the rain-proofing of the exterior walls in the area of the beam ends, and apply hydrophobic treatment of facing masonry if necessary. Check whether mechanical drying will be possible in the event of water penetration.
→ Remove the skirting board and two or three floorboards from the edge adjoining the wall.
→ Take out the wattle-and-daub, any other filling, and any other sub-construction below the floor for this width.
→ Coat the beam ends and all the faces of the beam with a vapour-retarding substance for a length of 20–25 cm (e.g. with bitumen or emulsion paint).
→ Insert vapour-retarding insulation panels (foam glass, XPS, EPS, PU) into the spaces between the beams. The insulation panels must have a thick coat of vapour-retardant adhesive compound so that a tight bond is formed with all uneven surfaces when inserted. Cold bitumen adhesive or PU adhesive is helpful here. Seal the connecting joint between the wall insula-

tion and the insulating panels in the spaces between the beams, using the same compound.

→ Fill in the remaining cavities.

→ Refit the floorboards as far as the wall insulation and refit the skirting boards.

5.2.4.2 Application area and reversibility

The main purpose of sealing procedures for wooden beams in particular is to preserve the building substance and improve thermal comfort for the occupants (absence of draughts). At the same time, heating energy is saved and CO_2 emissions are reduced. Of particular significance to protected historical buildings is the issue of the application area and the reversibility of these measures – that is, whether they can be undone or removed entirely.

This method can be applied to all buildings with wooden beams in the ceiling and / or in the roof if these beams penetrate the airtight layer, for example the interior plaster. An essential prerequisite for this is that beams in the area of penetration (sealing area) are exposed completely and cleaned thoroughly. It is often necessary to open up the wooden floor near the wall – at least from one side – in order to check the load-bearing structure during a refurbishment in any case.

The sealing measures only affect a limited area of the exposed surfaces of the wooden beams at their penetration of the airtight layer (about five to ten centimetres wide). The surface of the adjacent airtight layer, meaning the surrounding wall area (reinforced or new plaster etc), is also affected. The building characteristics are specifically altered by these measures; airtightness is increased, leading to a reduction in the ventilation heat losses and a decrease in the amount of water entering the construction. The improvement of airtightness should be carried out simultaneously with the installation of a ventilation system.

The purpose of sealing is to create a permanent joint with the airtight layer. The area of the wooden beams and the wall (for example) affected by this is relatively small. Depending on the method and workmanship, most of the sealing work is reversible; only small residues will remain on the surface. Depending on the individual case, drilled cracks in beams can be sealed with wooden dowels instead of sealant in order to avoid inserting foreign materials. Besides wooden dowels, special products that are designed for durability can also be used.

5.2.5 Assessment of the moisture risk in constructions, including convection in air cavities

Mould growth and structural damage can affect timber building components if the critical moisture content is exceeded. In the study discussed here [Bianchi Janetti; Ochs; Feist, 2013] the prediction of the moisture content at the timber beam heads of a real building with applied internal insulation was undertaken. The effect of air flowing through the gap between the timber beams and the masonry was taken into account.

Different scenarios were analysed, created by varying the pressure drop over the air gap. The results show that increasing air flux leads to higher water content inside the construction. The maximal value of volumetric air flux that is compatible with the preservation of the construction was determined.

Air is supposed to flow from the lower to the upper part of the building through the thin air gap between the beam ends and the masonry (bold line in Figure 5.12). Under different conditions, which are not discussed here, air may also flow from the inside to the outside of the building. Because internal insulation is applied, the external wall remains cold during the winter season.

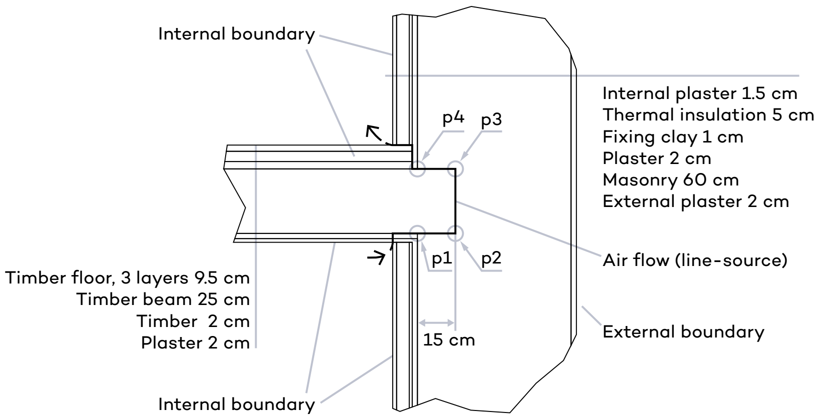


Fig. 5.12: Vertical section through the ceiling-wall junction. Positions 1 to 4 refer to the results reported in the following.

In order to prevent moisture damage, the ceiling-wall junction should be accurately sealed so as to avoid convection as far as possible. However, perfect sealing is practically impossible in real constructions. The purpose of the simulation presented below is to determine the maximal volumetric air flow that is compatible with protecting a construction from moisture damage.

The boundary and initial conditions used for the simulation are given in the upper table (A) of Figure 5.13. The interior values of temperature and relative humidity are assumed to be constant, whereas on the exterior periodic functions with an annual period are used (external temperature range: min. 2°C, max. 23°C; external RH range: min. 65 %, max. 73 %)

The volumetric air flow was calculated employing an empirical model (power low) which was calibrated by means of measurements performed by PHI [Peper; Bangert; Bastian, 2014]. In Table B of Figure 5.13, different sealing systems are reported upon. Case (a) represents a perfect airtight construction. This ideal condition is very difficult to achieve in practice. Case (b) concerns a very accurately sealed connection executed with sealing compound and adhesive tape, whereas case (c) represents an inexact execution of the same sealing method, resulting in higher air leakage. Case (d) concerns sealing with adhesive tape only (see Fig. 5.10). This last solution allows significant air leakage. The two graphs at the bottom of Figure 5.13 display the pressure drop and the volumetric air flow respectively, calculated according to [Bianchi Janetti; Ochs; Feist, 2013].

TABLE A. BOUNDARY AND INITIAL CONDITIONS

PARAMETER		INTERIOR	EXTERIOR	AIR GAP	INITIAL CONDITIONS
Temperature	[°C]	20	ϑe(t)	ϑa(s,t)	20
Relative humidity	[%]	40	φe(t)	φa(s,t)	60
Heat transfer coefficient	[W/(m² K)]	6	25	46.2	-
Moisture transfer coefficient	[Kg/(m² s Pa)]	3e-8	2e-7	3e-7	-

TABLE B. SIMULATED CASES

CASE	SEALING METHOD	MAX. VOLUMETRIC FLOW [m³/h]	MAX. AIR VELOCITY* [m/s]
a (no air flow)	-	0	0
b	Sealing compound + adhesive tape (accurate execution)	0.02	0.0028
c	Sealing compound + adhesive tape (mediocre execution)	0.07	0.009
d	Adhesive tape only	1.32	0.183
*calculated with a gap thickness of 0.002 m for the given boundary conditions			

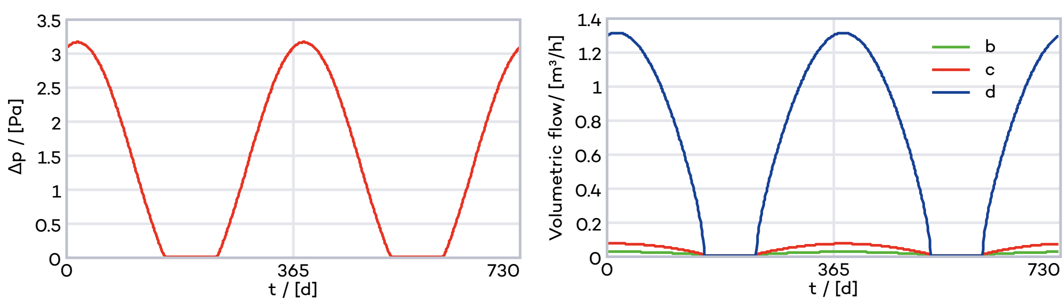


Fig. 5.13: Pressure drop across the gap (left) and volumetric air flow (right), calculated according to [Bianchi Janetti; Ochs; Feist, 2013] for cases b, c and d (see Tab. B)

In the diagrams shown in Figure 5.14, the wood-damage (W.D.) limit and the mould-germination (M.G.) limit are plotted. The sixteen-day isopleth for contaminated substrate has been taken as the mould germination limit. According to this isopleth model, mould germination can start after sixteen days of values over the said limit. The results for the four simulated variants (see Fig. 5.13, Tab. B) are shown on identical temperature/relative humidity (RH) diagrams. Each point represents the mean values over two weeks. Notice that cases (a) (airtight construction) and (b) (very good sealing) do not present any kind of risk. In case (c) there is no risk of wood damage, but mould growth may occur. In case (d) (significant air flow) even wood damage may occur. From these results, it is evident that a sealing quality corresponding to case (b) is the minimum necessary to protect the construction.

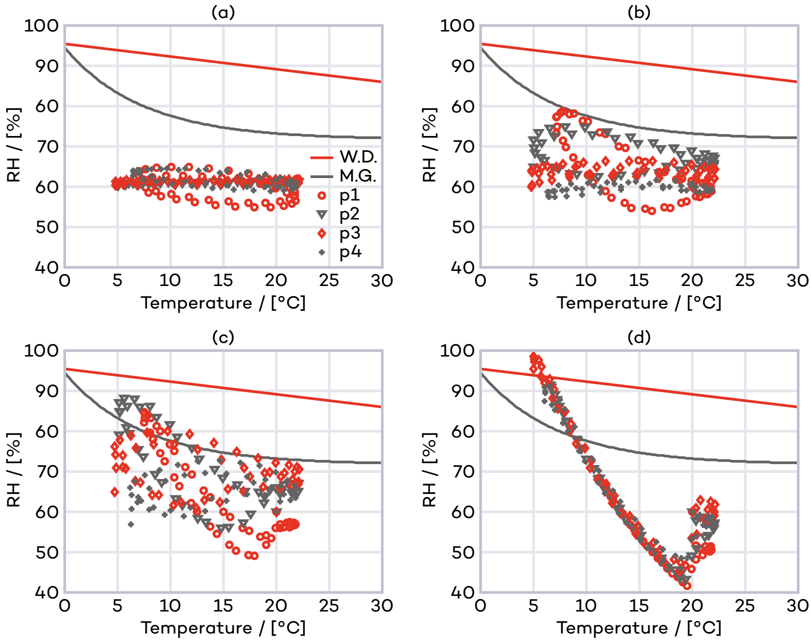


Fig. 5.14: Risk assessment of wood damage (W.D.) and mould germination (M.G., sixteen-days isopleth, dirty substrate) for increasing air velocity in the gap between beam and wall (cases (a) to (d)). In the diagrams the values of moisture and temperature at different positions (p1 to p4, Fig. 5.12) are plotted. Each point represents mean values over two weeks.

Note that the presence of internal insulation has significant influence not only on the temperature, but also on the humidity distribution. In Figure 5.15, the results for case (c) and case (d) are plotted for the same construction without thermal insulation. Neither wood damage nor mould germination would occur in this case under the given boundary conditions.

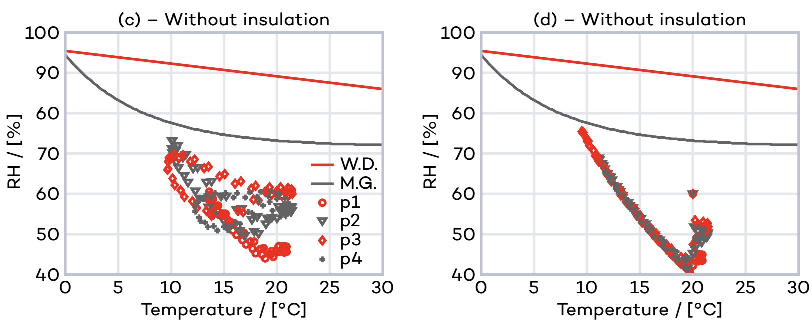


Fig. 5.15: Risk assessment of wood damage (W.D.) and mould germination (M.G., sixteen-days isopleth, dirty substrate) for a construction without internal insulation and for increasing air velocity in the gap between beam and wall (cases (c) and (d), see Fig. 5.13, Tab. B). In the diagrams the values of moisture and temperature at different positions (p1 to p4, see Fig. 5.12) are plotted. Each point represents mean values over two weeks.

5.2.6 Conclusion

The moisture risk at the ends of timber beams embedded in a wall with internal insulation was assessed, taking into account the influence of air convection between beam and masonry. The numerical results confirm the importance of achieving air tightness at the ceiling-beam junction, in order to avoid moisture damage. Considering that a perfectly airtight construction is difficult to produce in practice, different sealing systems were tested. The maximal value of volumetric air flow that is compatible with keeping a construction safe from water damage was determined (case (b), Fig. 5.13). This degree of protection can be achieved by employing sealing compound in combination with adhesive tape. These have to be applied as accurately as possible. Possible practical solutions, as well as references to the materials to be employed, are discussed in section 5.2.4.

The pressure drop across the air gap was determined by employing a simple model, which may introduce some inaccuracy into the results. This matter is to be investigated in further research. Further work will also concentrate on more accurate determination of the volumetric air flow and experimental validation of the numerical model.

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5.3 WINDOWS AND SHADING

Benjamin Krick, Passive House Institute

Windows play an important role in the character of a building and have to be treated with care. Original historic windows, however, do not fulfil today's requirements in terms of hygiene, comfort and energy efficiency. Using a historic building in a reasonable way means (among other things) improving the thermal quality of its windows in accordance with the historic context.

5.3.1 Thermal performance of windows

The thermal transmittance coefficient for the installed window is determined from the U-values of the glazing (U_g) and the frame (U_f), the thermal bridge loss coefficients of the glazing edge (Ψ_g) and the window installation ($\Psi_{Install}$), and the respective areas or lengths (see Fig. 5.16):

Equation 1: Determining the U-value for an installed window

$$U_{w,installed} = \frac{U_g \cdot A_g + U_f \cdot A_f + \Psi_g \cdot l_g + \Psi_{install} \cdot l_{install}}{A_g + A_f}$$

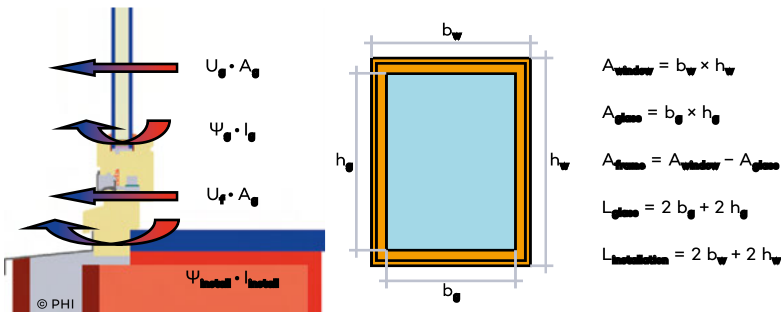


Fig. 5.16: Thermal and geometric inputs for the calculation of U_W installed

For the overall concept, heat loss and solar gain through the windows are important. Besides the orientation and shading of the windows, the total solar transmission factor of the glass g [-] and the frame proportion also influence the solar gains. Since gains cannot be achieved by opaque frames, a high proportion of glass is important.

5.3.2 Glazing

5.3.2.1. Suggested glazing in various European regions with regard to economic aspects

For reasons of comfort, hygiene, and environmental protection, triple glazing should be used all over Europe except for coastal Mediterranean and south-west coastal Atlantic climates, where low-e double glazing is acceptable. South and westwards of the Alps, low-e double glazing with an additional single pane might be valid too. In the very north and east of Europe, triple glazing with an additional single pane, quadruple glazing or even vacuum glazing might be the better solution.

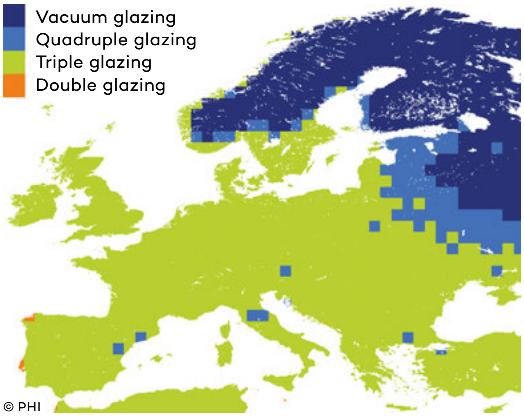


Fig. 5.17: Recommended types of glazing in Europe for a detached, shaded town house with little window area

In 3ENCULT and preceding projects, the Passive House Institute has carried out research to determine the optimal glazing in terms of life-cycle costs [Schnieders et al., 2011]. Figure 5.17 shows the recommended glazing types for a historic town house with exterior insulation. Interior insulation, as well as no insulation, would lead to even better recommended qualities (more quadruple glazing). For less shaded, solar-optimised buildings in Mediterranean climates, low-e double glazing would be the optimum solution. The research assumed that shading elements are used anyway and produce no additional costs. If additional costs for shading were assumed, these would lead to anti-sun coatings in the south of Europe. The figure shows some quadruple glazing in Mediterranean regions. This is the result of the combination of a low g-value and low U-value.

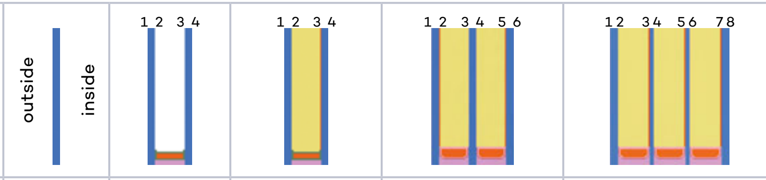
5.3.2.2 Thermal performance of glazing

A single glass pane has an U_g-value (U-value of the glazing) of around 5.75 W/(m²K), determined by EN 673. By adding a second pane, the U_g level can be halved. By filling the gap between the two panes with Argon, the U_g can be reduced to 2.2 W/(m²K). The main feature that aids efficient glazing is the low-e coating, which can achieve a reduction in radiation loss and bring the U_g down to 1.1 W/(m²K). If triple glazing is used, U_g-values of as low as 0.50 or 0.32 W/(m²K) (with quadruple glazing) are possible (see Fig. 5.18). Vacuum glazing is still better, but will probably not become widely available in the next decade.

The width of the gas gap has an influence on U_g. For Central European climates and triple glazing, the optimum gap width is 18 mm for Argon filling and 12 mm for krypton. For double glazing, as well as for colder climates, the optimal distance is a bit smaller.

An advantage of highly energy-efficient glazing is that the temperature of the inner surface increases with decreasing U-values. This way cold downdraught, radiation loss, condensate, and mould growth can be avoided.

The total solar transmission factor g (determined by EN 410 in Europe) refers to the proportion of solar radiation which enters the building. If the g-value is 0.3 or 30 %, for example, this means that 30 % of the solar radiation passes through the glazing. The transmission of the visible spectrum of daylight is around 80 % (for current double-glazing) or 70 % (for triple-glazing) (see Fig. 5.18).



Glazing	Single pane	Double pane with air	IGU with low-e coating (Pos. 3) and Argon	Tripple IGU, low-e-coating (Pos. 2 a. 5) and Argon	Quadrouple IGU, low-e-c. (Pos. 3, 5 a. 7) and Argon
Glass-U-value U_g(W/(m²K))	5,8	2,7	1,1 ... 1,3	0,53 ... 0,75	0,36 ... 0,44
Inner surface temperature @ −10 °C ambient, 20 °C room	−2,6 °C	9,5 °C	14,9 ... 15,7 °C	17,1 ... 17,9 °C	18,3 ... 18,6 °C
Total transmittance g-value	0,87	0,78	0,62 ... 0,71	0,49 ... 0,60	0,43 ... 0,57

Annual energy balance kWh/m²

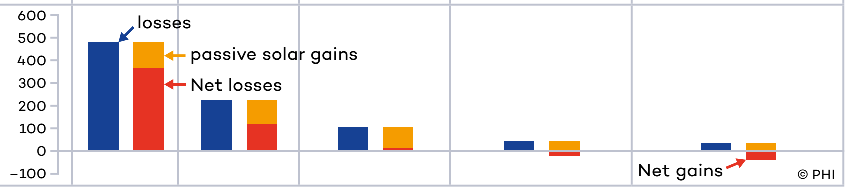


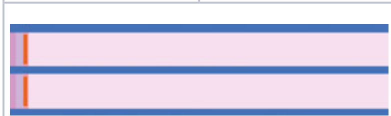
Fig. 5.18: Performance and evolution of glazing (energy balance for east or west orientation in Central Europe)

The g-value is lower if there are special requirements in terms of the robustness of the glass or fire protection regulations. This should be taken into consideration for the energy balance at an early stage. In moderate climates, glass with lower g-values should only be used if very high internal heat loads are expected. In climates that require buildings to have a high level of cooling, solar protection glass can be used, if that fits the aesthetic requirements of the historic building.

5.3.2.3 Thin-layer glazing

Compared to historic glass panes, triple glazing is heavy (30 kg/m²) and thick (48 mm). This often does not fit the character and stability of historic frames. One way to reduce this problem is to use the recently introduced thin-layer glazing. It is strengthened by semi-tempering, so a thickness of 2 mm is sufficient [Mader, 2012]. In this case, thin-layer triple glazing is less heavy than standard (2*4 mm) double glazing and has only twice the weight of a 3 mm single pane. Combined with krypton, the thickness can be reduced to 26 mm at comparable U-values, but at a higher cost. The g-value will increase slightly (see Fig. 5.19).

Glass setting	4/18/4/18/4
Thickness	48 mm
Gas	Argon
Ug	0.53 W/(m²K)
Weight	30 kg/m²



Glass setting	2/10/2/10/2
Thickness	26 mm
Gas	Krypton
Ug	0.56 W/(m²K)
Weight	15 kg/m²

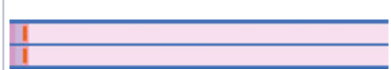


Fig. 5.19: Standard glazing compared to thin layer glazing

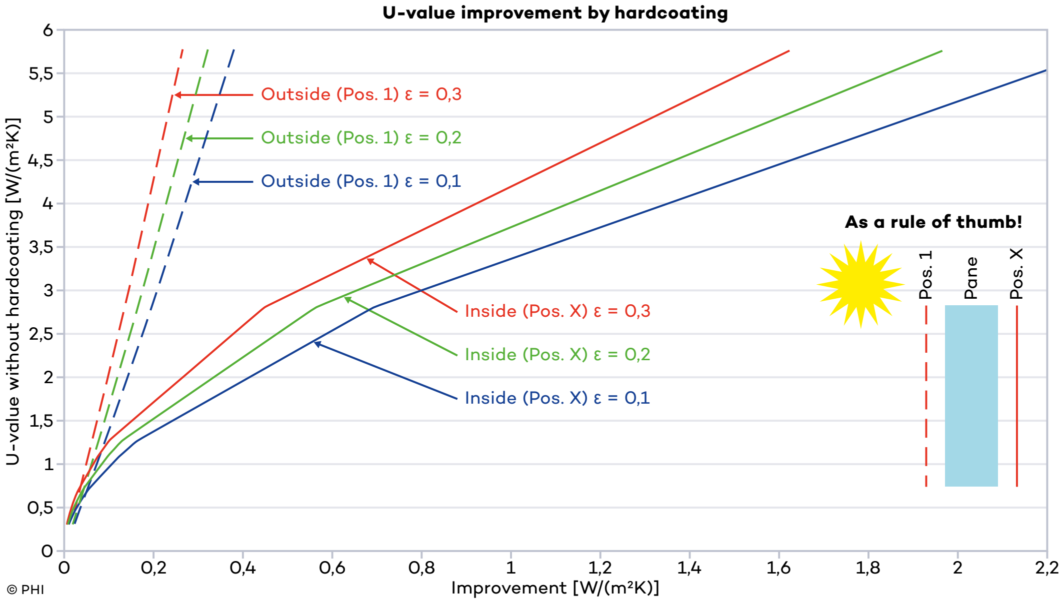


Fig. 5.20: Improvement by hard coating (x-axis) at different U-values for uncoated glazing (y-axis) at emissivity of 10%, 20%, and 30%

5.3.2.4 Possible enhancements achieved using hard coatings

Historic windows can be improved by adding hard coating. This coating reduces the emission of infrared radiation just like common low-e coating does. It is less effective than the soft coating normally used, but is resilient against mechanical stress, so it can be applied on the exterior surfaces of a pane.

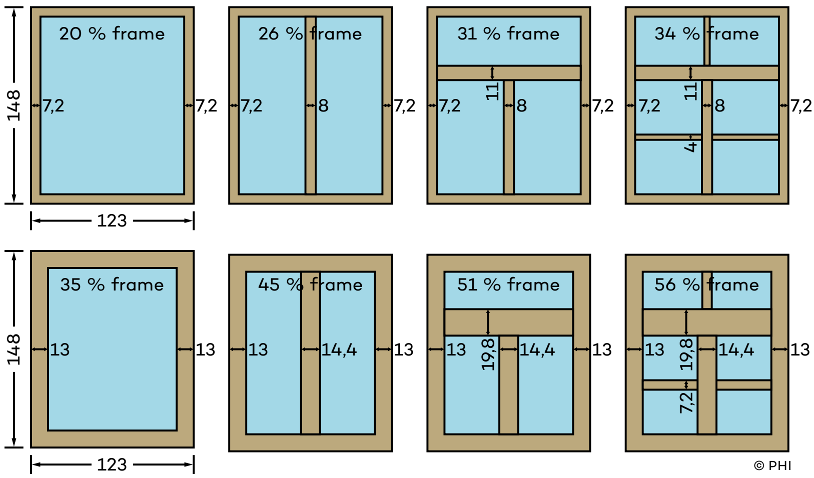
Because exterior coating can not be considered by EN 673, the Passive House Institute has set up a method for 3ENCULT. The U_g-value of single glazing can be reduced to 3.8 W/(m²K) by an interior coating (which is more effective than an exterior coating in this case) with an emissivity of 20 %. Hard coatings can improve the panes of double and triple glazing too, but with less effect (see Fig. 5.20). Using a hard-coated pane as the only measure is not enough to raise the thermal performance of a historic window to a state-of-the-art level, but it might be a good idea if there are no other opportunities.

5.3.3 Improving window frame and edge bond

The purpose of a window frame is to hold the glazing in place and to allow the window to be opened. Besides that, frames have higher U-values than the glazing (except for single pane glazing) and do not transmit solar gains. Thus frames should be as slim as possible (see Fig. 5.21).

In most cases, timber window frames are used in listed buildings. If the frame itself deserves protection, there are some ways to enhance its thermal properties. As an example, we will have a look at a window with a flying mullion (see Fig. 5.22). In its original state, it is single-glazed and not insulated. The U_W value is 4.79 W/(m²K). By the use of an internally hard-coated pane, the U_W value can be improved to 3.34 W/(m²K) (f_{Rsi} is not affected by this measure).

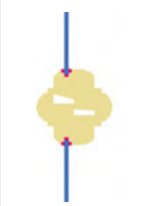
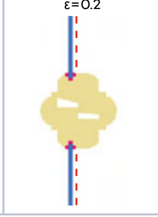
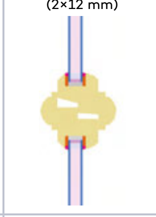
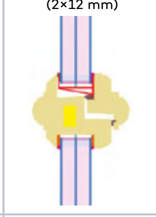
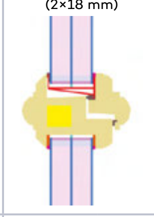
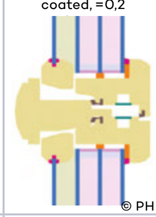
Fig. 5.21: Frame proportion of a window with different frame dimensions and dividing elements. While the slim example fits historical proportions, the other refers to dimensions often seen in modern windows.



If a double, krypton-filled Insulation Glass Unit (IGU) is used, the U_W can be improved to 1.39 W/(m²K). This window is suitable for climates like Lisbon and Rome. As soon as there is a gas gap to be sealed, an edge bond has to be used for both sealing the gas gap and keeping the spacing. Conventional spacers are made of aluminium. Because such spacers lead to very high thermal bridges and low temperature factors, plastic spacers should be used.

Further improvements are made possible by the use of triple glazing. For that, the original frame is not deep enough. One possibility is to cut the frame into two shells and insert a new layer, ideally consisting of an insulation material and fixed with adhesive. In our example, nano-insulation fleece was used. The result is a U_W-value of 0.77, which is sufficient for locations like Frankfurt. Since krypton is expensive, using argon-filled glazing was also investigated. Because the optimum gas gap is wider in that case, the glazing unit is made thicker. This makes it possible to put more insulation in the frame, reducing U_W levels to 0.73 W/(m²K).

Fig. 5.22: Thermal properties of several windows and their suitability for European climates (The maximum U-values for the climate zones stated in the table refer to installed windows).

Frame	Original historic frame		Original frame, pane hard coated ε=0.2		Original frame, double glazing Kr (2×12 mm)		Frame insulated, triple glazing Kr (2×12 mm)		Frame insulated, triple glazing Ar (2×18 mm)		Two-layer principle, outer pane hard coated, =0,2	
											 © PHI	
U_f [W/(m²K)]	2,12				1,78		1,18		1,03		0,91	
Ψ_g [W/(m²K)]	−0,01				0,038		0,031		0,023		0,016	
U_g [W/(m²K)]	5,74		3,79		1,00		0,46		0,50		0,36	
	U_W [W/(m²K)]	f_{si} [–]	U_W [W/(m²K)]	f_{si} [–]	U_W [W/(m²K)]	f_{si} [–]	U_W [W/(m²K)]	f_{si} [–]	U_W [W/(m²K)]	f_{si} [–]	U_W [W/(m²K)]	f_{si} [–]
	4,79	0,15	3,34	0,15	1,39	0,52	0,77	0,69	0,73	0,73	0,62	0,78
Lisbon	2,00	0,48	2,00	0,48	2,00	0,48	2,00	0,48	2,00	0,48	2,00	0,48
Rome	1,35	0,51	1,35	0,51	1,35	0,51	1,35	0,51	1,35	0,51	1,35	0,51
Frankfurt	0,85	0,70	0,85	0,70	0,85	0,70	0,85	0,70	0,85	0,70	0,85	0,70
Warsaw	0,67	0,75	0,67	0,75	0,67	0,75	0,67	0,75	0,67	0,75	0,67	0,75

Another option is to leave the old window untouched and build a second window as a thermal layer inside it. This can be called the two-layer principle. In the 3ENCULT project, such a window system (called 'smartwin historic') was designed by a project partner, Menuiserie André. Two variants, a box-type window and a casement window, are possible. Smartwin historic achieves a U_W-value of 0.62 and a temperature factor of 0.78 and is thus suitable for all of the sample locations shown in Figure 5.22.

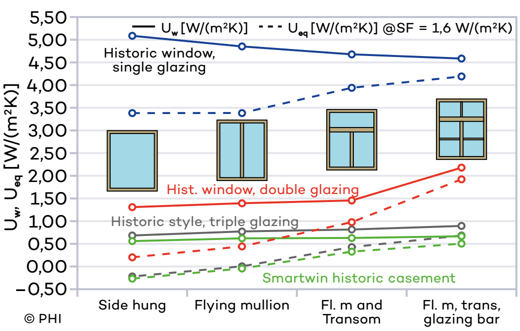
5.3.4 Glass-dividing elements

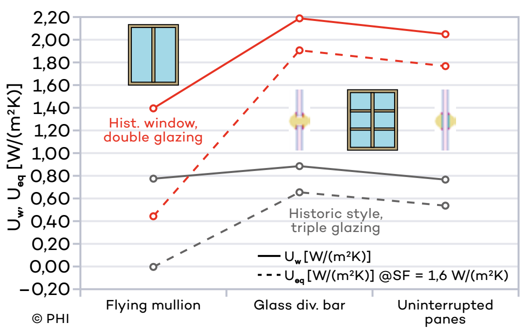
Glass-dividing elements (mullions, transoms, bars) have energy-relevant effects: the higher the frame proportion is, the higher the U-value of the window (except for single glazing). The light transmission and the solar heat gain are reduced. Edge-bond losses increase proportionally with the longer edge bonds. Investment and maintenance costs also rise. For all these reasons, it would be advisable to avoid such elements if possible. Figure 5.23 shows the impact of glass-dividing elements on the window-U-value and the equivalent U-value, which includes solar gains and provides a rough annual window energy balance.

The losses can be reduced by using bars that are attached only to the exterior glazing surface, thus leaving the space between the panes uninterrupted. The impact is shown in Figure 5.24. It is evident that the effect of glass-dividing bars is higher for double than for triple glazed windows because of the much higher edge-bond losses for the double glazing.

Fig. 5.23: Influence of glass dividing elements on the U-value and the equivalent U-value of different windows (in Central Europe, east or west-facing). For the historic window: slim example in Fig. 5.21.

Fig. 5.24: Impact of glass dividing and non-glass dividing elements on the U-value and the equivalent U-value of different windows





5.3.5 Installation of windows

If the installation is not done properly, construction damage, mould growth and significant energy loss can occur. It is best to install a window in the centre of the insulation layer, but it is more practicable to install it right in front of the wall (see Fig. 5.25). It is important to cover the frame with insulation. However in historic buildings, exterior insulation may not be permitted. In this case it is strongly recommended to use insulation plaster (though as little as possible) in order to enhance the wall, achieve hygienically acceptable conditions and avoid construction damage (see Fig. 5.26).

Interior insulation should be used if exterior insulation is not possible. Care has to be taken particularly at the joints of construction elements. The airtightness layer has to be designed and installed perfectly in order to avoid construction damage and mould. It is also very important to cover the reveal with insulating material (see Fig. 5.27). Otherwise, the result will be a low temperature factor as well as a huge thermal bridge (see Fig. 5.28).

5.3.6 Impact of the windows' thermal performance on the heating demand of a building

In order to show the impact of different windows on the heating demand, as well as the net heat losses (heat losses through the windows subtracted from the solar gains), a compact and well-shaded town house (see Fig. 5.29) with interior insulation (U_{wall} = 0,43 W/(m²K)) was modelled with PHPP in three different cases: historic window, historic window improved with low-e double glazing and smartwin historic. The roof and ceiling were insulated and a heat recovery ventilation unit was installed. Reveal insulation was only applied in combination with the smartwin historic casement windows.

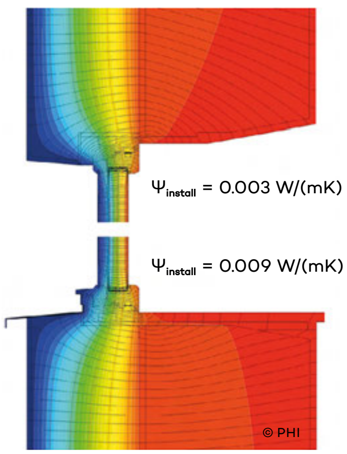


Fig. 5.25: Recommended installation position in a wall with exterior insulation

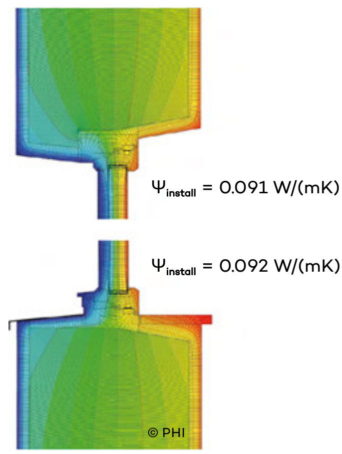


Fig. 5.26: Window installation in a non-insulated wall (only insulating plaster used)

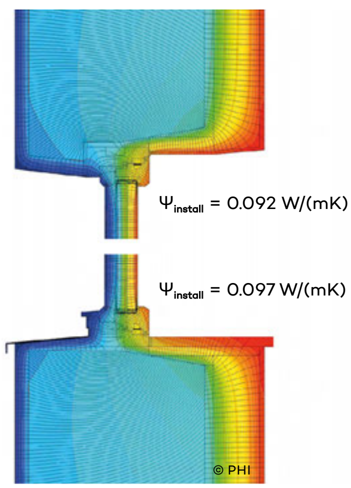


Fig. 5.27: Recommended installation in a wall with interior insulation and exterior insulating plaster

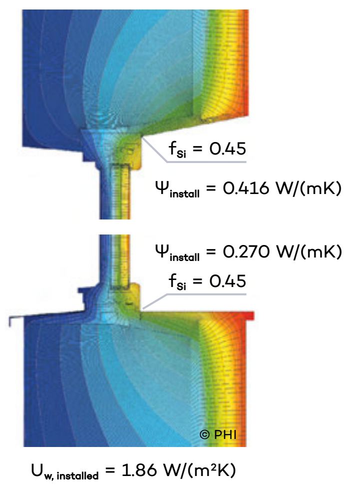


Fig. 5.28: Installation in a wall with exterior insulation, but without exterior insulating plaster and reveal insulation

Fig. 5.29:
Reference building

Figure 5.30 shows the heating demand, net losses and present values for heating energy savings based on the climate of Frankfurt, Germany. Compared to the historic window, smartwin historic casement saves a current value of nearly 1000€ in energy costs throughout its lifetime (35 years) per square metre of window. Compared to the double-glazed window, it saves around 400€/m². So it makes sense also from an economic point of view to use smartwin instead of a double-glazed window, if the difference between the investment costs for the smartwin and the double-glazed window is not more than 400€.

Figure 5.31 shows the same comparison for several European cities. In climates with a lower heating demand, the cost benefit of smartwin historic decreases. Thus smartwin historic generates no savings in a mild climate like Lisbon's.

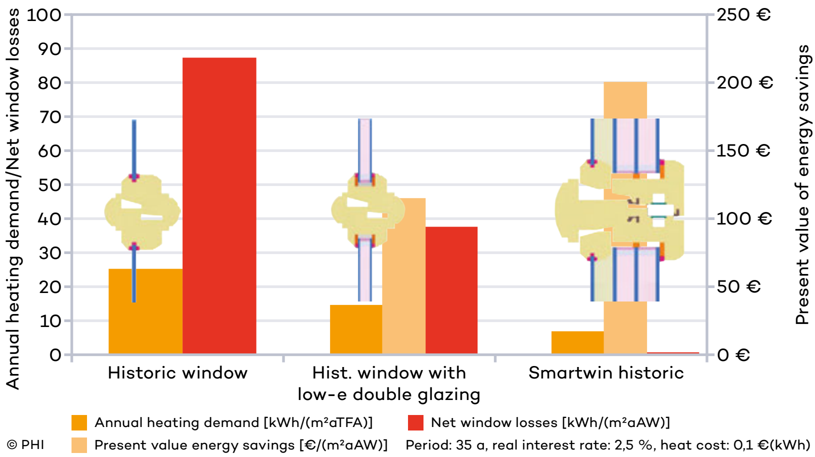


Fig. 5.30: Windows with different thermal qualities installed in an example building and their influence on the annual heating demand, the net window losses and the present value (in German climate)

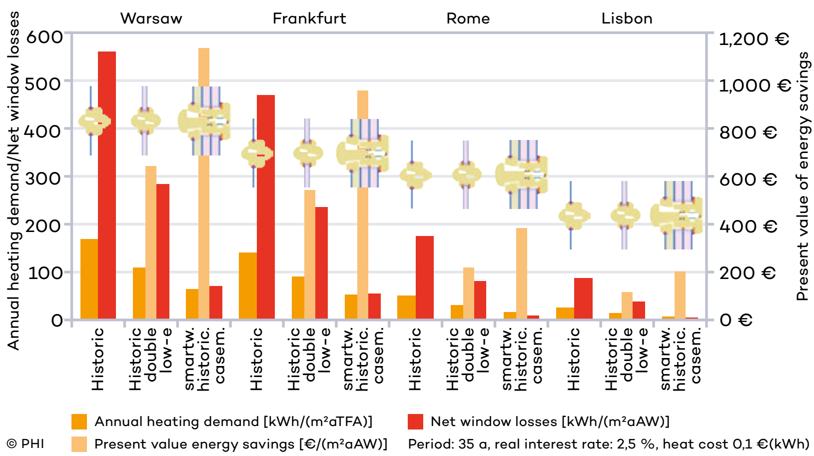


Fig. 5.31: Windows with different thermal qualities installed in a sample building and their influence on the annual heating demand, the net window losses and the present value (climates: Warsaw, Frankfurt, Rome and Lisbon)

5.3.7 Natural light and shading

Rooms with optimal daylighting are beautiful, healthy and save artificial light (and thus cooling energy). Natural lighting may also, however, cause overheating problems and glare. In winter, when solar gains are normally welcome, the low angle of sunlight can cause glare. In order to solve this problem, the installation of an interior shading device is recommended. This should allow solar irradiation to enter the room and warm it without glare.

In summer, on the contrary, interior shading devices are ineffective: they allow sunlight to enter the room, increasing cooling loads. The best option here is exterior shading (which may, however, not always fit the building's historical context), see Fig. 5.32. In any case, it is important that the user can control the shading element.

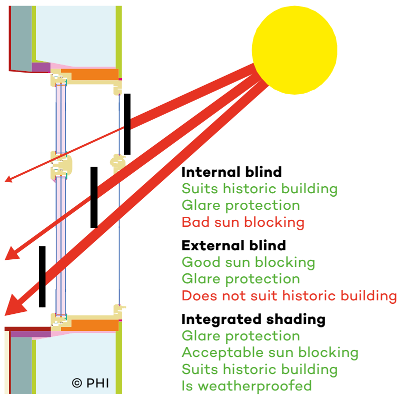


Fig. 5.32: Positions of shading elements

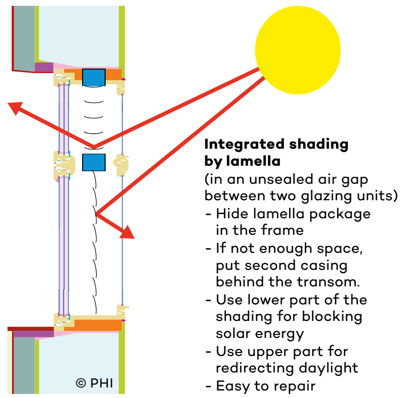


Fig. 5.33: Integrated shading by lamella blinds

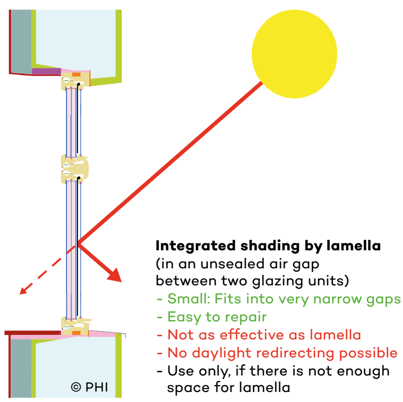


Fig. 5.34: Integrated shading by screen

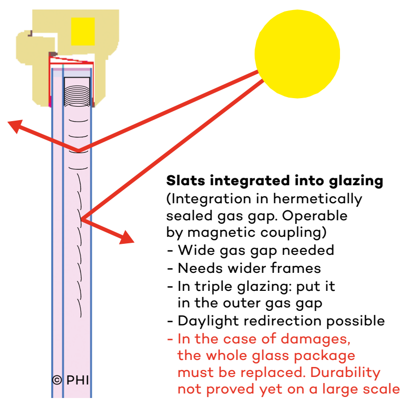


Fig. 5.35: Integrated shading by slat blinds in the sealed gas gap

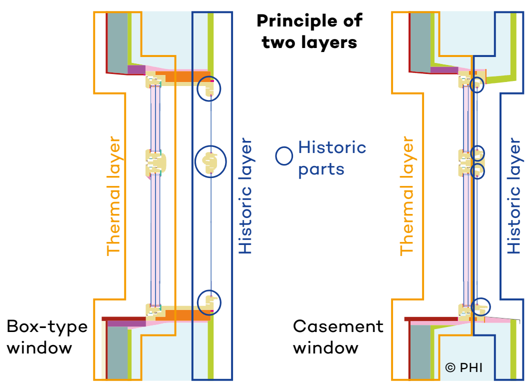
One promising possibility is the installation of integrated shading devices. In casement or box-type windows, a shading device can be located in the air gap. The nearer the shading device is to the interior of the building in terms of separate layers, the more solar energy enters the room. The farther the shading is towards the outside, the less solar energy enters the building. Slat blinds are recommended because their shading coefficient is variable and redirection of daylight is possible. Thus anti-glare protection and daylighting can be provided by one system (see Fig. 5.33). Screens (see Fig. 5.34) should only be used if there is not enough space for slat blinds. They are not as efficient, daylight redirection is not possible, and they are often not as durable.

If no air gap is available, glazing-integrated slat blinds are an option, but if they get damaged, the whole glazing unit must be removed. Slat blinds need a wider gas gap and thicker panes, which are harder to integrate into a slim frame. If the window frame has to be wider in order to cover the slats, less solar gain can be harvested in winter (see Fig. 5.35).

5.3.8 Example: Smartwin historic

Smartwin historic was developed by Menuiserie André in cooperation with Franz Freundorfer, as well as with the Passive House Institute, the Bolzano conservation office and EURAC, who supported the 3ENCULT project as consultants.

Based on detailed studies of historic windows and their specific requirements and problems, the two-layer concept was introduced. This concept means separating the 'historic style' outside layer from a new inner layer whose function it is to improve the window's thermal properties (see Fig. 5.36). A box-type window and a casement window were installed here as two variants. For both it is possible to integrate the original historic window or parts of it into the new one. The box-type window offers greater flexibility, but the casement window is cheaper. The thermal properties of the variants are comparable. In general, box-type windows can be installed with smaller thermal bridges and their temperature factors are higher.



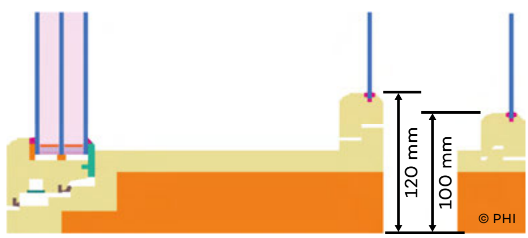


Fig. 5.36: Principle of the two layers

Fig. 5.37: Reduction of frame width by using the traditional 'goat foot'

Fig. 5.38: Smartwin historic casement window …

Fig. 5.39: … installed in the Waaghaus, exterior view …

Fig. 5.40: … and interior view.

The intensive study of historic windows and a deep knowledge of more recently designed, very energy-efficient windows led to the discovery of astonishing solutions for the overall window concept, as well as the details. One example is the traditional 'goat foot' which was used in the box-type window, reducing the frame width to only 100 mm, which is extremely narrow for a box-type window (see Fig. 5.37). Prototypes of the smartwin historic casement window were built and installed in the Waaghaus (public weigh house) in Bolzano (see Figs. 5.38–5.40), a 3ENCULT case study building (see Case Study 1).

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5.4 HEAT RECOVERY VENTILATION

Rainer Pfluger, University of Innsbruck / Kristin Bräunlich, Passive House Institute

5.4.1 Integration of heat recovery in historic buildings – the state of the art

A summary of ventilation systems with heat recovery for integration in existing buildings is given in [Feist, 2004]. It describes possible ways of integrating the heat exchanger in the building structure, such as walls or ceiling. Within the last few years, several manufacturers have developed products especially for refurbishing purposes.

Up to now, however, in most cases the systems have not really been integrated into the structure of the building and most of them are not suitable for use in cultural heritage structures. Concepts and systems especially adapted for this purpose have been investigated and developed by members of the 3ENCULT project. In this chapter, the pros and cons of different systems are discussed with a special focus on conservation issues. The reader is guided through the design criteria and decisions that are necessary before implementing any measures.

Basic information on the need for ventilation (indoor air quality, health and comfort), as well as on energy-efficient ventilation systems with heat recovery, can be found in: http://passipedia.passiv.de/passipedia_en/planning/building_services/ventilation

5.4.2 The planning phase: ventilation from scratch

5.4.2.1 Mechanical ventilation in historic buildings – how can these two go together?

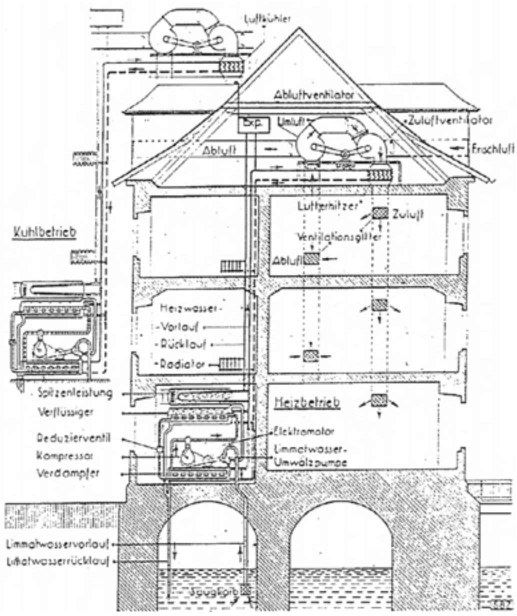
Historic buildings up to the turn of the twentieth century were originally vented by natural ventilation (openable windows). From that time onwards, HVAC systems were available. One famous example is the Zurich city hall (House of the City Council and of the Cantonal Council – 'Rathaus Zürich'), which is one of the first buildings to have been fitted with mechanical ventilation and a heat pump (see Fig. 5.41).

So how should we deal with historic buildings that were originally vented solely by opening windows? Does it make sense to integrate mechanical ventilation in such buildings? What does it mean in terms of building physics and how do the two go together from a conservation and architectural point of view?

To answer these questions, a step-by-step approach by an interdisciplinary, integrated planning team is advisable. This is the best way to reach a sustainable solution. The following chapter goes through the main steps, from decision-making to installation. Ventilation with heat recovery is one of the best examples of conservation and energy efficiency going hand in hand, as long as a solution tailored to the individual building can be found.

5.4.2.2 Building documentation and diagnosis

A thorough documentation of the *status quo* (history, plans, building diagnosis, user feedback, etc) of the historic building provides a good basis for planning the intervention and deciding whether a controlled ventilation system should be installed or not. The decision on the future use of the building (occupied and heated zones, type of use in terms of emissions and humidity sources) is the most important criterion besides the conservation issues when it comes to the question of how to ventilate the building.



The occupants and their activities within the building are the key parameters in deciding upon the appropriate ventilation system. The dimensioning of the necessary ventilation flow rate mainly depends on the use of the building. In historic buildings, additional criteria have to be satisfied, such as special humidity requirements in the case of historic paintings, or special materials.

Sometimes user comfort and demands of conservation are contradictory. For example, the indoor air humidity should be as low as possible during the heating season in the case of a building with internal insulation, in order to avoid moisture problems. On the other hand, from a physiological point of view (otolaryngology, dermatology and ophthalmology), the air should not be too dry (indoor air humidity below 35 % r.H.) for a long period of the year. In this case, the construction needs to be optimised as far as possible from a building-physics point of view, in order to come up with a solution that is beneficial both for the listed building and for its occupants.

Fig. 5.41: Zurich city hall (House of the City Council and of the Cantonal Council – 'Rathaus Zürich')

Table 5.2 gives an overview of the different types of use and the appropriate flow rates:

TYPE OF USE	RELATED TO	FLOW RATE [m³/h]
Dwelling	inhabitant	25–30
Office	workstation	30–35
School	pupil	15–20
Other	contamination load	adapt to cope with load

Tab. 5.2: Appropriate flow rate depending on the type of use

In the case of an unheated building without (or with only minor) humidity sources inside it, window ventilation and ventilation by infiltration are the best and cheapest solutions in winter. In buildings with high thermal inertia, the moisture content of the outdoor air might cause condensation and mould growth on the walls. In this case, a controlled ventilation system will help to avoid humidity damages, especially in the spring and early summer. A measurement system should be installed to evaluate the difference in absolute humidity between outdoor air and indoor air. If the absolute humidity of the outdoor air is lower than that of the indoor air, ventilation will contribute to the drying of the building. The effect of moisture transport by ventilation with humid outdoor air has to be taken into account too: in the case of night ventilation for enhancement of comfort in the summer. Depending on the climate, night ventilation might cause a significant additional dehumidification demand. Hence it is often not a good solution for humid climates.

A pressurisation test of the building (blower-door test) should be performed to measure the air change rate at 50 Pa. The better the value is, the better is the potential reduction of ventilation heat loss if ventilation with heat recovery is installed. From the financial point of view, the air tightness of the building should be better than 1 h^{-1}. Otherwise, the infiltration and exfiltration through leaks, which bypass the heat recovery process, reduce the savings significantly. In respect of comfort, moreover, heat recovery helps to reduce the likelihood of draughts from incoming air by preheating it.

In the event of moisture problems, controlled ventilation can be beneficial for building preservation and the reduction of ventilation losses at the same time. Automatic flow balance control helps to reach this goal, as is described in the following section.

5.4.2.3 Automatic flow balance control – techniques, economy and building physics

Significance of volume flow balancing If a ventilation system is operated in unbalanced state (e.g. due to filter clogging) the ventilation heat losses will increase accordingly, because either positive or negative pressure is created in the building and thus some of the air volume enters the building through leaks in the building envelope rather than via the heat-recovery system.

A ventilation system with heat recovery should always be operated in a balanced way. This is the only way to ensure that the ventilation unit recovers heat efficiently over the long term and thus achieves energy savings compared with exhaust-only systems. Devices with automatically balanced volume flow rates can secure balanced operation on a permanent basis.

Besides reducing the heat losses from ventilation, automatic balancing of volume flow rates has another essential purpose, namely the prevention of structural damage, which is especially important in historic buildings. If warm, humid indoor air penetrates the thermal building envelope towards the outside through leaks, condensation occurs at materials with temperatures below the dew-point temperature and may lead to structural damage.

In terms of building physics, the risk of damage due to moisture in historic buildings is much higher than in the case of new constructions; in historic buildings, it may be difficult to achieve a consistently airtight building envelope that is equally effective all over, on account of problems due to existing structures, such as wooden beam ceilings. In order to compensate for these weak points, the balanced operation of the ventilation system becomes even more important.

Automatic volume flow balancing – practical recommendations When installing new ventilation systems, it should be ensured that these are equipped with a system for the automatic balancing of volume flow rates. In this case, the additional investment provides the following benefits for the user:

- → Prevention of structural damage: balanced operation of the ventilation system minimises leakage flows through the building envelope. The potential for structural damage is reduced, since lower leakage flow rates lead to a lower risk of condensation forming inside the building structure.
- → Reduction of ventilation heat losses and thus lower running costs for energy: the balanced operation of the ventilation system ensures long-term heat-recovery efficiency.
- → Reduction in maintenance costs: due to a ventilation system which automatically ensures constant volume flow rates. No costs are incurred for the readjustment of the system (which should be carried out at least every five years in the case of a ventilation system without automatic volume flow balance).
- → Simplified adjustment of the volume flow rates during commissioning.

The higher the heat recovery efficiency of the ventilation system and the better the airtightness of the building are, the higher the savings will be with a system that automatically balances volume flow rates. With regard to the investment costs (manufacturers' estimate of extra costs for end-users: 150–200€ for separate ventilation units per apartment), in principle this measure will be cost-effective if the air tightness of the building is 1.0 h^{-1} or better. Air tightness values worse than 1.0 h^{-1} can only produce cost benefits with very high heat recovery rates.

Even for historic buildings, automatic volume flow balancing should still be considered, in spite of their mostly rather modest levels of airtightness. In this connection, priority should be given to the preservation of the building substance as an item of cultural heritage.

The following points should be kept in mind when choosing the system:

- → As far as possible, devices with built-in systems should be used, as these do not depend on incoming flow conditions in the supply duct and require no extra effort for installation. In addition, one source of possible error is avoided because the volume flow measurement device is usually integrated into the fan system.
- → Ventilation systems with a ventilation performance of >600 m^3/h are usually equipped with a system for automatic balance adjustment in any case. High quality is essential; this can easily be checked by performing a test stand measurement and then comparing the test measurement result with that of the built-in volume flow rate measuring device. Larger venti-

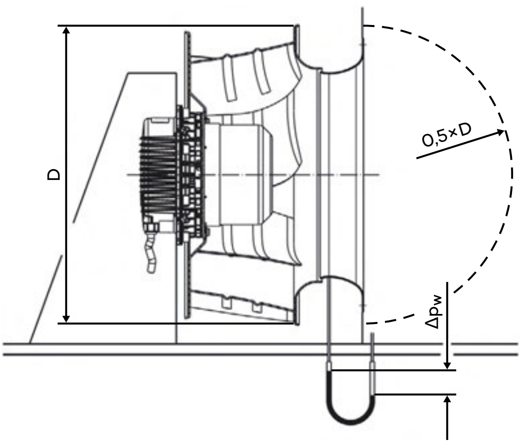


Fig. 5.42: The principle behind the measurement of effective pressure Δp_W at the fan's inlet. The volume flow can be determined from the difference between the static pressure in front of the intake nozzle and that inside it.

lation devices are often equipped with a system that ascertains the volume flow rate by measuring the effective pressure at the fan's inlet. With this arrangement, relatively high accuracy is achieved. Laboratory measurements of ventilation units with air flow rates of > 600 m³/h (carried out within the framework of the Passive House component certification of ventilation units with ventilation performance > 600 m³/h) have demonstrated that, at high and medium air flow rates, deviations of less than 3 % between device measurement and laboratory measurement can be achieved.

→ Today many smaller ventilation units (ventilation performance < 600 m³/h) also have systems for automatic volume flow balancing. Constant volume flow fans utilise the relationships between the fans' rotational frequency (rpm), their power consumption, and the volume flow rate. In the case of fans that have forward-curved blades, the volume flow rate can be determined clearly from its characteristic curve solely on the basis of the rotational frequency and the power consumption. By comparing the actual and set values and then readjusting by the control unit of the fan correspondingly, the volume flow rate can be kept constant despite pressure variation inside the duct network. However, there are still large differences between the units providing this system of automatic air flow balance relating to the maintenance of this balance. Calibration of the flow rate measuring system of the fan relating to the respective device in the installed state can significantly improve the accuracy of the built-in flow rate measuring system and thus improve the balancing system as well.

Attention should be given to the following points when adjusting the balance:

→ The balance between the outdoor air flow and the exhaust air flow should always be adjusted as accurately as possible.

→ In the case of historic buildings, if it is not possible to improve airtightness to a high standard during the thermal optimisation of the building envelope, a small surplus of extract air (maximum of 10 %) can be set when adjusting the ventilation system in order to protect the building substance.

→ However, in order to maintain the extract air surplus, the ventilation system must provide a system for automatically keeping the adjusted air flow rates constant. It is desirable to regulate the extract air surplus in response to the pressure difference between critical rooms and the outside by means of suitable sensors. Owing to thermal lift, the critical areas are mainly on the upper floors. It is therefore advisable to measure the interior-exterior pressure difference there at least, in order to keep a slight negative pressure indoors.

5.4.2.4 Design criteria: central versus decentralised systems

The most important decision in the choice of ventilation system is whether a central unit or decentralised systems are appropriate for a particular solution. Most of them can be used for ventilation in historic buildings, as described below:

Central ventilation system A ventilation system based on using one heat recovery system for the whole building or subsection of a building is called a 'central' system, which means that a heat exchanger and fans are necessary only once. In a historic building, the weight and size of the central unit has to be taken into account. Moreover, space for the supply and extract ductwork has to be considered.

Advantages

→ The number of openings that need to be made in the façade is reduced significantly. If the ambient air intake and the exhaust air outlet are placed on the roof or run underground, no openings in the façade are necessary. The central unit can be placed in a plant room, so no space has to be taken away from the occupied area. This is also a big advantage in terms of sound protection and maintenance (change of air filters etc). In most cases (but not always!) a system with a central unit has lower investment and maintenance costs than decentralised units because it uses a lower quantity of repetitive elements. Highly efficient units are available in different sizes.

Disadvantages

→ The planning costs are relatively high. In historic buildings, especially, individual solutions have to be found in any case – the system is tailor-made for the building and has to respect its architectural and historic value as a protected monument.
→ A plant room for accommodating the central unit is not available in every case. Moreover, the building needs to provide space not only for the heat exchanger, but also for the duct system. Sometimes old chimneys can be used for the vertical ducts, but horizontal distribution is also necessary.
→ If a duct passes through a fire compartment boundary, additional fire-protection measures are necessary.

Decentralised ventilation system A decentralised ventilation system uses smaller heat recovery units for specific zones or dwellings within a building.

Advantages

→ Reversibility for all interventions is essential for historic buildings. This type of system helps to avoid installing ductwork in the building, as long as the unit is placed close to the thermal envelope. A dedicated plant room is not necessary. The heat recovery unit can be placed directly in the occupied rooms.

→ The planning and installation costs are low, because standardised systems are installed.
→ Each unit can be controlled and operated directly by the user.

Disadvantages
→ Outdoor air intake and exhaust air outlet have to be conducted through the façade. In the case of listed buildings, altering the appearance of the historic façade in such a way may not be permitted. Solutions have to be found that are acceptable in respect of the preservation issues, because each unit needs an outdoor-supply duct and an exhaust duct running between the unit and the outside.
→ In the case of a system placed directly in the occupied zones of the building, sound protection has to be ensured. Ease of access for maintenance is another important requirement, especially in the case of rented flats.

Central or decentralised – an integral planning task There is no general recommendation for a certain type of system, neither in terms of preservation nor in terms of costs. The following sections may help to find the optimum solution for a particular building. New products and concepts may well help to solve upcoming problems in the refurbishing context.

Principle of cascade ventilation Cascade ventilation, in which the air is led from supply air zones (bedrooms, living rooms, etc) via a transfer zone (e.g. corridor) to the extract air zones (kitchen, bathroom, and toilet) is rather efficient in terms of flow rate and ductwork.

However, there is still room for improvement. If the living rooms (in a broad sense) are regarded as overflow zones too, then supply air need only be provided for bedrooms. From there, the air can be transferred via the living rooms and the corridor to the extract air zones. This principle allows reduction of the ductwork – a fact that is especially important for historic buildings. Moreover it makes it easier to build energy-efficient and cost-effective ventilation systems (see Fig. 5.43). More information on cascade ventilation can be found at http://www.passipedia.org/passipedia _ en/planning/building _ services/ventilation/basics/optimization _ of _ dwelling _ floor _ plan _ configuration _ for _ cascade _ ventilation

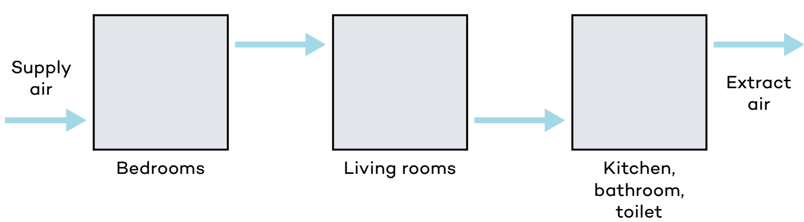


Fig. 5.43: Principle of cascade ventilation (supply air only in bedrooms; living rooms are regarded as overflow zones)

Principle of active overflow ventilation Application of the principle of cascade ventilation reduces the number and length of supply air ducts, but does not eliminate the corresponding need. In some listed buildings, no supply air duct at all may be installed, for architectural or conservation reasons. In this case, the principle of active overflow can be a good solution. The heat recovery unit takes the extract air from the toilet, kitchen etc and vents preheated fresh air into the distribution zone (corridor, staircase).

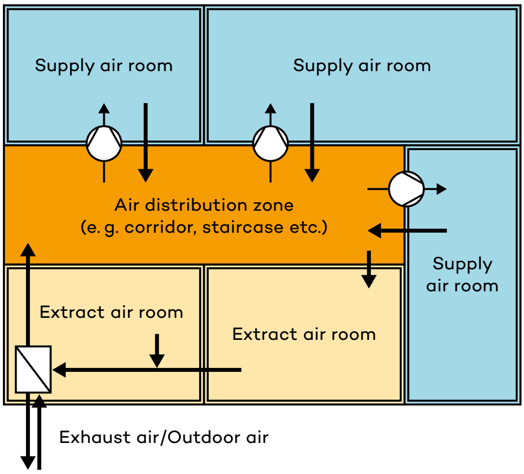


Fig. 5.44: Principle of active overflow ventilation (supply air is fed into the distribution zone, small fans are used to vent the supply air rooms individually)

Small fans are necessary to lead the air from the corridor to the supply air rooms and back again. This way, vertical and horizontal supply air ducts can be avoided, because the staircase and corridors are used as a duct. The drawback of this system compared to cascade ventilation is that the ventilation efficiency is not as high, because of the air mixing in the corridor.

This principle is frequently used when refurbishing residential buildings. Within the 3ENCULT project, a ventilation system based on the overflow principle was used in school buildings for the first time, as described in Case Study 5 in this handbook. Compared to residential buildings, more effort has to be put into sound protection and draught-free air distribution.

5.4.2.5 Where should the heat recovery unit be placed?

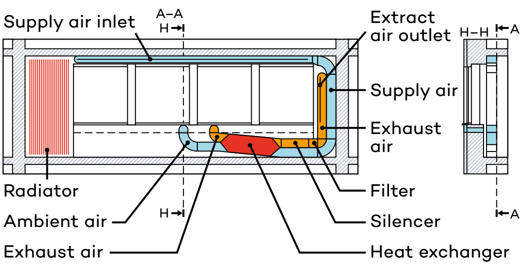
In general, the heat recovery unit should be placed as close as possible to the thermal envelope of the building, in order to keep duct runs short. If the unit is placed within the thermal envelope of the building, the cold ducts (i.e. exhaust and outdoor air ducts) have to be well-insulated so as to minimise heat loss. This insulation has to be vapour-tight in order to avoid condensation from humid indoor air. If the unit is placed outside the thermal envelope, it is the warm ducts (i.e. supply and extract air) from the unit to the envelope that have to be insulated well.

If the unit is integrated in the wall, the length of the cold ducts is reduced to the absolute minimum, thus saving material and installation costs as well as heat loss and maintenance costs. In the case of a listed building, it has to be clarified whether or not a ventilation system may be mounted on the inner surface of an exterior wall. The answer to this question also depends on the type and shape of the heat recovery system, as described in the next chapter.

5.4.2.6 Type and shape of heat recovery system

Recently, new products for refurbishing purposes have been developed that are especially designed for wall or ceiling integration. To suit this special type of application, the heat exchanger has to be flat in order to minimise the depth of the suspended ceiling or the thickness of the unit at the wall.

In the case of wall integration, there are different places where such a unit can be mounted: under the window (if there is no radiator), beside the window or above the window (if there is space enough and this does not impair the load-bearing capacity of the lintel). Depending on the volume and area available, the geometry of the heat exchanger will need to be adapted. If the air flow within the heat exchanger is vertical in direction, the cold side should be at the bottom to guarantee that the condensate is drained well. If the heat exchanger is orientated horizontally, it should be mounted with a shallow incline, for the same reason. In any case, the drainage of condensate is a problem, because this has to be led away to the waste-water system, which might be far away from the unit. In units with humidity recovery, condensation should not occur under normal conditions, which makes them well suited for wall integration.



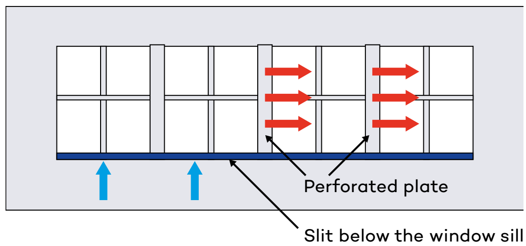


Fig. 5.45: Wall-integrated decentral ventilation system for school buildings with flat counter-flow heat exchangers for heat recovery

Fig. 5.46: Wall-integrated decentral ventilation system (view from outside). Exhaust air outlet via perforated plate, outdoor air inlet via slit below the window sill.

Solutions for decentralised, wall-integrated systems have been developed for listed school buildings within the 3ENCULT project (see an example of a flat counter-flow heat exchanger mounted between floor and sill in Fig. 5.45). The supply air inlet and the exhaust air outlet are placed above and beside the window respectively. In order to avoid fitting a grille into the façade for ambient air intake, a slit can be made below the window sill. This solution is not possible for exhaust air outlet, because condensation and possibly freezing would occur at the wall surface. Therefore a perforated plate or a cover plate in front of the window post is suggested for the exhaust air outlet (see Fig. 5.46).

The suggested design can be used in buildings where external insulation is to be applied. In such cases, the flat air ducts for ambient and exhaust air can be fitted into the insulation layer. After finishing the render (outside) and dry lining (inside), no ductwork is visible from either side. For most listed buildings, however, external insulation is not appropriate. In those cases, a central heat recovery system is preferable.

5.4.2.7 Air inlet and outlet: positioning and design

As with the wall-integrated solution for school buildings described above, special solutions have to be found for historic buildings, since the façades have to be preserved as well as the majority of the materials and surfaces. If conservation requirements prevent openings from being made in the walls, a closer investigation of the existing structures has to be performed. If there are chimneys that are no longer in use, they could serve as a shaft for ventilation ducts. The other possibility is to put the ducts in the ground and run them into the cellar of the building, if the central system is to be placed there.

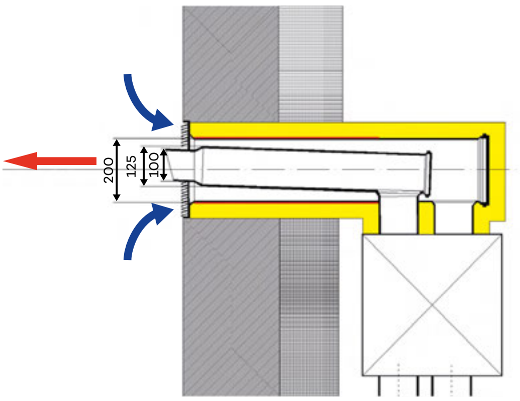


Fig. 5.47: Coaxial duct for outdoor air intake and exhaust air outlet, developed by University of Innsbruck within the research project low_vent.com; prototype built by POLOPLAST

Generally, ambient air intake and exhaust air outlet make two ducts necessary – and consequently two wall openings. The coaxial duct systems developed by the University of Innsbruck can help to minimise the number of holes to be made through the external walls. The outdoor air is drawn in through the annular gap, whereas the exhaust air is blown farther out through the central duct (see Fig. 5.47). As shown by tracer gas measurement, there is no danger of short-circuit flow from the exhaust air outlet to the outdoor air inlet. Protection against a frost-risk inside the heat exchanger is also possible through a heating foil which is wrapped around the outer duct [Sibille, 2014].

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5.5 DAYLIGHT AND ARTIFICIAL LIGHTING

Robert Weitlaner, Wilfried Pohl, Bartenbach

Daylight has determined the development of human vision. Our visual perception system has developed the capability of adapting to any situation in daylight, and even at night. The intensity of daylight changes throughout the day and year, as do, its spectral power distribution and its direction (e.g. strong parallel beam with clear sky, scattered light without sun from cloudy sky), depending on the time, location and climate. Our basic and unconscious biological (=circadian) rhythms are steered by these dynamics. Evidence was found for a biochemical reaction a decade ago and today this response is incorporated in the description of our sensor system for shortwave radiation, under the title 'non-visual system'. 'Non-visual' because this reaction is completely separate from our ability to perceive pictorial information about our environment. The highest levels of sensitivity in our visual system are measured in daylight situations. This is not a recent finding, but a fact that has been known for a long time: in the architecture of prestige, daylight has been used to convey specific moods or ideas (power, belief, etc) throughout the ages. People have known for a long time about its physical and (unconscious) emotional (psychological) impact. In contrast to state, public and aristocratic buildings, run-of-the-mill residential buildings have not used daylight much as a design component. Yet both in prestigious buildings and in vernacular architecture, window areas have been defined by climatic boundaries, safety considerations and structural requirements (e.g. problems due to overheating or frost both used to be solved by reducing the window area).

For the following case study, we have taken a trip back in time to a prestigious building of 1400 in Bologna which provides interesting insights. The building is intended to show lordship and wealth, the walls are covered with frescoes. The epoch was a prosperous one and as a result, the building grew year by year. The windows were large, in order to illuminate the huge depths of the rooms. Artificial lighting was provided by a few torches or candles. People worked, lived or entertained guests in this building. For each of these purposes, different lighting arrays were installed.

What we see here today is a 'listed' building, which has partially been turned into a museum and office. The Sala degli Stemmi' in the Palazzo d'Accursio, Bologna, is a room very typical of those found in listed buildings that are now used as museums. Its dimensions are still enormous; the exhibition consists in part of the room itself, for example the frescoes on the walls. The use of other sections of the building has been changed to accommodate public administration offices. These modern uses require illumination techniques that respond to the needs of those using the structure today, yet also take into account the historic fabric of the building.

5.5.1 Basic human requirements

Any modern daylight and artificial lighting solutions should be designed according to the appropriate standards (visual: EN 12464, DIN 5034; conservatory: CIE 157:2004 and EN 15193 for energy requirements). These constitute the minimum requirements to be fulfilled.

However, lighting design is much more than the planning of stipulated light source intensities and surface illuminance levels; it is more than just the fulfilment of normative guidelines. Lighting design means the creation of an appearance (e.g. of a room) that not only complies with the technical requirements (including visual performance) but also satisfies the emotional and aesthetic needs of the user. At the same time, it still has to pay due attention to the psychological and physiological effects of light, some of which are formulated in specialised requirements such as luminance distribution, colour rendering and glare.

Among the minimal conditions for good lighting are adequate illuminance and luminance levels, both horizontal and vertical (depending on features such as the room use or visual tasks), properly balanced luminances in the field of view, the control of direct and reflected glare, and adequate colour rendering. The lighting quality (visual comfort) is not measurable, but there are a few criteria (measurement values) which make it possible to assess the quality:

→ horizontal illuminance distribution;
→ vertical / cylindrical illuminance distribution;
→ luminances in the field of view;
→ colour temperature and colour rendering indices;
→ glare;
→ radiation field (light directions, shadowing, contrasts);
→ flicker frequency;
→ daylight availability.

The European standard EN 12464 *Light and Lighting – Lighting of work places* gives guidelines and boundary values for these criteria. Different rooms have to be illuminated according to their use (museum, showroom, office, restaurant, etc), and sufficient illuminance/luminance levels for visual perception are defined for different tasks (see Tab. 5.3).

The minimal mean illuminance on the task area is E_{mean}, the glare is evaluated with the unified glare rating (UGR) method, and the colour rendering features are measured as the CRI value.

Tab. 5.3: Examples of requirements for different room types and tasks acc. to EN 12464

ROOM TYPE OR TASK	E_{mean}	UGR	MIN. CRI
Office			
floors	100	28	40
writing, reading	500	19	80
technical drawing	750	16	80
Restaurants	-	-	80
Parking garage, way in and out	300	25	20
Health Care			
Surgery rooms	1000	19	90
Autopsy	5000	-	90

In addition to these quantities, the following features also have to be taken into account:
→ balanced luminances in the field of view (allowing stable perception);
→ avoiding glare in general;
→ high colour rendering (CRI);
→ adequate colour temperature (CCT);
→ illuminating special zones of interest (called zoning);
→ modelling of interior (showing structure);
→ high homogeneity where needed (e.g. in task fields);
→ high energy efficiency of installation > 85lm/W.

For daylighting, similar rules regarding visual perception have to be applied, and a few additional topics need to be considered:
→ daylight redirection into room depths (reduces artificial lighting energy demand);
→ for visual tasks decrease window luminances to indoor levels (to allow stable perception);
→ avoid glare caused by daylight;
→ prevent direct insolation (if not explicitly desired);
→ preserve daylight spectrum (e.g. colour rendering);
→ variable solar heat gain coefficient (SHGC) values (solar gains in winter and shading in summer);
→ minimal SHGC in summer (avoids overheating);
→ balance thermal comfort (surface temperatures, thermal radiation).

In addition, daylighting devices and artificial lighting both have to fit into the architectural concept of the building (lighting design should be part of the architectural design, or it should be cleverly concealed). Further, the lighting must be in line with conservation requirements (material deterioration), and the installation should be non-invasive and reversible. Of course, planning should take into account the balance between investment and maintenance costs.

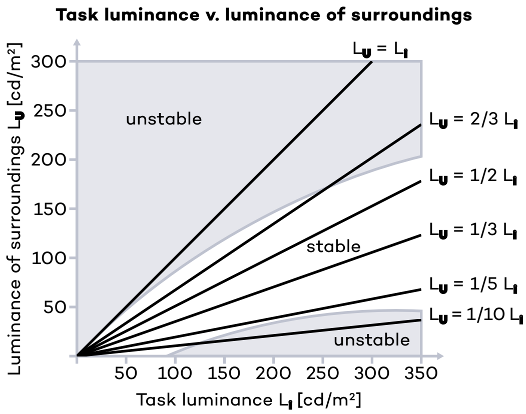


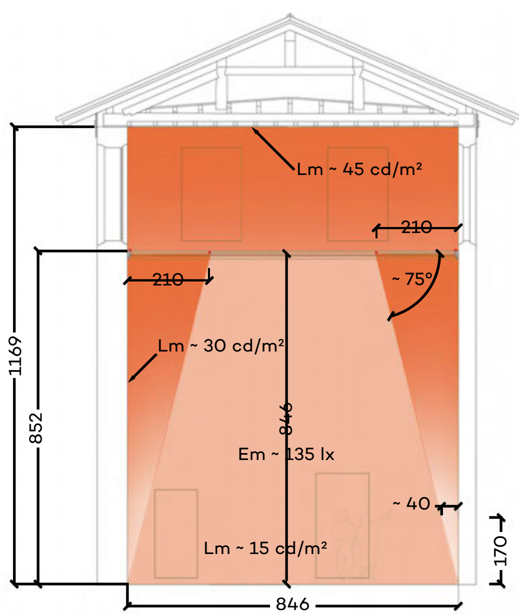
Fig. 5.48: Luminance ratios for stable perception

Special ratios of luminances in the field of view are necessary for ensuring the optimal visual perception of humans. The 'field of view' is split into two main areas of interest: the task area (called infield), with an average luminance L_i, and the surrounding area with an average luminance L_s. The ratios of L_i to L_s should be contained in a specific range in order to have optimal visual perception [8] (see Fig. 5.48). Recommended minimum luminances of ~15cd/m² in daylight vision (photopic vision under daylight situations) require much higher illuminances than 50 lux on many materials. This is an established value (and paradigm) in the conservation community. A general recommendation for illuminances is not possible because illumination is radiation weighted by the visual response (of the eye), whereas materials have a completely different sensitivity, which is particularly vulnerable in the short wavelengths.

For the present case study in Bologna, the luminances shown in Figure 5.49 were defined as a target for the optimal perception of the frescoes on the walls. They result in illuminance levels of approx. 160lx (for a reflectivity of 30 %).

The appearance (colour rendering) of the works of art is determined by the spectral power distribution of the light source in combination with a reflector or lens. During the past fifteen years, LED sources have had some typical deficits in rendering colours. This has caused many controversial discussions about their integration into luminaires for the presentation of art and have even caused a general reluctance to apply this technology. According to colour rendering assessments in 2014, LEDs are now available in any category (Colour Rendering Index CRI > 90 or CRI > 95). However, the lighting market has many products of poor quality on offer. Hence, care should be taken when purchasing.

Fig. 5.49: Illuminance distribution for optimised visual perception taking into account the conservation aspects in the Sala Urbana, Palazzo d'Accursio



Daylighting means creating a balance between visual and thermal comfort and energy demands for cooling, heating and artificial illumination [2,4,6,7]. Considering the energy-related characteristics of the building (for example the thickness and materials of walls and window-to-floor ratios) and the use of the building's interior, the definition of specific requirements is mandatory. In offices or residential rooms, a view outside is usually attributed a high level of importance, besides visual and thermal comfort. A connection to the exterior is needed for gaining information about the time of day or, for example, weather conditions and it also generally contributes to our wellbeing. Other effects of a balanced illumination solution include improved motivation and mood, higher energy levels, lower fatigue and reduced eyestrain.

In addition to the physiological and psychological effect, daylight is responsible for the deterioration of materials and surfaces. This effect has to be evaluated and controlled in order to preserve specific parts of listed buildings. The perceptible wavelengths are between 380 and 780 nm, while deterioration is caused by all wavelengths – the shorter the worse. By applying films to the glass of windows, the damage potential of radiation is significantly reduced. It should be borne in mind that such films might have a detrimental effect on the transmitted colour temperature. One film that performs very well is produced by Madico (CLS 200 XSR).

All of the above-mentioned criteria define the lighting design of a historic building. Humans, materials and energy efficiency require very specific solutions.

5.5.2 Palazzo d'Accursio

As it happens, a poor quality of lighting design can be observed when visiting Palazzo d'Accursio today. The existing installation uses incandescent halogen lamps with very low performance, in particular extremely low efficiency, bad illuminance distribution, and a lot of glare [3]. Some luminaires are orientated to illuminate the floor and they produce high glare levels for the viewers of the frescoes. This is the case with the luminaire on the right in Figure 5.50, while the one on the left is directed at the wall but it succeeds only in producing non-homogeneous illumination with patches of high intensity. The resulting luminance distribution is very different from the well-established and recommended ratios.

Fig. 5.50: Pre-3ENCULT: the lighting system produces high inhomogenities and glare.

5.5.3 3ENCULT wallwasher

A wallwasher is a luminaire that is meant to illuminate walls from positions quite close to this wall. The luminous intensity distribution of common wallwashers is not limited to a lateral direction. This means that when mounted on adjacent walls they will always also partly illuminate the neighbouring wall, where a significant pattern will then be visible. This well-known problem of common wallwashers is solved by the 3ENCULT wallwasher (see Fig. 5.51).

Fig. 5.51: The luminaire 3ENCULT LED wallwasher. Each small reflector contains two LEDs for different colour temperatures.

The wallwasher below is illuminating a rectangle on a surface with a high degree of homogeneity (see Fig. 5.52), which can be applied to many other scenarios (such as blackboards in schools). The luminous intensity distribution curve is exquisitely accurate, which causes it to blend into the background and hence does not inhibit the view of the frescoes in the historic room (see Fig. 5.53).

Fig. 5.52: Non-invasive installation on a cable, illuminating a precise rectangle

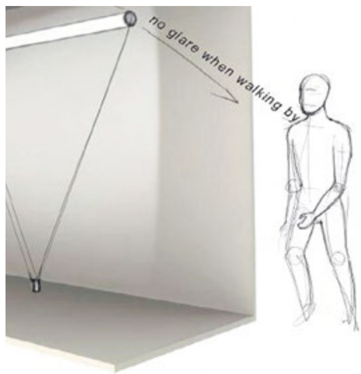


Fig. 5.53: The lateral cut-off cancels glare when walking by

The design of the luminaire allows it either to be mounted on a cable (fixed with only a few screws that can be hidden on top of existing cornices), or installed as a completely reversible stand-alone luminaire. Hence, it is possible to achieve a non-invasive or minimal impact on the internal structure (see Fig. 5.54).

The deterioration of, for example, works of art is slowed down because LEDs do not emit invisible, yet damaging ranges of the electromagnetic spectrum. Moreover, specific reflector coatings provide illumination down to 2200 K, which resembles historic incandescent light.

The energy efficiency is optimised by the special optical design and by use of an LED from 2013 (overall efficacy 90lm/W).

Fig. 5.54: Different installation methods

5.5.4 Visions on daylighting

Fig. 5.55: Daylight redirecting slatted blinds in box-type windows

Box-type windows are typical of listed buildings. They offer the possibility of including shading devices between the sashes. In Hötting Secondary School in Innsbruck (see Case Study 5), daylight-redirecting horizontal slats were integrated by cutting away the top inner board of the wooden box type window to create space for the blinds' casing. The casing (to house the retracted blind as well as the motor) is thus not visible from the exterior, which made the solution acceptable to the conservation officer (see Fig. 5.55).

The daylight-redirecting blinds were integrated into an open loop control. This system also controls the artificial lighting system in the school, based on integral algorithms (see Fig. 5.55).

Shutters are typical shading devices for many European regions. A shutter was originally used for solar blocking and for security. One proposal shows how some of the louvres could be transformed into daylight-redirecting devices (see Fig. 5.56). If minimum g-values are required, all of the louvres will be rotated to close the face completely, but if the energy specifications allow it, some of them could be shaped so as to redirect daylight into the room.

At the Waaghaus (Public Weigh House) in Bolzano (see Case Study 1), the roof, not visible for the most part, was identified for its daylighting potential. The chimneys were gutted to form tubular daylighting devices that are fed with sunlight by heliostats. The heliostats are located on the roof of the building to redirect light into the chimneys of the west facade, so the system is not visible from the street and hence does not detract from the historical appearance of the Waaghaus.

The chimneys will be opened on the side that is fed by the heliostats, in order to catch more sunlight. The change will be minimal and not noticeable by the observer. The resulting light tubes will bring light into the first and second floors of the building, where illumination levels are low – due mainly to the narrowness of the street and the presence of a building opposite (see Fig. 5.57).

Fig. 5.56: Shutter

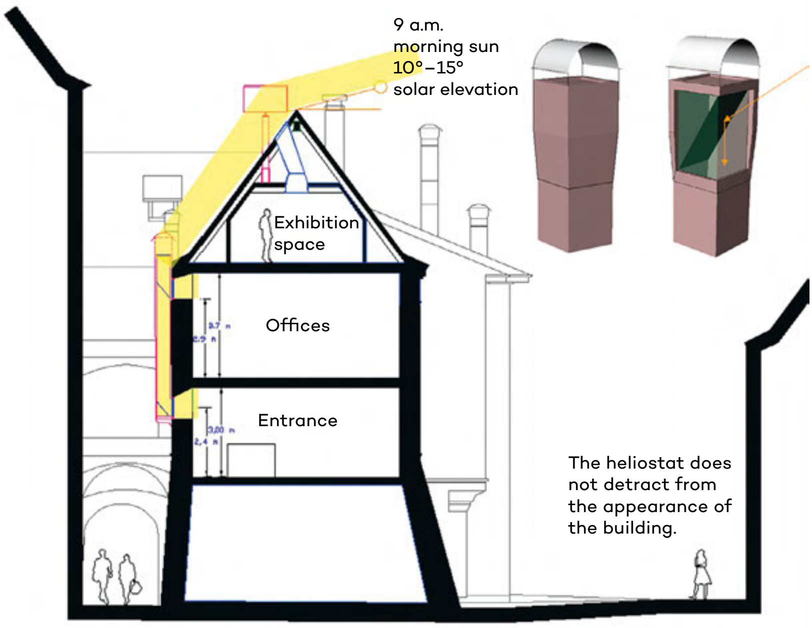


Fig. 5.57: View of heliostats used for illuminating rooms adjacent to narrow alleys

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[5] EN 15193, European standard, *Energy performance of buildings – Energy requirements for lighting.*

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5.6 PASSIVE HEATING AND COOLING

Alexandra Troi, Elena Lucchi, Francesca Roberti, Ulrich Filippi Oberegger, EURAC research

How do heating and cooling interact together; insulation, solid walls, and ventilation; solar gains and internal loads? And how can they be optimised in different climates? This is the main focus of this chapter, rather than the well known principles around passive heating, which we already understand as the minimisation of losses, and using and optimising the gains (for windows see Section 5.3).

The first step when optimising passive heating and cooling is to understand the architecture of a historic building, which often portrays the accumulated local and regional experience on how to minimise energy demand and improve comfort. The Portici di Bolzano (see Case Study 1) shows that a very compact construction minimises losses through the walls, while atria provide natural light and cooling using the stack effect in summer. Building activities are distributed so that activities demanding more light are assigned to the upper storeys and goods are stored in the cellars, which are dark but have good ventilation.

It is often not possible to view a historic building in the present from the same perspective as it was when first constructed since both the building's use and the related comfort demands may have considerably changed. For example, in an office, heat gains from computers and other equipment may make the original cooling strategies insufficient.

It is important, however, to understand the original strategy, and typically questions will arise around the role of the inertia of solid walls – both for heating and cooling, especially in warmer climates.

The following four sections explore the behaviour of solid walls and the role of insulation and ventilation in different climates. Measured data are presented and analysed and completed with calculations on the behaviour of the wall and the consequences on the heating and cooling demand. The basis for the calculations is the Waaghaus of Bolzano (see Case Study 1) with its solid stone walls. The calculations are done for three different climates: Bolzano, in northern Italy; Bologna, in central Italy; and Palermo, with a hot Mediterranean climate.

The final section looks specifically at cooling needs in a cool climate and how to avoid using active cooling measures (Copenhagen, Denmark).

5.6.1 How does a thick solid wall behave?

When looking at historic buildings with thick brick or stone masonry walls, one question is: What does this wall achieve for energy efficiency?

Compared to an insulation material, it contributes little to limit the heat flow through the wall. The recorded data at Ansitz Kofler (Bolzano, Italy) illustrate this: 60 cm stone masonry walls (see Fig. 5.58) have been insulated on the interior side with 12 + 4 cm mineral wool. While the major temperature drop occurs along the insulation layer between the new interior surface and the original interior stone wall surface (see Fig. 5.58), the latter is only slightly higher than the temperature of the outside surface – the notable change is that temperature oscillation reduces.

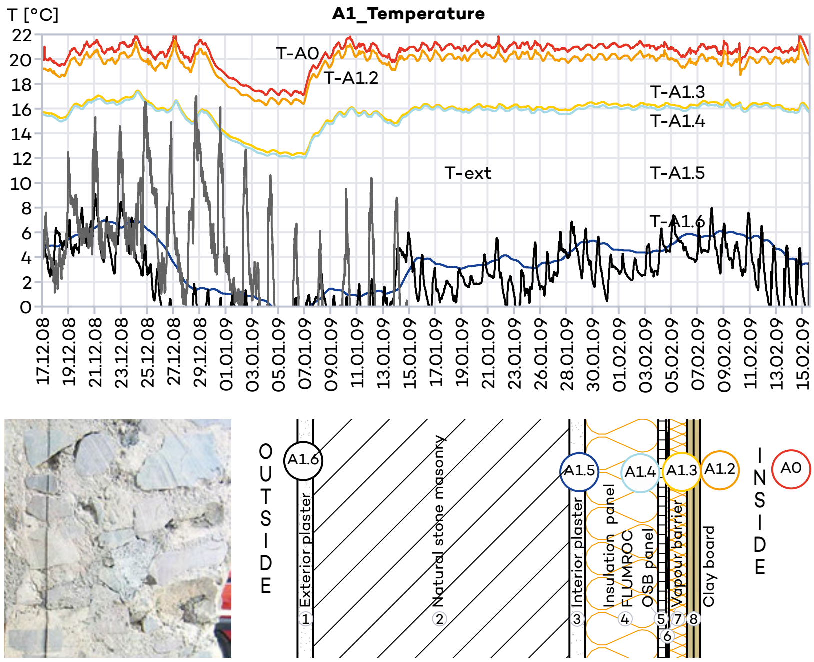


Fig. 5.58: Temperatures over one winter month at different positions in the solid stone wall at Ansitz Kofler in Bolzano, Italy (measurement points in section) illustrate the dominant role of the insulation layer for the temperature profile and heat flow.

This is as physically expected. With a λ-value (thermal conductivity value) of 0.04 W/mK (thermal transmittance in watts per metre kelvin), the mineral wool conducts heat more than ten times less effectively than the masonry which consists of stone and mortar with a λ-value of around 2 W/mK and around 0.8 W/mK respectively.

At the Waaghaus, U-value measurements have been performed on the as yet uninsulated wall (see Fig. 5.59). The instantaneous heat flux from the room into the wall is rather independent from what happens on the outer surface, as the overall temperature of the solid wall changes slowly: even if the outside surface warms up during the day (blue line), the heat flux into

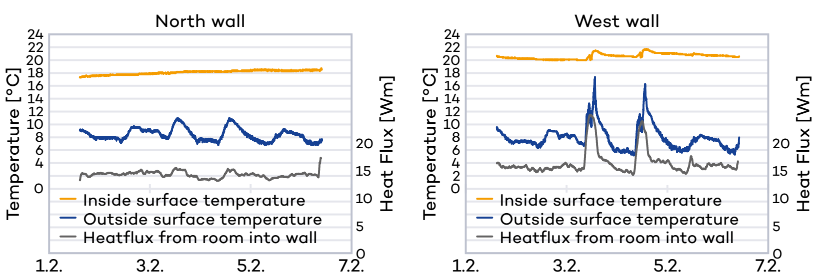


Fig. 5.59: U-value measurement at north and west wall of the Waaghaus (CS1)

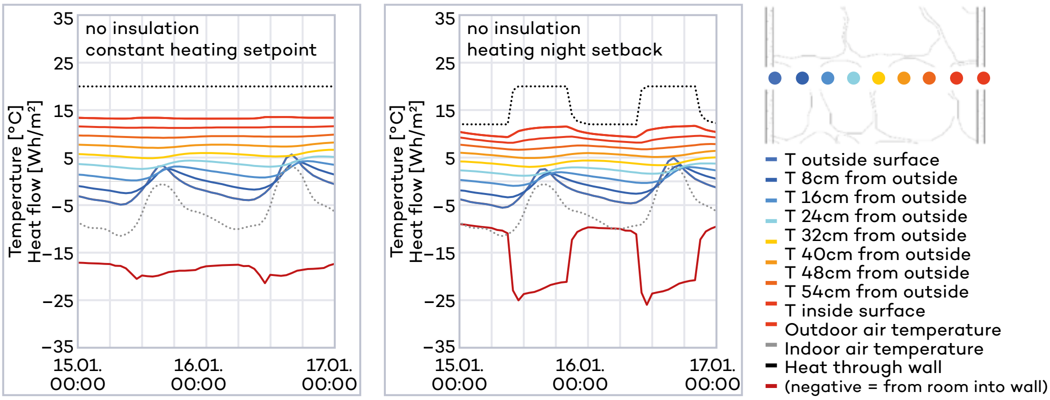


Fig. 5.60: Simulation of an uninsulated solid stone wall in Bolzano with constant temperature (left) and night setback (middle), influencing the instantaneous heat flux into the wall much more than the sun heating up the outer surface.

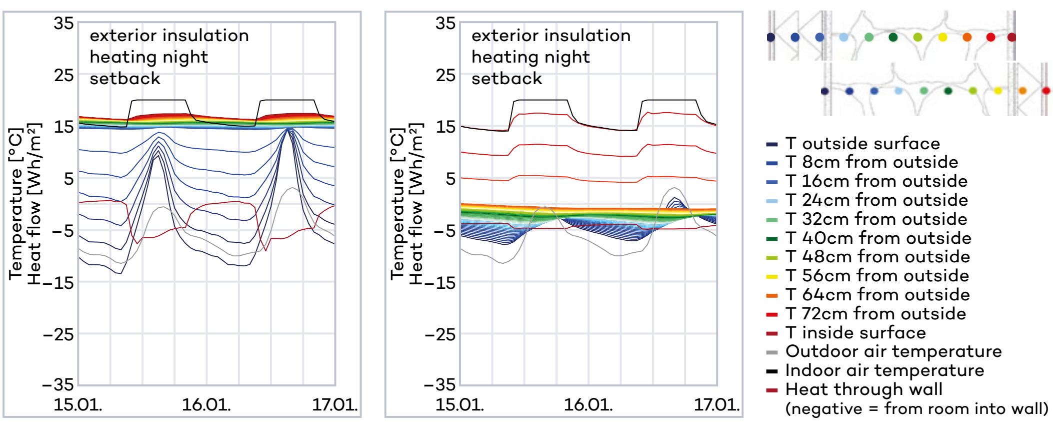
the wall (grey) does not shrink – rather it grows when the interior temperature rises (i) slightly in the north oriented room and (ii) more markedly in the south-west oriented room with the sun shining in.

The phenomenon of the sun heating the outer surface on a cold but sunny day remaining superficial can be understood through simulations, which also allow internal evaluation (see Fig. 5.60). The outer surface heats up and after midday is above the temperature of the wall at about 10 cm depth (where the dark blue line crosses the lighter blue one), but the flux from the room into the wall depends mainly on the difference between the indoor air and interior wall surface. This is relatively constant in the constant set point example and variable from day to night for the night setback example.

The average temperature of the wall in both of these cases is around 5°C and the interior surface at about 13°C (for continuous heating), varying between 10°C and 12°C (for night setback) respectively.

Insulating the wall changes the situation completely, with the main temperature drop now in the insulation layer, leading to a warm wall with external insulation (around 15°C, see Fig. 5.61 left) and a cold one with interior insulation (see Fig. 5.61 right, compare also monitored data in Fig. 5.58). The heat flux into the wall is reduced to one fifth compared to the uninsulated wall.

Fig. 5.61: Simulation of a solid stone wall in winter in Bolzano: with exterior insulation and thus warm historic wall (left), as well as interior insulation leading to a cold historic wall (middle)



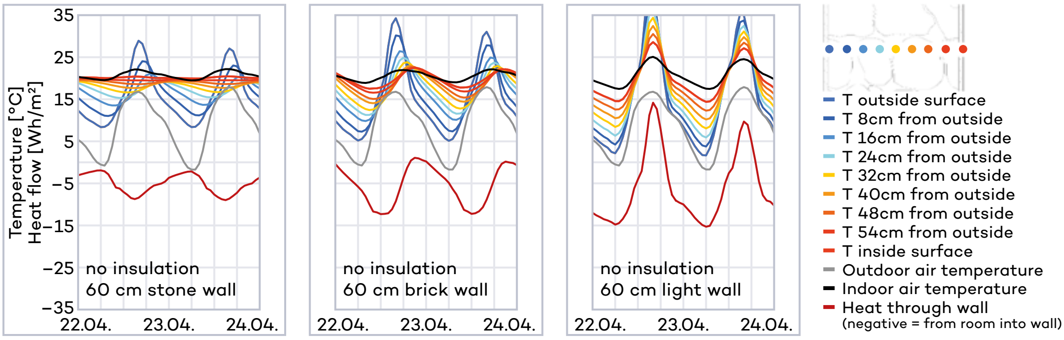


Fig. 5.62: Thermal mass effect for daily cycles – the simulation of temperatures in uninsulated walls with the same U-value but different mass (Bolzano climate)

The thermal mass effect of solid stone walls is clearly present for daily cycles (see Fig. 5.62) and can help regulate both the external cycles and internal loads. But a phenomenon like a cool church on a hot summer day cannot be transferred to residential and office buildings. With their solar and interior loads, the higher inertia of solid stone walls cannot help for longer than a few days (see Fig. 5.63).

5.6.2 Passive heating

In winter, solid walls can help exploit solar gains and internal loads. They absorb the heat and therefore temperature spikes which otherwise would have to be ventilated are limited. However, walls have to be insulated so that the stored heat is not just conducted towards the exterior.

In climates where heating is an issue (i.e. Bologna and Bolzano) the effect of heat conducted through the wall is much more pronounced than the effect of better passive utilisation due to thermal lag. This means that if exterior insulation is not possible, interior insulation is still preferred to no insulation, especially if inertia is also provided by interior walls. Furthermore, insulation shortens the heating period and allows the building to run passively over a longer period. The higher surface temperature also reduces mould risk and increases comfort.

In Palermo, heating is not a major issue. With some insulation the heating demand can easily be brought to zero, but the main reason to decide for or against insulation of a wall in such a climate will be that insulation will reduce the cooling load.

5.6.3 Passive cooling

The most important passive cooling strategies include night ventilation, shading to reduce solar gains, and the reduction of internal gains with efficient equipment. Night ventilation in particular, whether mechanical or natural, depends on the local conditions. The lag effect of walls combined with ventilation may reduce the active cooling load considerably, as shown in Figure 5.64 for the case of Bologna: Without ventilation (cases a and c) the interior surface temperature is about 28°C, heat flows into or out of the wall (red) are small and the cooling demand is quite high (blue dotted). With ventilation

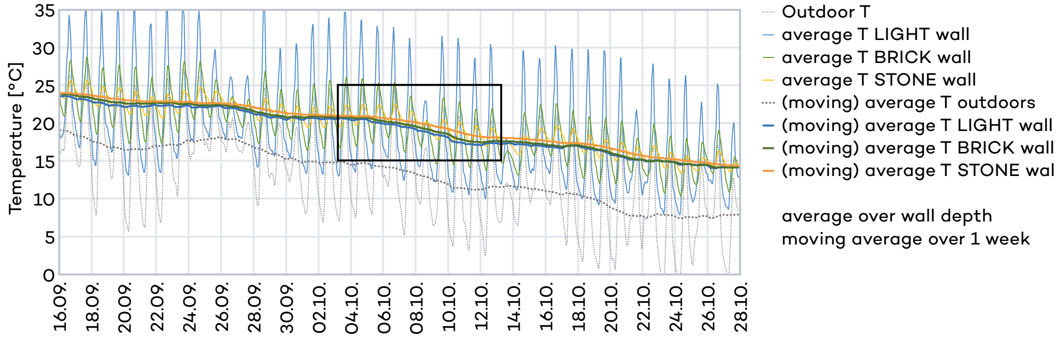
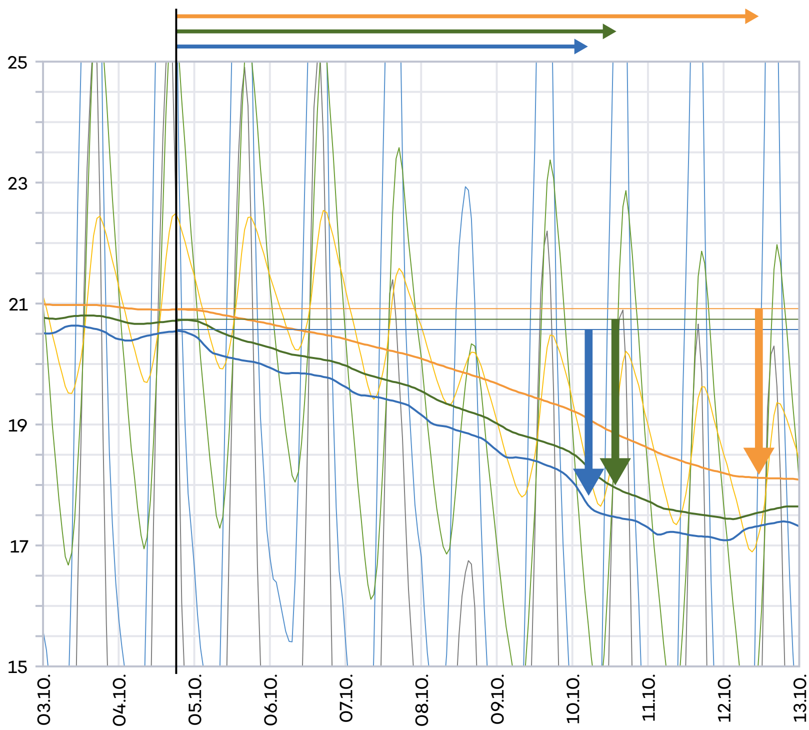


Fig. 5.63: Over a longer period, a heavy wall follows a lighter wall with only a small delay: heat cannot be brought easily from summer to winter or vice versa (simulation cases as described for Figure 5.62).



(b and d) the interior surface is about 26°c, the cooling demand is strongly reduced and the storage of heat is visible. During the day heat flows into the wall, during the night back into the room where it is ventilated off.

If only interior insulation is possible, whether due to the historic context or conservation restrictions, night ventilation still remains effective if enough thermal mass is provided by the interior partition walls. In the Waaghaus the interior brick walls were sufficient to show no discernable difference both in cooling demand and comfort from the interior and exterior insulation solutions. This changes with lightweight internal partitions – calculated for the Bologna case, the cooling demand becomes three times as high.

Without ventilation, one of the few mechanisms to reduce the heat from solar gains and internal loads is to transfer it via the wall. Since, however, the temperature difference between the interior and exterior is small in summer, this mechanism is ineffective. In all three analysed cases the average temperature of the uninsulated wall rises above 26°C during summer and heat flows from the exterior into the room rather than the reverse – in Bolzano for one month, in Bologna for two months, and in Palermo for more than four months.

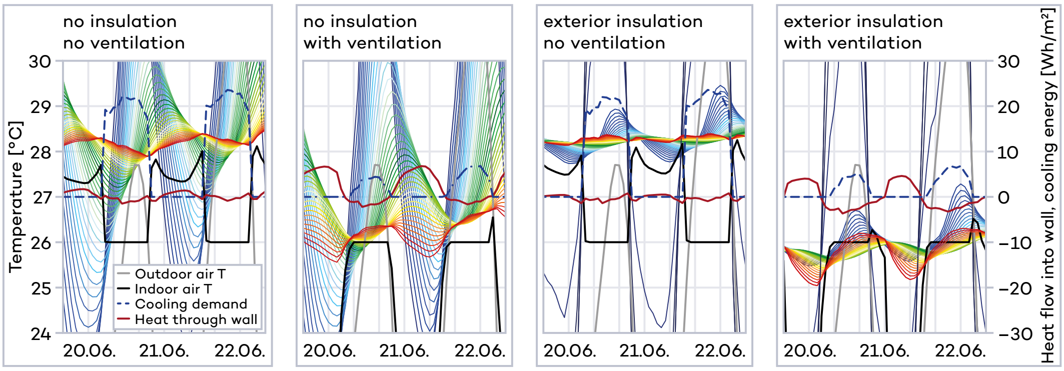


Fig. 5.64: Day cycle of the temperature profile within the solid wall in the Bologna climate.

5.6.4 Year-round optimisation

The sections above show that winter and summer optimisation are complementary and that in a good design the insulation for winter optimisation does not infringe on summer comfort and cooling demand. Ventilation and load reduction are the key issues.

Two examples illustrate this. In Bolzano the cooling demand may rise with more insulation if ventilation is restricted, since the low night temperature will allow for some heat transfer through the wall at night. The absolute savings in cooling energy without insulation are small compared to the additional heat losses in winter without insulation. Year-round optimisation is still clearly in favour of insulation!

In Bologna, the insulation installed for winter comfort does not affect summer comfort. Outdoor temperatures in summer are high, and heat transfer through the opaque wall is minimal. Passive cooling strategies have to rely on gain minimisation, i.e. shading to reduce solar gains and efficient equipment to minimise interior gains, and ventilation strategies.

5.6.5 Is cooling an issue even in the cool climate of Copenhagen?

The 3ENCULT project established a case study in Copenhagen (see Case Study 4), where it had previously been decided not to insulate the walls because the savings were not high enough. In winter, insulation clearly would have contributed to saving energy, but the year-round evaluation showed an increase in cooling demand in summer.

The decision process had taken place before 3ENCULT, and the case study focused on evaluating both the original process and the results. It was taken

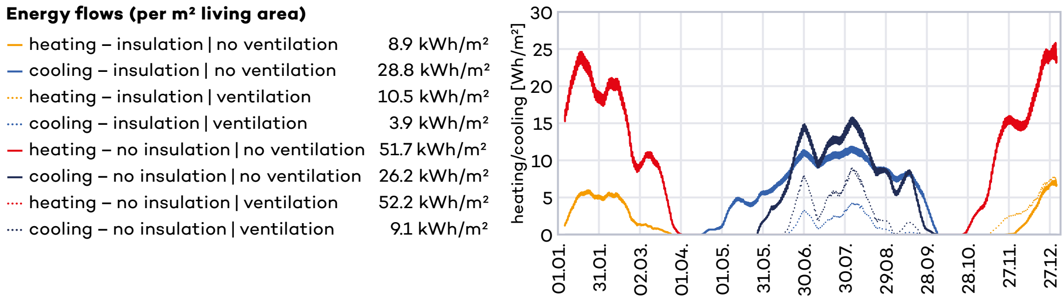


Fig. 5.65: For Bologna, year-round optimisation to reduce heating demand with insulation is more important than cooling. If thorough ventilation is possible, the cooling demand can also be considerably reduced, even more with insulation.

up in a dedicated workshop and with the multidisciplinary 3ENCULT team. The results are summarised here as questions and answers.

– *Question 1*: What is causing the cooling demand in the case study in Copenhagen?

With nearly 100 kWh/m²a the electrical office equipment was identified as a major cause. It is four times higher than the estimated internal load from people and light, and in the same order of magnitude than the remaining heating demand. This means that the offices are actually 50 % heated electrically in winter (with resulting bad primary energy and CO_2 balance in most European countries).

During summer this load has to be mitigated, and without any ventilation possibility the opaque walls must be used to reduce the heat. Considering the difference between the internal and external temperature is relatively small, this is an inefficient method.

– *Question 2:* Can the high electricity demand for equipment be reduced?

Yes, with a realistic degree of energy efficient equipment, and, in the case of high computer power needs, as, for example, architects often have, by relocating the server. By doing these things, the internal loads due to electrical equipment can be reduced to one fifth, i.e. about 20 kWh/m²a.

– *Question 3:* Can active cooling be avoided with this reduced load?

Yes, it can be avoided. With high internal loads the Passive House Planning Package (PHPP) calculates a cooling demand of 20 kWh/m²a (consistent also with dynamic simulation) and a respective overheating frequency of 20 % if no active cooling is provided, but the cooling demand drops to 5.5 kWh/m²a with energy efficient equipment. If no active cooling is provided, the overheating frequency drops to 3 %. The indoor comfort during summer can be further increased if natural ventilation via window opening is considered, dropping to an overheating frequency of 1.7 %, and overheating actually reduced to nil using night ventilation via tilted windows on the second floor.

– *Question 4:* Is it now possible to reduce the heating demand without worsening the summer situation?

Yes, it is. Without any additional insulation measures, the heating demand will actually increase since the offices are no longer heated by the equipment. However, insulation measures that were rejected due to insufficient energy

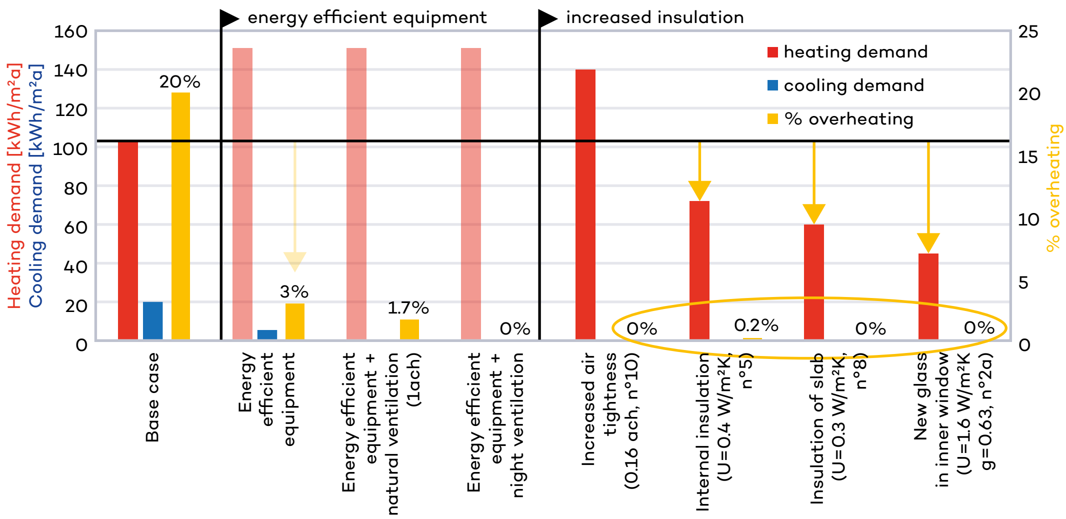


Fig. 5.66: Heating and cooling demand and % of overheating if no active cooling is provided – for different design options in the case study in Copenhagen, elaborated within a 3ENCULT workshop, with the aim of avoiding the need for active cooling and optimising the year-round performance.

savings in the case study's original decision process can now contribute considerably to energy saving in winter without compromising the summer comfort. Interior insulation of the walls, insulation of the slab, improved airtightness, and new glass in the inner sashes of the existing windows reduce the heating demand to 40 % compared to the baseline.

Energy can be saved three times, therefore, by reducing the electrical equipment load!

1. The *direct electricity saved* for running the equipment
   → 80 kWh_{el}/m^2a * 0.25€/kWh_{el} = 20€/m^2a
2. The indirect saving due to *reduced cooling demand* and reduced investment where cooling is avoided
   → 20 kWh_{th}/m^2a * 0.25€/kWh_{el} * (1 kWh_{el}/3 kWh_{th}) = 1.6€/m^2a
   → investment for cooling system avoided
3. The indirect saving due to *reduced heating demand* since insulation measures no longer compromise summer comfort
   → 60 kWh_{th}/m^2a * 0.1€/kWh_{th} = 6€/m^2a

In owner-occupied offices this is clearly the most economical solution. Approaches for rented offices have to be discussed between the tenant and the owner, but perhaps renting the central server and computer power to the tenants is a smart solution and a unique selling point, perhaps providing an advantage over competitors. These are the key points that resulted from the 3ENCULT workshop.

5.7 INTEGRATION OF RENEWABLE ENERGY SOURCES

Javier Antolín Gutiérrez, José L. Hernández, Cristina de Torre, CARTIF

5.7.1 RES integration in historic buildings

Historic buildings are often energy inefficient and environmentally unfriendly. Renewable energy sources (RES) can be implemented within refurbishment projects in order to defray the high consumption with energy from sustainable sources. One of the most challenging issues of the integration is preserving (or enhancing) the original form and value of the buildings. A study of the impact of available RES was carried out within the 3ENCULT project, where different types of RES were studied and classified. The extent of substitution of conventional energy sources and the aesthetic and physical impacts are the aspects that were considered in order to assess the suitability of each kind of RES for different typologies of historic buildings.

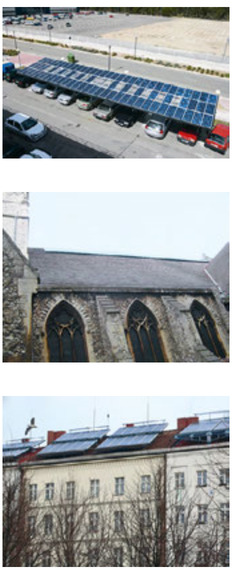
5.7.2 Solutions for electricity production

5.7.2.1 Photovoltaic

Photovoltaic (PV) is a method for generating electric power by using solar cells to convert energy from the sun into a flow of electrons. The PV array is generally sited on roofs, although as the technology develops, PV can increasingly be incorporated into other elements of a building such as roof tiles, glazing, walls, and sun shades (see Fig. 5.67).

PV installation on a roof could be timed to coincide with replacing the roof covering. Where a tiled or slated roof needs to be replaced, it can be particularly cost-effective to install PV roof tiles as new roof covering.

Fig. 5.67: Different ways to incorporate a PV array



The PV system should always be sized to match at least the individual needs of a property, but it is also important to consider future needs. Nevertheless, in countries where it is possible to feed energy into the grid (i.e. receiving money for it), it makes sense to use the total area available for PV.

On the one hand, the basic requirements for this technology are sunlight (global radiation), unshaded space for the solar panels ideally facing to the south, a strong enough roof, a back-up electricity source, and space for the back-up source if it is not grid connected. The more light the PV array receives, the more electricity is generated. It works better with direct sun impact (global radiation), and although it also works in diffuse radiation conditions, the efficiency is reduced because the gains of the solar array are directly proportional to the solar radiation, the diffuse radiation being lower than the global radiation. An important issue, therefore, is to ensure, at least in new constructions, that extensions and tree growth will not overshadow the solar panels in the future. As almost any part of the building that is well exposed to sunlight can be used for PV integration, the design of the installation offers a certain degree of freedom. However, the space requirements for

Fig. 5.68: Integration of PV in a glass facade

the PV installation have to be taken into account, as well as avoiding, whenever possible, the main elevation of the building or a dominant roof line.

On the other hand, architectural integration is an important topic, even more for old buildings than for new ones. In this way, the PV could give an added value to the aesthetics of the building, as happens in the example of the Cartif offices building where the photovoltaic cells are integrated into the glass facade of the building (see Fig. 5.68). However, it is not always possible and sometimes it needs to be hidden to reduce the visual impact.

In the case of historic buildings, sometimes the PV may have to be integrated somewhere other than in or on the building itself (see example in Fig. 5.67) if there are regulations banning interventions. Nevertheless, other cases allow low impact intervention like, for example, the 'Kirchgemeinde Carlow' church in Carlow, Germany. The church roof was equipped with PV in the course of roof repairs. The polycrystalline module was produced to match the existing roof tiles in shape and colour; one photovoltaic module replaced six roof tiles. The PVs are integrated into only a small part of the roof, replacing the normal roofing material. Thus the historic appearance of the church was maintained as stipulated by the monument protection authority.

For all these reasons, requirements, and constraints, the 3ENCULT project has developed an innovative solution based on semi-transparent double-glazed PV windows (see Fig. 5.69). This solution offers the possibility of integration in buildings through the replacement of the window glass, providing higher shade level inside. It is easier to integrate into the building because it may enhance the aesthetics and does not have such restrictive regulations as roof interventions.

Fig. 5.69: Semi-transparent double-glazed PV window

5.7.2.2 Wind energy

A wind turbine is a device that converts kinetic energy from the wind, also called wind energy, into mechanical energy; this process is known as wind power. A wind turbine only generates electricity when it is turning and has no capacity to store electricity; therefore a back-up system is needed. A domestic wind system will typically produce 1–6 kW, but smaller systems can be used to recharge batteries or to power low-voltage equipment.

Fig. 5.70: Wind turbine fixed to a building

The main system components are the mast (fixed directly to a building or freestanding away from the building), turbine, and core electrical components. The basic requirements of these systems are the space to install the turbine, suitable site conditions (free of obstacles), adequate wind speed (above 5–6 m/s), a back-up electricity source, and the space for this back-up source if it is not grid connected. Besides wind speed, wind direction is also important, although nowadays turbines can be designed that change their direction according to the wind; therefore they can generate electricity whatever the wind direction is.

The majority of wind turbines have a horizontal axis (they work by the wind passing horizontally past the blades). The vertical axis turbines are less common, they have a different appearance and are often less efficient. However, the vertical axis turbines can perform better in areas where air turbulence is common, making them potentially more viable for urban areas.

Building-mounted turbines are often not permitted on historic buildings due to their visual impact (see Fig. 5.70). Moreover, the installation process or any vibration could also affect the building fabric. This makes freestanding mast-mounted turbines more viable for many historic properties. It is important to note that wind turbines produce some noise, which may be audible within a certain distance, and also under determined light conditions the turning blades create flicker and shadows – if the shadows extend to a property or garden they could be annoying.

As mentioned before, turbines must be placed in a reasonably exposed location and at heights where wind speeds are high, without obstructions, trees, or other objects that could cause turbulence. Consequently, they are often difficult to integrate successfully into an urban environment and are more suitable for rural locations. It is also important to note that future obstacles, such as tree growth or new buildings, could compromise the wind turbine's performance. Finally, for building-mounted turbines, a structural survey of the building is needed to ensure that it can support the proposed installation without subsequent damage.

5.7.2.3 Hydropower

A hydro turbine works in the same way as a wind turbine, generating electricity as it rotates with water driving the turbine, and has no capacity to store electricity. Micro hydro systems are among the most reliable, durable and cost-effective renewable energy options available. They provide a steady, predictable source of electricity, run very efficiently and cost less per installed kilowatt than other electricity generation technologies. The basic requirements for these systems are a nearby source of running water with a relatively consistent flow, a back-up electricity source, and space for the back-up if it is not grid connected.

The power that can be taken from the water is dependent on two things: the volume of running water (flow) and the difference in height between the point where the water is taken from the source and the point where it is returned to the source after passing by the turbine.

Fig. 5.71: Historic mill utilised for a modern hydroelectric scheme

In some cases, hydropower offers an excellent opportunity to enhance the character of a historic building, making it more appealing due to the incorporation of vintage elements (see Fig. 5.71). Thus, many old mills or former mill sites that are listed can be taken advantage of in order to provide suitable locations for new hydroelectric installations. Some consideration, however, needs to be given to the historic impact due to vibrations, noise, regulations, landscape issues (size depends on the desired power), or any other concern. If the building is situated near a suitable water source, hydropower can be the best source of renewable energy. This becomes more important in rural sites, ideally either hilly locations with fast-flowing rivers or lowland areas with wide rivers.

5.7.3 Solutions for thermal energy production

5.7.3.1 Solar thermal energy

Solar water heating systems take advantage of natural solar radiation by absorbing it and using the energy to heat water. It is possible to install an oversized solar water heating system and use it to supplement the space heating. The basic requirements for these systems are sun radiation (global and diffuse) and space for both solar panels and a hot water tank. Additionally, the stored hot water must be heated to 60°C regularly to avoid the risk of legionella bacteria.

There are a number of key components in this system, like solar panels (for collecting solar radiation), pipework, a hot water cylinder (for storing the heated water), and a pump. Two main types of solar panel are manufactured: the flat plate collector (see Fig. 5.72, left) and the evacuated tube collector (see Fig. 5.72, right).

Fig. 5.72: Types of solar panels fixed to a roof

Depending on the location of the installation, structural surveys are required, such as with roof integration. The existing roof structure must be strong enough to accommodate the combined weight of the panels. The panels are generally straightforward to install and can usually be simply linked up to the existing heating system. However, solar panels may not be permitted on roofs above the main elevation (the side of the building most viewed, generally that facing a street). If the south-facing roof space is above the

Fig. 5.73: Different installations of solar collectors

principal elevation, it may not be a viable installation. A potential solution is to install a panel system where it is more or less hidden from sight, by inserting the solar systems on outbuildings or subordinate extensions, for instance. This reduces the visual impact of the panels and may satisfy planning requirements (see Fig. 5.73).

Solar collectors are most frequently sited on roof slopes with a south-west to south-east orientation and at a pitch of 30–50 degrees. However, there are other ideal locations for these solar collectors depending on the sun incidence angle.

5.7.3.2 Biomass

As a trending renewable energy source, biomass can be used directly via combustion to produce heat. Modern biomass heating systems can provide both space and water heating and come in a wide range of sizes, from individual room-heaters to whole-house systems. The system will provide most of the annual heating requirement, and a small back-up system can be installed to provide top-up heating at times of peak demand.

The basic requirements for these systems are a source of fuel which is available on an on-going basis, space for the heating system (stove or boiler and hot water cylinder if applicable), space for fuel storage (an existing shed, garage or outbuilding may sometimes be used), adequate access to the fuel storage, a flue (can be an existing chimney although it may have to be lined, which can be relatively expensive), and adequate ventilation. If there is no chimney a new flue can be installed, siting it as discreetly as possible and away from the principal elevation, and exiting the property through the roof or a wall. The fuel is either manually or automatically fed into the system. Automatic systems are generally more efficient and minimise the need for manual intervention. Finally, three main forms of fuel readily available are logs, pellets and woodchips.

There are two main biomass systems:

→ Biomass stoves: generally have a capacity of around 6–12 kW and provide direct heat to the room in which they are installed. This heat may spread to adjoining rooms and possibly to upstairs rooms if vents are installed in the ceiling. Stoves can also be connected to a back boiler, allowing them to provide hot water that can then be used for domestic hot water needs or for space heating via a central heating system.

→ Biomass boilers: generally have a capacity of at least 15 kW and work by heating water that then can be stored in a large hot water cylinder. This water can then be used to provide space heating via a central heating system and to provide domestic hot water. Biomass boilers can supply water at different temperatures and pressures depending on the heating distribution system (radiators or under-floor heating).

Biomass systems must be appropriately sized for the property and for the occupants' heating needs. These systems can be very easily controlled, making them an excellent heating solution. Biomass systems operate more efficiently when they are hot and working close to their maximum capacity, so over-sizing a system will lower its efficiency.

Many old properties were also designed and built with similar heating systems in mind and have fireplaces and chimneys ideal for siting modern stoves, although they may have to be lined. In fact, in historic buildings it is a very common retrofitting strategy because the low visual impact and the high efficiency, as illustrated in Figure 5.76, even in poorly insulated buildings, make them an excellent option for traditionally built properties which are often draughty and have less insulation. These buildings frequently offer space for placing the boiler, although if there is a suitable outbuilding this could be used to install the biomass system; otherwise a purpose-built structure may be needed. It must, however, be taken into consideration that the ventilation system may need improvement in order to ventilate the equipment and piping and to supply the air required for combustion.

Fig. 5.74: Biomass pellet boiler in Colegiata de San Isidoro, León, Spain

5.7.3.3 Geothermal energy

Geothermal energy takes heat from the ground though ground heat pumps and distributes it in usable temperatures. It is generally used for space heating and sometimes for hot water.

The requirements for these systems are the space for the heat pump, ground space, high levels of insulation and airtightness in a property (meaning that they are not suitable for historic buildings where improving airtightness and insulation are not possible), a top-up heating system for times of peak need, a heating distribution system, and a power source to start the heat pump. The main components of a heat pump system are the heat exchanger (extracts heat from the ground), the heat pump (increases the extracted heat to a high enough temperature to heat a property), and the distribution system (radiators or under-floor heating).

The heat is collected in a series of narrow boreholes, approximately 100 metres deep, or alternatively, in a horizontal ground loop installed around 1.8 metres below the surface of the ground where the temperature is relatively stable. Boreholes (vertical) are normally drilled where there is not a large land area available and tend to be more expensive to install. Moreover, boreholes must be correctly spaced because if they are too close together, the efficiency of the system will be reduced. Horizontal ground loops or trench loops require a larger land area than borehole loops. Horizontal loops can be considerably cheaper than vertical boreholes, but are usually less efficient due to the fluctuating ground temperature near the surface.

Heat pumps provide more efficiency when running constantly rather than switching on and off, as well as when the temperature of the heating circuit is lower. It is good practice to incorporate water heating, which ensures continuous demand, and / or adding more or larger radiators. The distribution of the energy from the pumps is normally distributed via underfloor heating or radiators, but the first option is preferable because it effectively uses the floor as a large low temperature radiator. Where old central heating systems are already present, the radiators may have been over-sized, and in such cases it is sometimes possible to use these existing radiators with a heat pump system as their greater surface area could compensate for the lower water temperature. New, low temperature radiators may also be an option, but their appearance is a consideration as they are bulky and look different to conventional radiators, making them potentially more visually intrusive. Besides the performance, under-floor heating is the most discreet, although where there is an original floor, careful consideration is needed to avoid damaging any original fabric. It should be possible to lift the original flooring and re-lay it on top of the under-floor system. Alternatively, a floor covering in keeping with the property could be installed (see Fig. 5.75).

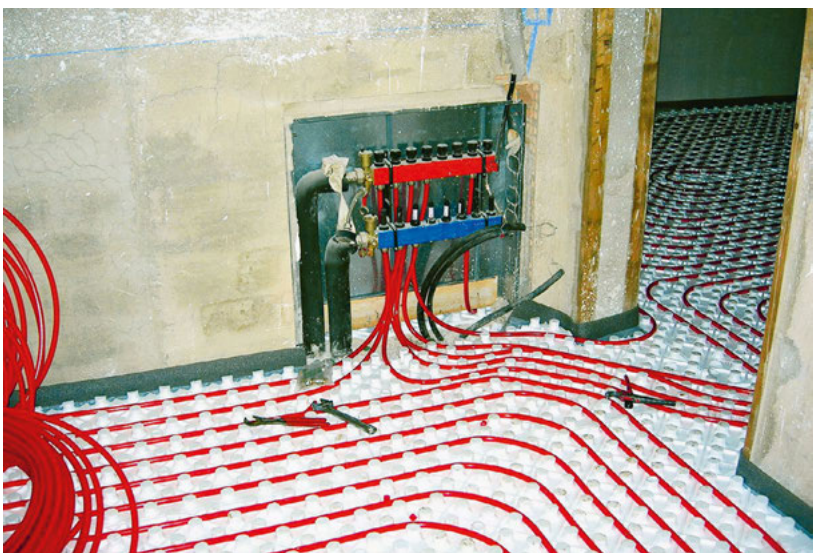


Fig. 5.75: Under-floor heating system in an old construction

Some heat pumps can be reversed during warmer periods to cool a property rather than heat it. It should be noted, however, that a heat pump is optimised for heating, while air conditioners are optimised for cooling. If there is no absolute requirement for cooling, it is better to choose a non-reversible heat pump, which will be cheaper.

The visual impact of the heat pump system is vital to the success of the project. All parts of the system that can be seen should be considered carefully. The minimal visibility of ground heat pumps is beneficial from a planning perspective as they have no external visual impact on a historic building. Nevertheless, it is not always achievable since pipes will need to run between the heat source and the heat pump, and it will be necessary to find a path through, under, over, or around the external wall that does not cause irreparable damage. Thus, in certain cases, a historic building may benefit from constant, low-level heating to protect its fabric or its contents (for example, paintings, artefacts, furniture, etc).

5.7.4 Conclusions of conservation issues

From the perspective of integration into historic buildings, aesthetic aspects are very important, but other relevant aspects should be considered in order to preserve all the characteristics of this type of building.

These installations should be planned carefully to maintain the historic character of each site and to make best use of the available renewable energy sources. It is important to make sure that the system works effectively but it is vital to consider its visual effect on the external appearance of the building.

The appearance of the building may be damaged when the equipment covers over or replaces historic fabric in obtrusive locations, or if it is visible in the profile of the building, and furthermore, the appearance may be damaged when free standing equipment is located in the path of principal views to or from the building. Besides these aesthetic aspects, noise, emissions, and vibrations are other sensory factors that have to be considered in relation to planning permission.

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5.8 INTEGRATED APPLICATION OF SOLUTIONS

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To reduce the energy demand of historic buildings and existing buildings in general, passive and active energy efficiency solutions are implemented. The optimal solution for any single building will depend on its physical characteristics, its climate and current use, and its specific preservation demands.

5.8.1 How to find an integrated solution

The European standard EN 15603 recommends starting by calculating the building's current energy use with a dynamic or static mathematical model of the building. It is important that the model has enough detail regarding all relevant input variables and parameters (e.g. U-values, infiltration and ventilation, internal loads, shading, climate data) and does not rely on default values. Whether a dynamic or a static calculation is done depends also on the complexity of the building and on how important transient aspects are, for example simultaneous loads or changing heat flow direction between night and day.

For a retrofit design, EN 15603 recommends the model to be *tailored,* for example using actual climate and air changes as well as specific indoor temperatures (not the standard values used for certification), and *validated* with measured data (consumption and temperature). Any calculated results must always be evaluated by comparing them with energy bills or statistical data of similar building stock. Where possible, the model should be calibrated by using data collected through a monitoring system (see Chapter 6). The standard also points out that measures may interact and their effects cannot be simply totalled. It therefore recommends that several retrofit scenarios be prepared, each containing a list of compatible measures. For historic buildings, compatible measures also include preservation criteria, which are of equal importance.

If a static calculation is appropriate, it is possible to use the Passive House Planning Package (PHPP) which, in the version developed within the 3ENCULT, includes a tool for parametric analysis (see Section 4.4). This makes the comparison of different retrofit scenarios particularly easy. Alternatively, a dynamic calculation can be modelled and scenarios with different parameters can be easily compared with software such as EnergyPlus, TRNSYS, and Integrated Environmental Solutions (IES). All these tools create a geometrical model of the building with a user friendly 3D interface and are easily imported into a calculation tool, where it is completed with all necessary information on envelope and technology systems.

What both these approaches have in common is that there is a design team proposing the first scenario, analysing the results, and developing alternative scenarios for evaluation, with its experience guiding the process. It is recommended to always go one step beyond what is considered optimal – this will confirm expectations but may also develop new insights.

Criteria for comparison are heating demand, cooling demand, primary energy demand, and in this case also electric appliances should be included – their heat supply should not be a hidden result. CO_2 emissions should possibly be included and comfort aspects such as the operative temperature and light. Life cycle cost (initial investment, operation, maintenance), installation impact, and, in the case of historic buildings, conservation compatibility of the retrofit package must be assessed.

As an alternative to the design team driven scenario development, a mathematically driven optimisation approach can be adopted. This approach is more impartial and could lead to solutions a human might not consider. It considerably reduces the time effort and usually results in several optimal solutions for consideration. The design team still plays a fundamental role in this approach since it has to clearly define the context, possible constraints, types of variables and parameters to be considered, and a reasonable range of variations. Again it is recommended to go beyond the normal practice. Many software providers integrate such optimisation tools into their building energy simulations.

5.8.2 Practical examples

The following sections discuss several aspects of integrating solutions, based on the experiences of 3ENCULT case studies.

Firstly, the integration of different measures to reduce the heat loss in the Hötting Secondary School in Innsbruck are discussed (analysis with PHPP on monthly energy balances, see Section 4.4.2).

This building is then virtually transferred to other climates, and the intervention package is adapted to each new climatic situation and different needs for heating and cooling demand reduction are noted. It becomes clear that the impact calculated for single interventions cannot be simply added together – but can be both lower or higher than the sum would have been.

5.8.2.1 Different options at the Hötting Secondary School in Innsbruck

Let's look at the example of the Hötting Secondary School in Innsbruck (see Case Study 5). PHPP calculations before and after interventions demonstrate the range of potential savings. The comparison of different refurbishment solutions also shows the effects of single interventions as well as combinations of measures.

The annual heat losses (during heating period) for each of the refurbishment options divided into transmission heat losses from windows, external walls, the floor slab, and the ceiling, and the ventilation heat losses are presented in Figure 5.76. The first bar of the diagram refers to the status before renovation with total heat losses of 158 kWh/m^{2}a.

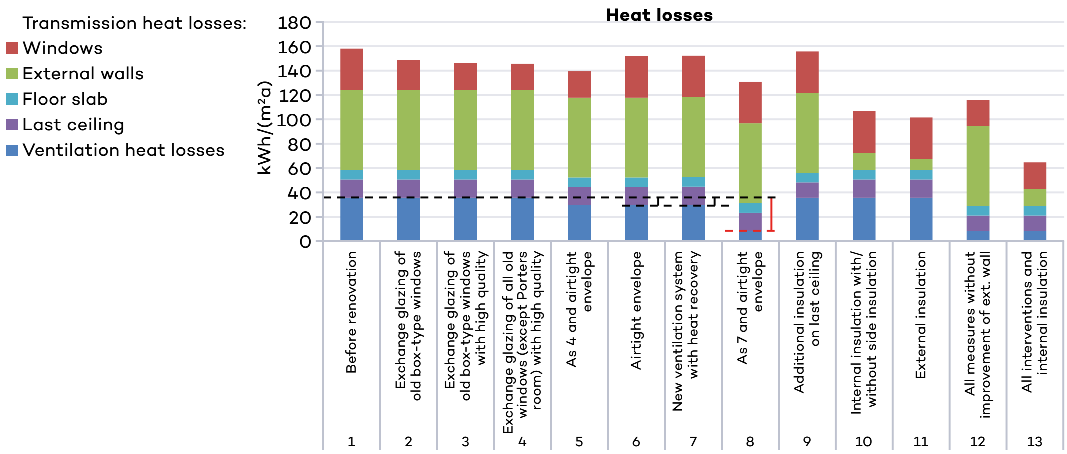

Fig. 5.76: Comparison of heat losses (during heating period) for different refurbishment options (Hötting Secondary School, Innsbruck, see also Case Study 5)

As is clearly visible in the diagram, most heat loss reductions are achieved by improving the external wall (green segment) and the ventilation (dark blue segment).

The proposed first option for improving the external wall is external insulation with a thickness of 120 mm (see variant eleven). This also reduces the high losses over the thermal bridges, for example the connection between the load bearing steel beams in the ceiling and the brickwork of the external wall. The external insulation has a possible reduction of 58 kWh/m²a, which has the highest impact on the heat losses of the building. Variant ten shows the possible savings using 80 mm internal insulation. With 53 kWh/m²a the measure has still a high impact, but the losses caused by the thermal bridges and points with potentially critically low temperatures are not affected, and in addition, all heating ducts have to be relocated inside.

6.5 kWh/m²a of heat losses can be avoided by improving airtightness, refurbishing the old windows with new seals, and fixing leakage in the thermal envelope (variant six). The 6 kWh/m²a reduction in variant seven is possible with a new ventilation system that has an energy efficient heat recovery. The comparison of variants six and seven with variant eight shows that, in terms of energy, the ventilation system works best when airtightness is improved: that way heat losses can be reduced by 28.5 kWh/m²a. Installing energy efficient ventilation in combination with improving airtightness is therefore the second most effective refurbishment task in this model.

It is also important to replace the old windows with new windows that are more airtight and have a better U-value. With this intervention, variant five in the diagram, a reduction of annual heat losses of 14.5 kWh/m²a should be possible. The airtight envelope in this variant is combined with the replacement of the windows as they cause the largest part of the heat loss due to insufficient airtightness.

Opting for internal insulation due to the conservation restrictions in this specific case, all interventions combined have a total possible reduction of heat losses of 91 kWh/m²a (variant thirteen).

5.8.2.2 Different strategies in different climates

The same building with the same use but in a different climate needs a different strategy to be developed by the designer. The six climates chosen here are from 3ENCULT case studies. The three cold locations are in the Alps, with Innsbruck as the existing location of the building, Appenzell as example of a cold alpine village, and Bolzano as a milder location where cooling needs start to become an issue. The three warm locations are Bologna in Italy, where both heating and cooling have to be considered, Bejar in Spain with heating and cooling demand (both less than in Bologna), and Palermo, an example of a place with little or no heating demand.

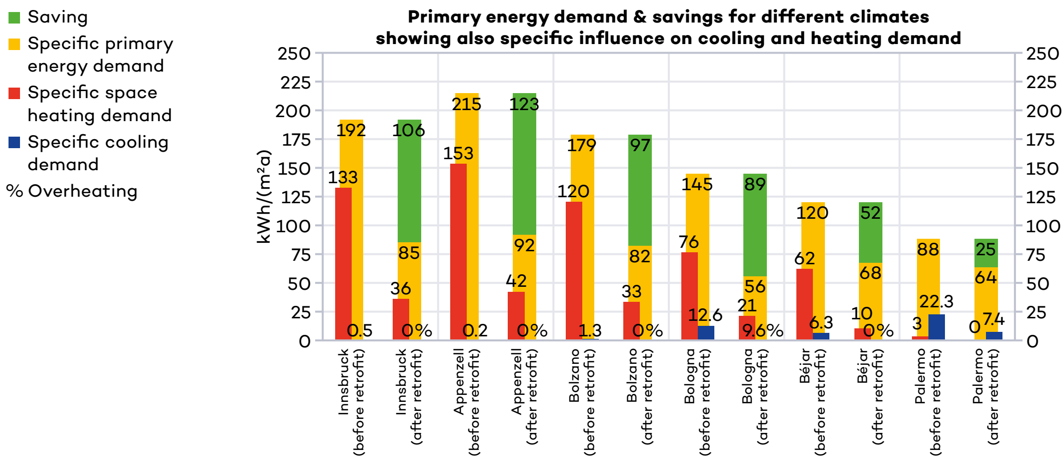

Fig. 5.77: The Hötting Secondary School in six different climates, with six different retrofit strategies

The diagram in Figure 5.77 shows the primary energy demand (including light and office equipment) and the respective possible savings with a proposed intervention package (presented below), as well heating and cooling demand, and the respective per cent of overheating (hours above 25°C) for the option without cooling.

→ In Appenzell and Innsbruck, new high efficiency windows are installed together with exterior insulation, airtightness is improved, and a ventilation system with heat recovery installed.
→ In Bolzano, in addition to the above measures, an exterior shading system and night ventilation are introduced to reduce cooling demand in summer.
→ In Bologna, the same measures as above reduce the heating demand. Additionally it is possible to dispense with a cooling system as less than 10 % overheating is possible with low g-value windows, higher night ventilation (3 vol/h), and reduced internal loads (e.g. LED lighting).
→ In Bejar slightly less emphasis has to be given to winter enhancement, while cooling demand can be reduced by using the same measures as in Bolzano.
→ In Palermo heating is not an issue at all, but, as shown further below (see Fig. 5.79), it is recommended that the windows be enhanced. With exterior insulation, shading, and night ventilation, the cooling demand can be reduced to one third.

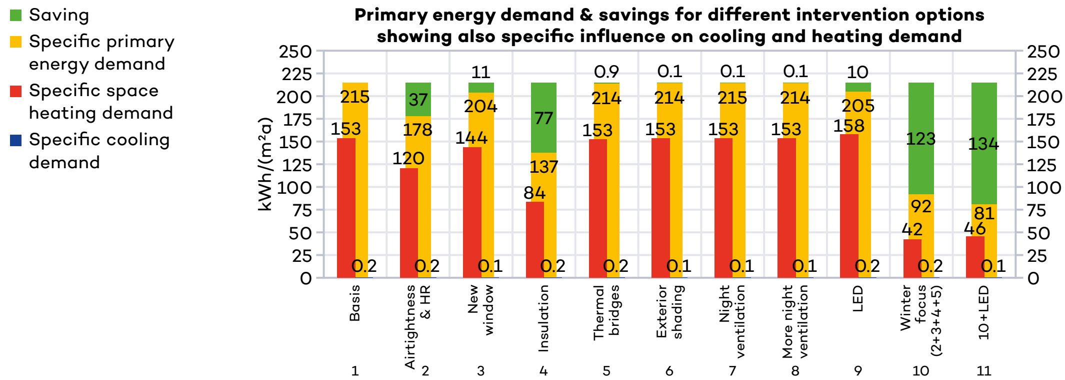

Fig. 5.78: In a cold climate like the alpine village Appenzell, the retrofit focus is on winter

A more detailed look at the Appenzell case shows that the most important measures to reduce heating demand are installing insulation (77 kWh$_{PE}$/m^{2}a), improving airtightness, and installing a ventilation system with heat recovery (37 kWh$_{PE}$/m^{2}a). In combination with new windows and removal of thermal bridges, the heating demand can be reduced from 153 kWh/m^{2}a to 42 kWh/m^{2}a – these are savings of 73 %!

At the same time, the primary energy demand goes down from 215 kWh/m^{2}a to 92 kWh$_{PE}$/m^{2}a. With the installation of LED lights, the primary energy demand can be further reduced to 81 kWh$_{PE}$/m^{2}a, while heating demand shows a slight increase.

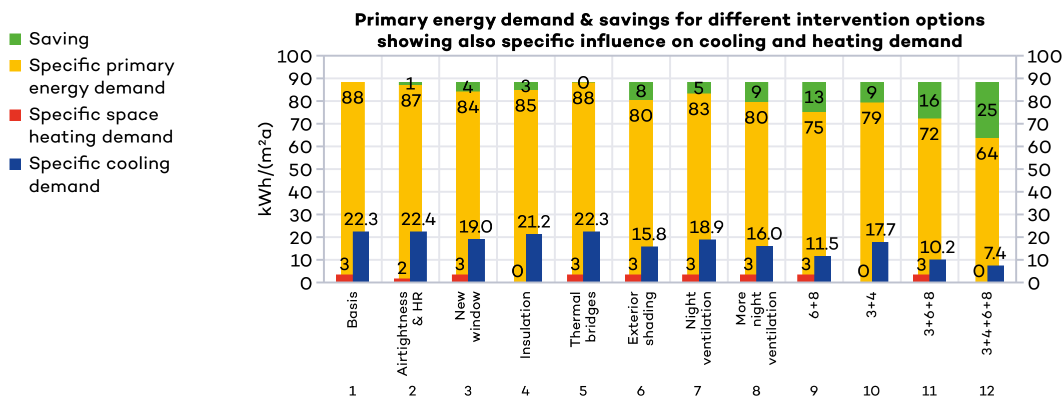

Fig. 5.79: In a hot climate like Palermo, the retrofit focus is on summer and reducing cooling demand

On the other hand, in a hot climate like Palermo, heating can be dispensed with as the focus is on reducing cooling demand. New windows alone reduce the cooling demand by 3.3 kWh/m^{2}a, exterior shading by a very significant –6.5 kWh/m^{2}a, similarly to intensive night ventilation at –6.3 kWh/m^{2}a. Together these measures bring the cooling demand down from 22.3 kWh/m^{2}a to 10.2 kWh/m^{2}a. Exterior insulation on its own does not seem that promising with a reduction of just 1.1 kWh/m^{2}a, but together with shading and night ventilation it has a greater impact and brings the cooling demand down

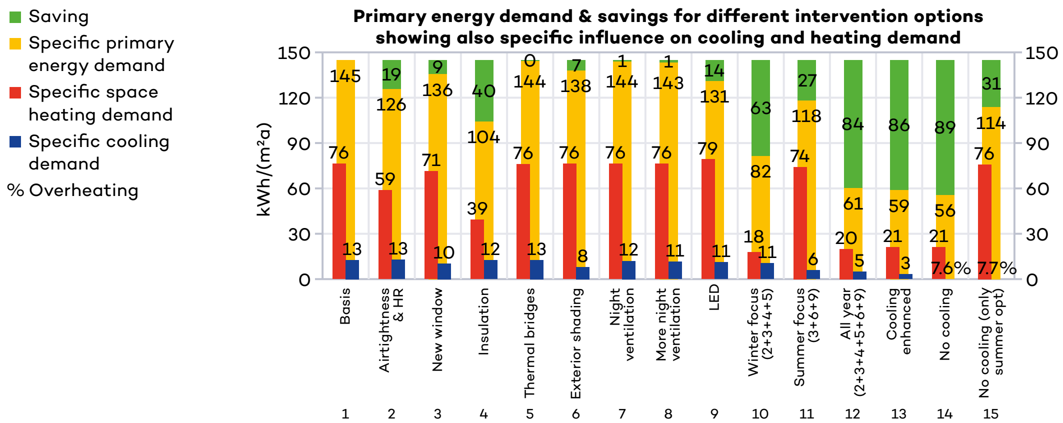

Fig. 5.80: In Bologna with both heating and cooling demand, year-round optimisation is essential and cooling interventions can be dispensed with if some overheating is accepted.

further, reducing it to one third of the pre-retrofit demand. At the same time, heating demand is decreased to zero.

In terms of primary energy, the total reduction amounts to 25 kWh_{PE}/m^2a. It is less pronounced as the values also include the electricity for light and office equipment, which is not changed in the proposed measures.

In a place with both heating and cooling demand like Bologna, ventilation with heat recovery, new windows, and insulation with thermal bridge removal bring the heating demand from 76 kWh/m^2a down to 18 kWh/m^2a (76 % reduction) and lowers cooling demand by 2 kWh/m^2a. With the focus on cooling demand, new windows, external shading, and LED lighting (3 vol/h) lead to a reduction of the cooling demand of 6 kWh/m^2a, and at the same a considerable primary energy saving of 27 kWh_{PE}/m^2a.

The focus on the winter case, however, already leads to a primary energy saving of 63 kWh_{PE}/m^2a, and this should therefore be the priority intervention. The year-round optimisation with all these measures applied leads to a primary energy saving of 84 kWh_{PE}/m^2a.

By reducing the g-value of the windows, optimising exterior shading, and with intensive night ventilation (5 vol/h), it is possible to bring the cooling demand down further, to 3.3 kWh/m^2a. If, however, a frequency of 7.6 % overheating can be accepted, no cooling system needs to be installed.

Reference

EN 15603:2008, *Energy performance of buildings. Overall energy use and definition of energy ratings*, 2008.

6 ENERGY COMMISSIONING

6.1 BUILDING MANAGEMENT SYSTEM

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6.1.1 What is a Building Management System?

A Building Management System (BMS) is a hi-tech computer based software system which is installed in buildings for monitoring and controlling the equipment and facilities. Some examples of equipment which can be added to a BMS are:

→ air handling and cooling plant systems;
→ lighting;
→ power systems;
→ fire systems;
→ security systems.

A BMS is a complex, multi-level, multi-objective, integrated, interrelated, and intelligently designed information management system which mixes software and hardware. The software is the entity in charge of communication with the physical network and the intelligent components. The hardware is the physical environment, and includes the devices, sensors, and actuators as well as the environment or facilities where the devices are placed.

The purpose of a Building Management System (BMS) is to automate and take control of these operations in the most efficient way possible for the occupiers/business, within the constraints of the installed plant.

6.1.1.1 Features of 3ENCULT Building Management System

The BMS defined in 3ENCULT is a multiservice system that has been developed according to a service-oriented and open (SOA) architecture. SOA architecture is a software design methodology based on structured collections of discrete software modules, known as services, that collectively provide the complete functionality of a large or complex software application. Each module implements a function through well-established interfaces for communicating with the remaining modules to allow complete interaction of the system. The software architecture followed is shown in Figure 6.1.

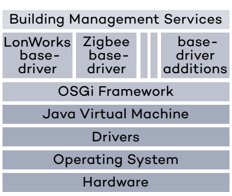


Fig. 6.1: SOA system architecture

The four generic basic functions of any BMS are:

→ Controlling: the BMS communicates actuation signals to the controllers. This is constrained by the capacity of the ZigBee sensors to receive control commands though the communication interface.
→ Monitoring: the BMS screens always display the monitoring values from the historic database, where the BMS stores sensor data and which is updated with the latest values from the sensor network.

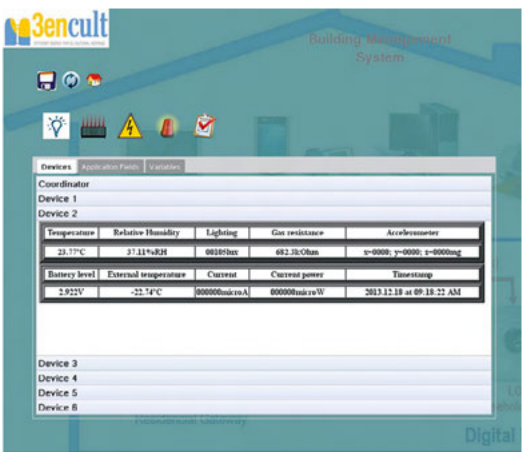
- Optimising: the BMS can incorporate control algorithms to calculate optimal performance of the systems before activating the actuators. Optimisation may translate to energy savings.
- Reporting: data is downloaded into the BMS and used to generate CSV files based on several filters.

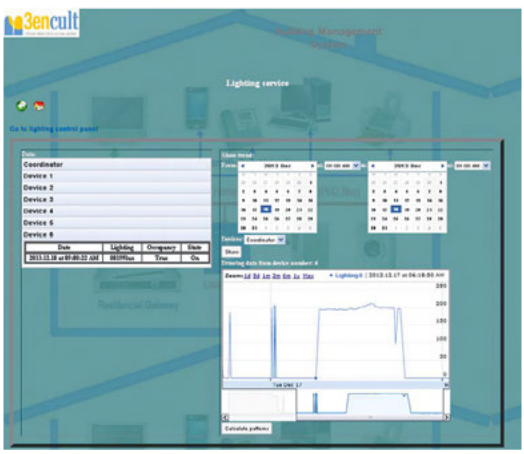
According to the basic functions defined by any BMS, the 3ENCULT BMS has integrated several services to be compliant, as follows:

- Monitoring service: the basic service monitors the database and the latest values gathered from the sensor network. It shows all the devices' and pairs' variable values in the ZigBee sensors, and the timestamp from when it was measured.
- Lighting service: the lighting service contains the list of devices and values related to lighting variables and displays the latest values for the lux levels of the devices. A graph with the trend of the variable is shown.
- HVAC Service: similar to the lighting service, plus this service includes the temperature and relative humidity values, as well as air quality values.
- Energy Monitoring Service: the ZigBee devices can measure battery and building electrical consumption through a current/ammeter sensor clamp adapted to the node, which the service monitors for values and trends of these parameters for the devices. It is also able to calculate the cost of electricity consumption.
- Technical Alarms: Through the accelerometer sensor in the motes, an alarm is generated if the acceleration in some axes is higher than a certain value. More alarms can be programmed, for example if the temperature exceeds a set value. This service lists all the alarms generated in the system and sends an e-mail when the alarm is thrown.

Fig. 6.2: Monitoring service

Fig. 6.3: Lighting service





6.1.2 Why do we need a BMS?

6.1.2.1 Advantages of a BMS

The incorporation of the 3ENCULT BMS contributes to the improvement of the performance of the building, and energy management can therefore be improved, yielding energy and cost savings. More tangible benefits of the BMS are:

- → monitoring and control of the indoor comfort conditions;
- → remote monitoring and control of the individual facilities of the building (for example AHUs);
- → individual room control with the appropriate device;
- → increased staff productivity;
- → effective targeting of energy consumption;
- → improved reliability;
- → time and money saved (higher rental value);
- → flexibility regarding change of the building's use;
- → early detection of problems in the building.

6.1.2.2 Conservation issues

One important 3ENCULT concern is conservation. Therefore ZigBee sensors are applied, which are wireless and avoid damage to the building structure. They are no larger than a few cubic centimetres and therefore adoptable in any space without affecting the aesthetic aspects. The life of the batteries can be several years, improving the performance of the sensor network by decreasing the energy requirements for the power supply.

The BMS does not require additional change in the building apart from the installation of the ZigBee network, being compliant with conservation issues. In that sense, it does not raise any potential preservation concerns.

The performance of the BMS also actively supports conservation. Firstly, the BMS monitors the comfort conditions (like air temperature, relative humidity) which can be very important in heritage buildings. In a museum with frescoes or a building with a damaged structure for example, improving comfort may assist in preventing deterioration of the interior. Control of the comfort conditions through the actuators and optimisation parameters can improve the indoor conditions in the building, offering a better environment. In addition, historic buildings often present low energy efficiency with high energy losses, and underused or overused energy generation systems. Monitoring and control of all these parameters with a BMS may lower the energy consumption, saving on energy and costs, as demonstrated in the Béjar Engineering School (see Case Study 7).

6.1.3 BMS features

6.1.3.1 System requirements

The deployment of a BMS does not require special characteristics and a standard domestic computer is sufficient. A summary of the microprocessor and

RAM requirements is shown in Table 6.1. The connectivity plugins require a network card for remote access to the BMS and a USB port for communication with the sensor network. The hard disk space should be large enough to cover the estimated database needs. A screen is optional, but is recommended in order to access the configuration of the BMS locally, although it could also be accessed remotely. The operating system can be Windows or Linux. Most important is the correct configuration of the ports for accessing from external networks, a public IP address and port, and the installation of USB drivers for the ZigBee dongle. A PostgreSQL database must be set up with a super-user and an empty database configured.

Tab. 6.1: Summary of the system requirements for the BMS

MICROPROCESSOR	Dual core: speed 1,5 GHz minimum
RAM MEMORY	2 Gb minimum
CONNECTIVITY	Network Card, USB 2.0
HARD DISK	500 Gb minimum
SCREEN	not mandatory, but recommendable
OPERATING SYSTEM	Linux/Windows

6.1.3.2 BMS integrity properties

All software systems have functions to indicate the integrity of the software application and understand the potential of the software components. The BMS developed by 3ENCULT has defined several characteristics as follows:

- → Reliability: The amount of time that the system is working and available. In this case, using the Equinox server assures that for almost 100% of the time the service is available. When the system is unavailable, it is due to computer or connectivity problems.
- → Interoperability: To make different services and entities work together in order to provide the service in a user friendly and transparent way. OSGi technology, specifically the Spring Dynamic Modules framework, offers understandable interfaces for interconnecting services and entities to exchange information.
- → Scalability: SOA provides loosely coupled services, allowing integration of new services in the platform and increasing their numbers. The sensor network is only limited by the wireless sensor network because the BMS receives the information as data streams that can be managed by the services.
- → Replicability: The BMS has been developed through open software, and therefore can be replicated in any other building.

References

Hernández; Reeb, 2013 Hernández, J.L.; Reeb, S., *A novel monitoring and control system for historical buildings*, EWCHP'2013, September 2013.

3ENCULT D4.4, 2014 3ENCULT deliverable 4.4, Hernández, J.; Garcia, D., *Report on development of BMS system*, 2014.

6.2 MONITORING

Harald Garrecht, Simone Reeb, University of Stuttgart / José Hernandez, CARTIF / Giacomo Paci, University of Bologna / Michele Bianchi Janetti, University of Innsbruck

6.2.1 Introduction

To improve the energy efficiency of historic buildings, one does not only need to search out structural engineering and system engineering measures that are relevant for these improvements; one must also assess the consequences of the type and intensity of use on the building material. Additionally, one must investigate the extent to which the comfort of the users must be taken into account. Data recorded from monitoring activities can make a valuable contribution when properly evaluated and analysed.

The term 'monitoring' is frequently used to mean recording measurement data, however this is just a part of monitoring. Monitoring also includes the systematic recording, observation, and continued supervision of processes using technical equipment. The main task is to compare results and draw conclusions from them. Another monitoring function is being able to intervene in a process that is being recorded, for example in the event that the process drops below or exceeds a threshold value. Based on this definition of monitoring, the following basics must be clarified before monitoring is undertaken:

→ Clarification of necessary tasks;
→ Definition of planned structural measures;
→ Which interventions are possible in the building structure;
→ Monitoring system to be used;
→ Description of the parameters to be recorded;
→ Clarification of the measurement sites and / or sensor positions.

Often there is only limited information available about a building. For that reason, it is very important to record the current condition of the building. In this context, investigations of the building climate with the monitoring regime adapted to the specific situation can be rational and cost effective. With the aid of monitoring, future damage can be prevented, for example if it is possible to predict the effects of planned interventions, such as wear, rebuilding, installation of new or different heating systems, installation of interior insulation, and window replacements. It is possible to derive predictions about the effects of the planned intervention on the energy consumption and / or thermo-hygric behaviour of the building's structure.

In order to assess the energy consumption and thermo-hygric behaviour of a historic building, one needs to monitor its climate. Firstly, this allows one to observe the valuable building structure, and, depending on the type and intensity of building use, any risk to the building structure and equipment can be recognised immediately. Secondly, monitoring can provide important information about thermal comfort and energy consumption of a room or building. An additional option is to optimise the operation of the building's technical systems for heating, ventilation, and air conditioning. The goal of monitoring is therefore to record by means of a suitable sensor network all parameters and measurable variables that characterise the energy consumption of the building, the indoor comfort and climate conditions, the climate related stress on valuable surfaces, the heat and moisture conditions, and the original and / or energy-modernised building structure. To this end the monitoring design must be planned and implemented specifically for the building. Table 6.2 provides an overview of relevant measurement parameters.

MONITORING TASK	PARAMETER	EVALUATION / CONTROL VARIABLES
Room climate	Temperature / rel. humidity Content of CO_2 Airflow Solar radiation / lighting	User comfort
Historic surfaces	Microclimate Temperature / rel. humidity / air flow Surface temperature Solar radiation / lighting	Occurrence of condensate Development of mould / dry rot Climate fluctuations Phase transformation of salt
Building construction	Microclimate Temperature / rel. humidity Surface temperature Moisture content	Occurrence of condensate Development of mould / dry rot
Energy	Heat quantity Hot water Heat flux Electricity Lighting Global solar radiation Room temperature Status door / window	Energy efficiency

Tab. 6.2: Measurement parameters and planned monitoring

With the assessment of these variables, one can reliably evaluate the energy consumption and structural physical behaviour of the building and use them as a basis for meeting the requirements for energy efficiency and monument preservation, for example by adapting and optimising the operation of the building's technical systems. Monitoring therefore also has the following purposes:

→ Recording and assessing energy consumption and user comfort;
→ Recording and evaluating the condition of the structure and historical surfaces.

By undertaking these two subtasks, one can record the actual situational behaviour of the building under variable daily and seasonal external weather conditions as well as the actual building use.

6.2.2 Basic evaluation

The basis for the development of a monitoring concept and/or system is a basic evaluation. The following process is recommended for this.

Record

→ and document the structural details, the existent technical systems, any historical surfaces present and possible problems with the building, for example salt pollution and increased moisture loads;
→ the day to day energy consumption using things such as heat meters, cost records, and invoices.

Inspect

→ and make an initial evaluation based on existing measurements with respect to the indoor and outdoor climate, or the micro-climate near or at the construction area or historical surfaces;
→ all assessments that have already been done, for example material analyses.

Define

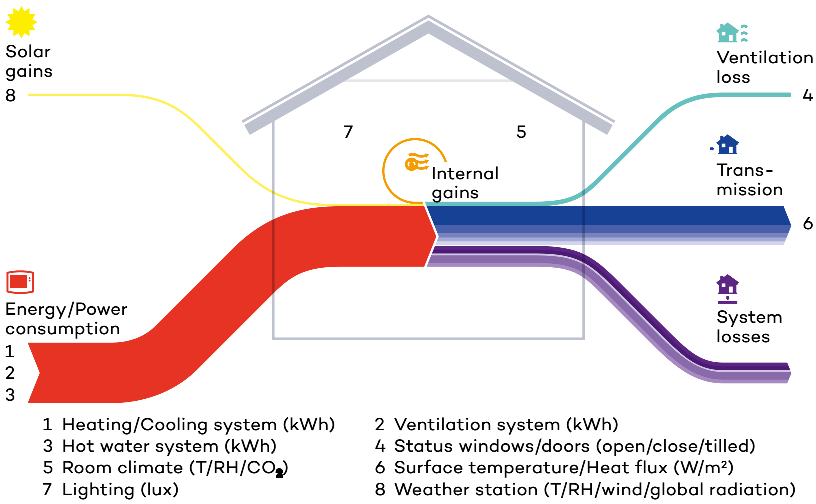
→ the planned energy efficiency measures and interventions;
→ future use or use zones.

Based on the information gathered and assessed, it is then possible to develop a sensor network that is customised to the structure and the monitoring task. When selecting the type of monitoring system (radio-based, cable-based, and/or stand-alone sensor nodes), one needs to consider whether and in what form this should be integrated into the building management system (BMS), if at all. In the following sections, basic and more detailed information is provided on developing a monitoring concept for the building's climate and positioning of sensors in historic buildings. It is important to evaluate the recorded data as a task independent of the monitoring task. The actions decided on by this evaluation can be implemented either by controlling existing actuators (for example heating valves, fans, humidifiers, and de-humidifiers) or by giving a set of behavioural recommendations to the occupants.

6.2.2.1 Energy and comfort

Figure 6.4 shows the measured variables that are needed for recording and archiving energy demand, user comfort, and user behaviour as well as their respective locations in the building. Before energy efficiency renovations of a building are undertaken, planning tools, such as the Passive House Planning Package (PHPP), are often used to calculate the primary energy demand of a building in its original condition. If there is already monitoring data available about energy demand, weather conditions, room temperatures, heat transmission coefficients for the structural components, and user behaviour, it is possible to generate model calculations that are very realistic.

Fig. 6.4: Energy and comfort monitoring



Based on these, one can calculate and assess with a high degree of accuracy the influences that the planned energy efficiency renovations will have on the building's energy consumption. Recording and archiving the data should, as far as possible, be done in relatively short time intervals. The measurement intervals shown in Table 6.3 are considered reasonable.

Tab. 6.3: Sampling intervals for each measuring task

MEASURING TASK	MINIMAL INTERVAL	OPTIMAL INTERVAL
Energy consumption	Monthly	4 hours
Comfort / Utilisation	5 minutes	1 minute
Outdoor/ Indoor climate	5 minutes	1 minute

6.2.2.2 Historic surfaces

The possible reciprocal effects between the exterior and / or interior climate and the historic surfaces are frequently neglected. As a result of an energy efficiency renovation, there is a risk of critical local variations in climate close to valuable historic surfaces, for example from heating, cooling, ventilation, humidifying, and de-humidifying. Things other than modifications in technical building systems can lead to a change in local climate condition close to historic surfaces. Structural measures, for example interior insulation, can also lead to complex stresses as a result of transient hygrothermic conditions. An initial assessment of the risk to historically significant surfaces requires recording the climate conditions in the immediate proximity of the historic surface by means of surface temperature sensors and temperature and humidity sensors. These should be distributed in adequate numbers along the surface in the affected room. The assessment criteria required are, as a rule, prescribed by the restorers or the responsible monument preservation authorities. However the criteria listed in Table 6.4 can serve as a basis for initial evaluation.

Tab. 6.4: Assessment criteria

PARAMETER	SET-POINT
Temperature [°C] seasonal	10–26
Relative humidity [%] seasonal	40–60
Relative humidity fluctuations [%/h]	10
Temperature fluctuations [K/h]	1

6.2.2.3 Critical construction details

Another key task of monitoring is recording the condition of the building structure as a result of the energy efficiency renovations. It is especially important to record thermal bridges and other critical structural details, since the renovation of a historic building by means of structural measures can have a great influence on the thermohygric condition of these. Recording surface temperatures and the climate in the immediate proximity of the structural element under observation makes it possible to assess the compatibility of the structural measures with the building, and it is therefore essential to install the corresponding sensors directly at the affected components of the building. Important assessment criteria for interior wall surfaces and/or in the area behind interior insulation are:

→ occurrence of condensate;
→ climatic conditions that favour biogenic attack.

Additional information detailing the assessment of the climate conditions in and on structural aspects is found in the standard EN ISO 138788:2001-11, the bulletins WTA 6-4:2009-05 and 6-3-05:2006-04, and the matching European/national standards.

6.2.3 Monitoring concepts based on selected case studies

The following examples of buildings investigated in the framework of the research project show the steps to be carried out in the development of a controllable monitoring concept once the initial evaluation is completed. This means data are recorded and evaluated, and rule algorithms are developed that are customised to the individual problems and questions relating to the structure. The development of all the examples shown hereafter proceeds in the five steps depicted in Figure 6.5.

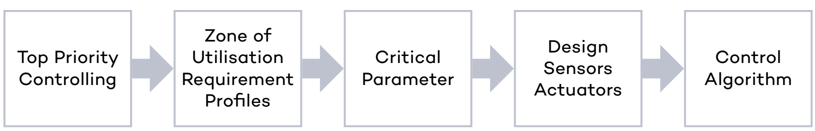


Fig. 6.5: Development of a monitoring and control system in five steps

6.2.3.1 Behaviour of construction elements – log house, Appenzell

Based on the structure and the energy efficiency renovation by means of interior insulation, the main focus of the monitoring concept is on not damaging the original structure. User comfort and energy efficiency are not neglected; however they are subordinate to the requirements deriving from the building construction and the insulation measures. Table 6.5 provides a brief overview of the building and the existing building systems as well as of those building systems which are possible or necessary after the energy retrofit.

Tab. 6.5: Brief description of the building and building equipment

Building	Log house built in the 17th century
Utilisation	Residential building
Building equipment present	→ Wood stove → Warm water (flow heater)
Building equipment options possible	→ Heaters (electrical or water based) → Air ventilation (maybe by using the old wood stove or by window or installing small air ducts with decentralised fans) → Heating cable (electrical)
Top priority for control	1. Behaviour of construction elements 2. User comfort 3. Energy saving

	Zone 1 Living	**Zone 2** Sleeping	**Zone 3** Bath	**Zone 4** Entrance
Set Point	Day = 23 °C Night = 18 °C	18 °C	Day = 23 °C Night = 18 °C	14 °C
Week-day	Day 5.30–9.00 5.00–11.00	24 h	Day 5.30–8.00 17.00–20.00	24 h
Week-end	Day 8.00–23.00	24 h	Day 8.00–10.00 17.00–22.00	24 h

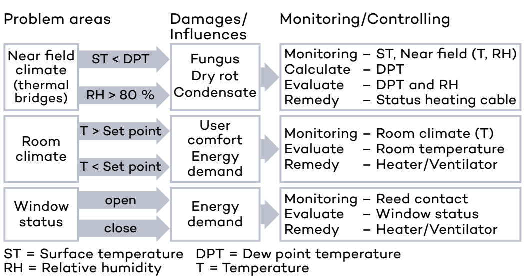


Fig. 6.6: Requirements for the indoor environment in different building zones

Fig. 6.7: Requirements of construction elements, user comfort, and energy demand

Once the control priorities were developed, the building was broken down into zones in the second step, i.e. various utilisation zones, and their room climate requirements were specified. Figure 6.6 shows the developed utilisation profile under the assumption that the building will continue to be used as a residence as it has been in the past.

Based on the control priorities, initial assessment, measures for an energy efficiency renovation, critical issues, damage risks, and the necessary counter-measures are all worked out. From this summary one can then determine the necessary actuators, the type and location of the sensors, and the resulting control factors. Figure 6.7 provides a typical overview of the issues of the building being assessed and the resulting monitoring and control factors.

The sensor and actuator network shown in Figure 6.8 was developed for the building taking these requirements into account. Since the previous method of generating heat in the building (single-oven heating in the living room) did not meet current utility standards, there was a need to install heaters in every room which could be controlled using the measurement, control and regulation (MCR) system. Additionally, a decentralised forced air ventilation system could be installed which can be used to cool at night during periods of warm weather and to reduce critical indoor humidity. To protect the structure, it is necessary to install a heating cable near the heat bridges, which raises the surface temperature when there is risk of condensation and can also counteract critical near field climates.

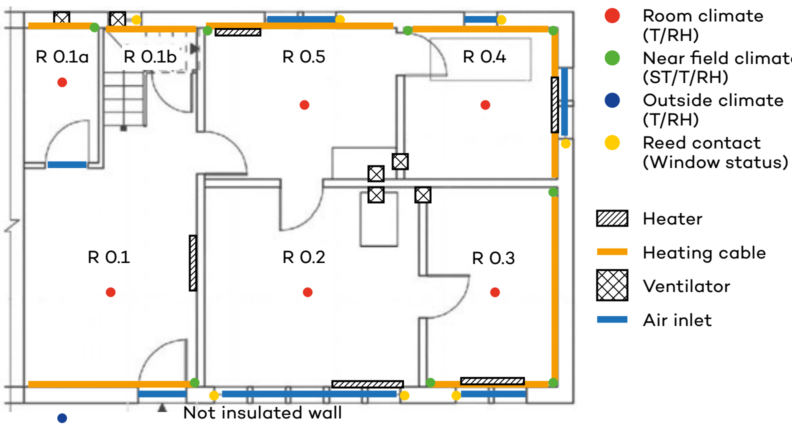


Fig. 6.8: Monitoring system

Another important building block of the MCR system is monitoring the window status. Using Reed contacts, one can record the status of the windows (open/closed) and an energy-efficient regulation of the heating and ventilation system components can be effected, determined by the weather conditions. Figure 6.9 shows the regulating algorithm resulting from the various requirements for a room in the building. Here it becomes clear that the regulating algorithm is expressed in a use and energy specific form and a structurally specific form. This division allows a use-driven energy efficiency regulation of the heating and ventilation systems used while at the same time protecting the structure.

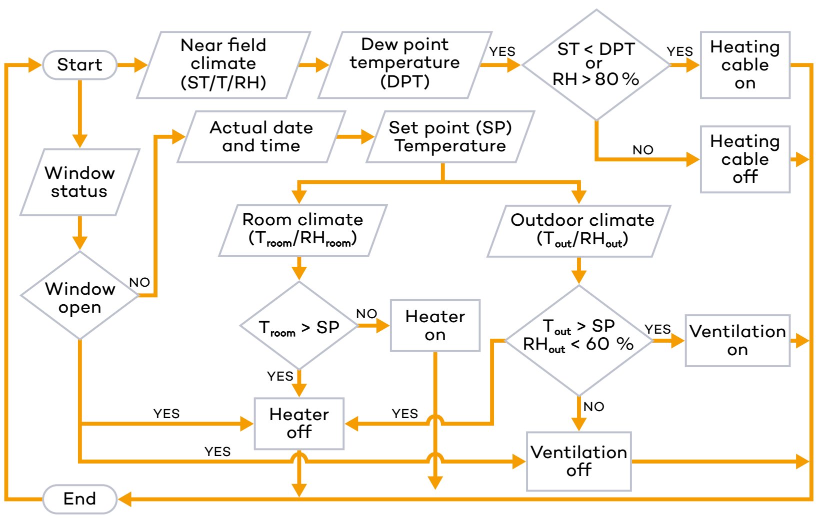


Fig. 6.9: Ideal implemented control algorithm for one room of the building

Tab. 6.6: Brief description of the building and building equipment

Building	Fifteenth century building renewed in 2011. The building is a unique architectural structure with wall and ceiling frescoes.
Utilisation	Headquarters of the Department of International Relationships (DIRI) of the University of Bologna. The building has offices and meeting rooms.
Building equipment present	→ Wireless Sensor Network (WSN) for cultural heritage building → HVAC with fan coil units and electric heater units, controlled by a central system
Building equipment optionally possible	→ BMS BMA → Remote BMS → Humidifier system
Top priority for control	1. Historic surfaces 2. User comfort 3. Energy saving

6.2.3.2 Protecting historic surfaces – Palazzina della Viola

The Palazzina della Viola, a fifteenth century building, has historic ceiling frescoes distributed throughout the entire building and also a large room with historic wall frescoes. In the first step, the focus is on the preservation and protection of the valuable wall frescoes, because it is not possible to install sensors close to the ceiling. The development of an MCR system must take into account both user comfort and energy efficiency; however these requirements must be treated as subordinate. Table 6.6 provides a short overview of the equipment present in the building or installed during the energy efficiency renovation.

Figure 6.10 shows the monument preservation requirements for the indoor climate. Monitoring data recorded after the completion of the energy efficient renovation shows, however, that the indoor climate frequently does not meet the conditions necessary for heritage preservation. Observation of the climate conditions for a year in the room containing the wall frescoes showed relative humidity readings considerably below 50 % were established for around 95 % of the time. As a result of heating the room during winter, these values sometimes dropped below 25 % RH. This indicates that the BMS or its regulation is insufficiently adapted.

Based on the regulations for monument preservation and the data already provided by the monitoring, it is possible to derive the critical issues, damage risks, the necessary types of sensors and positions, control factors, and necessary additional technical plant. These are shown in Figure 6.11 for the room with the historic wall frescoes.

Fig. 6.10: Requirements for the indoor environment in the fresco room

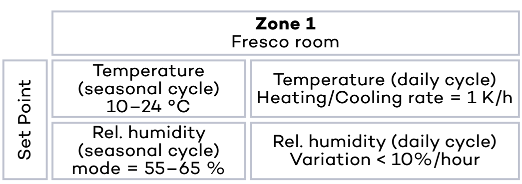
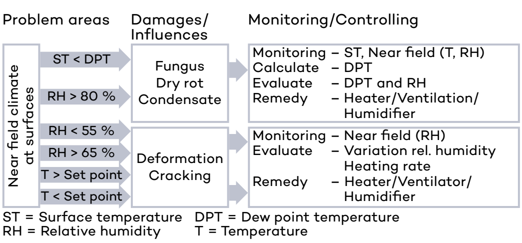


Fig. 6.11: Historic surface requirements for user comfort and energy demand



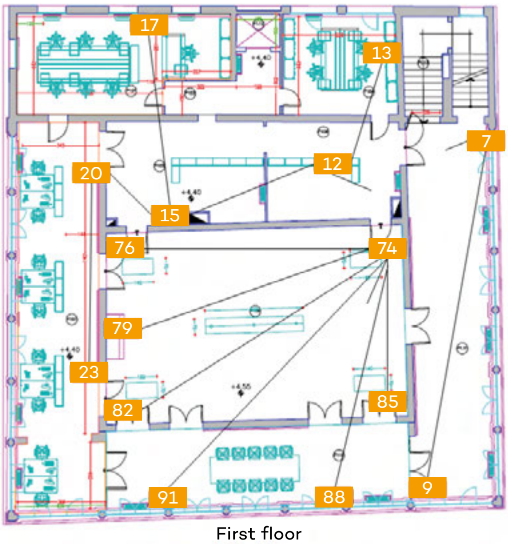


Fig. 6.12: Monitoring system (Fresco room – mid)

Based on the previously mentioned low relative humidity readings, it is necessary to operate humidifiers.

Figure 6.12 shows that the original sensor net must be expanded for future measurement and regulation tasks so that the near field climate and surface temperatures of the wall frescoes can be recorded at various heights. There are multiple humidifiers distributed in the room which can be controlled by means of a future BMS depending on the near field climate.

The regulation algorithms shown in Figure 6.13 consist, as in Figure 6.11, of two basic interacting regulating scenarios. Both regulating scenarios are based on the climate conditions in the near field of the historic surfaces. The first scenario consists of operating the ventilation system, adapted to climate requirements and for energy efficiency. The second scenario takes into account the comfort of the users in that the heating is not shut down at very low levels of relative humidity if the target temperature is not reached. Instead an increase of the relative humidity is achieved by operating, for example, mobile humidifiers.

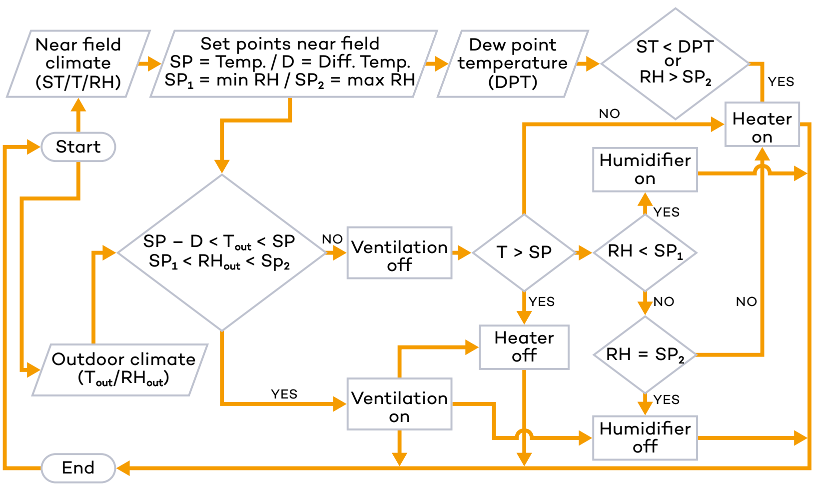


Fig. 6.13: Ideal implemented control algorithm for the fresco room

6.2.3.3 User comfort by CO_2 concentration, Hötting Secondary School

The Neue Mittelschule (NMS) Hötting in Innsbruck, a listed four storey school building, is an example of a building from early modernism (see Tab. 6.7). To develop and verify this energy efficient solution two classrooms of the building were renovated and provided with a monitoring system and a BMS for artificial and natural light control as well as ventilation.

Tab. 6.7: Brief description of the building and building equipment

Building	NMS Hötting, year of construction 1929/30. Innsbruck, Austria.
Utilisation	School building
Building equipment present	→ Radiators (water based) → Active overflow ventilation system with central heat recovery → Roller blinds (classroom 1) → Shade screen (classroom 2) → LED lighting system (classroom 1) → Luminescent screen tubes lighting system (classroom 2)
Building equipment optionally possible	→ Central or split heat recovery system → Shade lamellas
Top priority for control	1. User comfort (CO_2) 2. Energy saving 3. User friendliness

Besides reducing thermal losses and electricity consumption used for artificial light, the focus is on adaptation and optimisation of the ventilation system. This is controlled by CO_2 concentration sensors and presence sensors. Criteria used for the control system are shown in Figure 6.14.

For the ventilation system, the active overflow principle was used. The high flow rate (~700 m³/h) required a dedicated air distribution system to reduce drafts and excessive noise. To minimise the ductwork in the building, an active overflow system vents air from the corridor into the classroom. A central heat recovery system ventilates the staircase and the corridors with preheated fresh air. Two different control strategies for the ventilation system were considered. The first strategy uses timers to control the fans (see Fig. 6.15). This strategy presents low installation costs, since no sensor is necessary, but is not flexible when there are changes in actual occupation and class schedules.

This inflexibility is the reason a second strategy was considered, which is based on monitoring the CO_2 concentration. The indoor air quality is categorised according to EN 13799 in four classes, with IDA2 rated as good and IDA3 as moderate air quality. If a CO_2 sensor were installed in each classroom, the active overflow fans could be triggered when a set point, for example IDA3, was reached. This control strategy enables the more efficient demand-based control for the fans, especially if the number of pupils varies considerably. The drawback is the high cost of investment (twenty-five CO_2 sensors) and maintenance (recalibration and replacement).

The third control strategy, considered the most simple, cost effective, and robust strategy, is to measure the CO_2 concentration in the corridors or staircase only. The central fans can be controlled via a Proportional-Integral (PI) controller

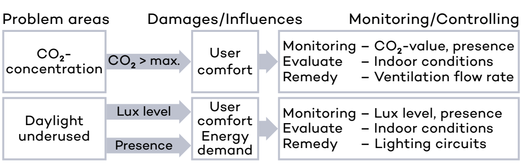


Fig. 6.14: Requirements of user comfort and energy demand

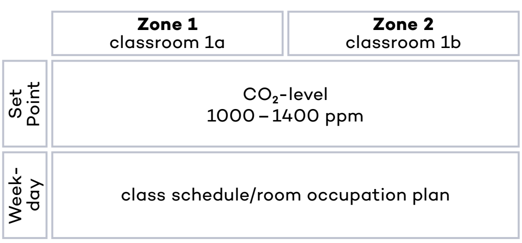


Fig. 6.15: Timer schedules based on occupation for the prototype class rooms

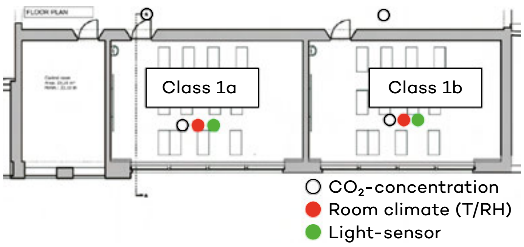


Fig. 6.16: Optimised monitoring system

to a set point, for example 600 ppm, to keep air quality high in the staircase and corridor zone as a fresh air reservoir for ventilation of the classrooms. The concentration in the corridors will vary according to the occupation of the adjacent classrooms; therefore at least one CO_2 sensor per corridor should be installed.

In the third, simplified control strategy, only the flow rate of the central fans are controlled via the CO_2 sensor, while the active overflow sensors in the class rooms are controlled with a timer and presence sensors. The disadvantage of this strategy is a lower savings potential if the number of pupils varies widely, because the on/off-control will always provide the flow rate necessary for the maximum number of pupils. The artificial light and the shading and daylight redirection lamellas are controlled via light sensors on top of the roof and in the classrooms. A customised BMS was installed for this purpose, enabling also an adaptive control of the colour temperature of the artificial light according to the daylight.

6.2.4 Monitoring systems

6.2.4.1 Wired monitoring systems

Worldwide, many different wired monitoring systems are available for the acquisition of, for example, energy, temperature, relative humidity, and air current. To undertake monitoring cost-effectively, a bus system was used in some case studies. The 1-Wire bus system was used for data measurement and control tasks. The 1-Wire network consists of a master device with associated communication devices and control software. For detection of the analogue sensor signals analogue converters are available. The master configures the connected 1-Wire modules and synchronises the data exchange. In addition, analogue and digital output modules for actuators can be used for controlling, for example, air-outlets, heaters, humidifiers, and dehumidifiers. With software developed and designed for specific building problems, the large amount of minutely recorded measurement data can be depicted. Furthermore typical decisions for the regulation process are derived from the evaluation. The user of the software can, depending on access permission, make more or less intrusive changes to the control parameters.

Another wired system is the Lonworks/LonTalk protocol which was created by Echelon and is based on twisted pair cables. The two-wire layer operates at 78 kbps using differential Manchester encoding. It also uses ethernet, power lines, and radiofrequency. The topology could be bus, star, ring or tree allowing for fewer restrictions in design. LonWorks is commonly used for diverse applications in smart buildings, such as HVAC systems, elevator controls, lighting systems, and advanced metering among others. LonWorks usually works as a stand-alone sensor network where the sensors, actuators, and data collector are working on the same backbone. These sensors and ac-

Fig. 6.17: Wispes W24TH node sensor specifics: *Temperature:* 14-bit codification, 0.01°C resolution, ±0.3 accuracy, -40 to 125°C operative range *Humidity:* 12-bit codification, 0.04% RH resolution, ±2% RH accuracy, 0 to 100% RH operative range *Ambient light sensor:* 0.23 to 100,000 lux operative range, ±15% accuracy

tuators integrate a Neuron chip with an 8-bit processor which implements the LonTalk protocol and identifies the transceivers in the network with a 48-bit code. LonWorks uses Internet protocol (IP) tunnelling in order to connect external devices (web applications, external data collectors, and controllers) to the sensor network. Advantages of LonWorks include interoperability as it can integrate different products which use the same language (LonTalk). Additionally, LonWorks is a cost-effective platform owing to the manufacturer's diversity.

6.2.4.2 Wireless monitoring systems

The 3ENCULT project aimed to develop a new WSN system to monitor cultural heritage buildings for preservation purpose. The system developed, 3ENCULT WSN, is a wireless network able to sense several building climate conditions and collect them in a central server unit. The central unit then analyses the data for environmental condition and risk conditions. Moreover the data can be used by a building management system in order to perform automatic building HAVC control. 3ENCULTWSN was designed to be easy to install with a small size to reduce its impact on the building; it was to have extended lifetime, less frequent maintenance, remote configuration and management, and be extensible and compatible with other systems like web servers and HVAC control. The 3ENCULTWSN is a network of small electronic boxes able to collect data from several environmental sensors and send them via radio to the central unit. The electronic boxes are the Wispes W24TH nodes, which have a 32-bit microcontroller, battery charger, 128 Kbyte of RAM, IEEE802.15.4 radio transceiver, accelerometer, temperature sensor, humidity sensor, light intensity sensor, gas sensor connector, and expansion connector. The W24TH has an excellent power management system, needing only two AA batteries which will last for several years. The node is enclosed in a box measuring 98 × 54 × 29 mm.

The users can interact with the 3ENCULTWSN using JavaTerminal with a commercial system like a printed circuit (pc) board, smartphone, or a tablet known as the gateway. Using JavaTerminal, the user can: configure a new network; collect and collate data; control each node in the network remotely; enable the sensors; select the time acquisition interval; depict the network structure; update the system software; and send the data to a remote server for internet base application and building management application. To install a new network the user connects the coordinator sensor to the gateway by USB cable. After that, the user must position other W24THs at points where the data needs to be collected. With the set of commands present in the system the user can customise the network to reach the desired performance and configuration.

GENERAL PROJECT DESCRIPTION

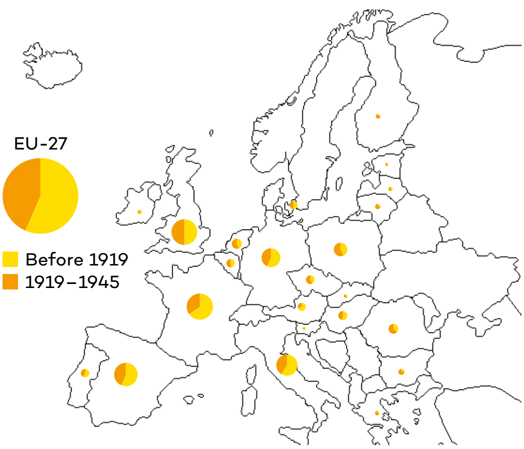
Alexandra Troi, EURAC research

In extreme synthesis, the project can be summarised in five sentences:

The FP7[1] project 3ENCULT bridges the gap between conservation and climate protection. This is not a contradiction at all: historic buildings will only survive if maintained as living space, and an energy-efficient retrofit can improve structural protection for the building, comfort for users, and preservation conditions for heritage objects. Reducing energy demand by factor 4 to 10 is feasible in historic buildings while still respecting their heritage value, if a multidisciplinary approach guarantees high-quality energy-efficiency solutions, targeted and adapted to the specific case. Twenty-two partners, including conservation, technical, and urban development experts, industry partners, and stakeholder associations collaborated on the development of both methods and tools to support the holistic approach, multidisciplinary exchange, and the needed technical solutions, both adapting existing retrofit solutions to the specific issues of historic buildings and developing new solutions and products. Eight case studies demonstrate and verify the solutions.

1 FP7 stands for the 7th European Framework Programme for research. 3ENCULT is co-funded under grant agreement 260162.

Fig. 0.1: Dwellings in Europe dating before 1919 and 1945

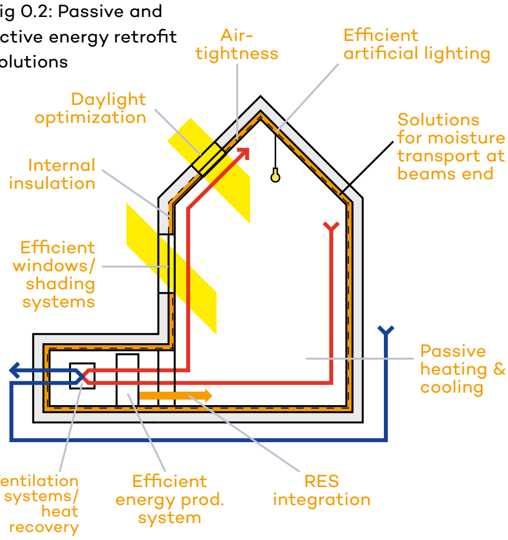


The project started from the belief that historic buildings are the trademark of numerous European cities, that they are a living symbol of Europe's rich cultural heritage and diversity, that they reflect the society's identity, and need to be protected. On the other hand, these buildings show a low level of energy efficiency, they contribute considerable CO_2 emissions, and do not always offer a comfortable environment for people or a conducive environment for protecting the integrity of the artwork.

Potential impact

Historic buildings, as the term is understood within the project, include officially listed buildings, but are not limited to them. For example, in Denmark about 9,000 buildings are listed as the best or most characteristic of their type and period, but 300,000 buildings have been assessed as worthy of preservation without being formally protected. In Bologna the urban building regulation identifies buildings with 'historic documentary value', typically

Fig 0.2: Passive and active energy retrofit solutions



those built before 1949, which includes 80% of the buildings in the city centre. Looking at numbers on a European level, 14% of the building stock dates before 1919, and another 12% before 1945 – this implies that more than one quarter of our building stock potentially characterises our cityscape and should be subject to particular attention when retrofitted, with regard to conservation and aesthetic values as well as structural and building physics issues. Interventions need interdisciplinary collaboration and a greater degree of effort, since there are no 'standard' solutions.

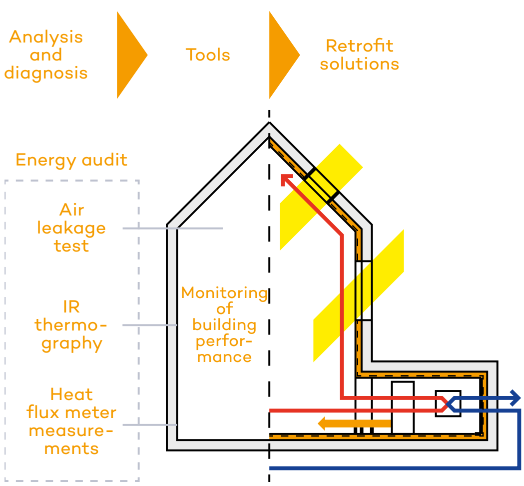
Objectives

In order to tap this potential in a sustainable way the project acted on the following different themes.

The project developed *passive and active energy retrofit solutions* as result of open and constructive dialogue among stakeholders and experts. The fields tackled cover all relevant aspects for historic building retrofit (see Fig. 0.2). Starting with materials and products already available on the market and from solutions already applied to new buildings, the project ensured the widest possible dissemination of the results achieved all around Europe. Results are presented in Chapter 5, and results of implemented solutions are found in the case studies.

Diagnosis and monitoring tools have been defined in order to: study historic buildings and find the best technological and constructive energy retrofit solutions; support their commissioning; assess the actual performances of buildings once retrofitted; and monitor such performance (see Fig. 0.3). Results of these activities are presented in Chapter 3.

Fig. 0.3: Diagnosis and monitoring tools



Tools and concepts to support implementation in different *urban contexts* and to ensure effective transferability to historic buildings' various locations include optimisation and dissemination of the calculation software used in the project, solutions inventories on the buildup portal, and assessment approaches (see Fig. 0.4). Results are presented mainly in Chapter 4.

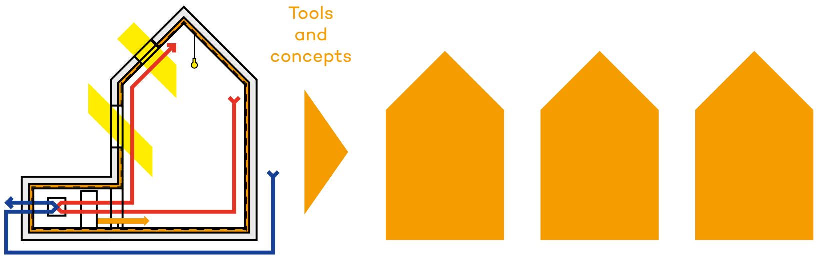


Fig. 0.4: Implementation in different urban contexts

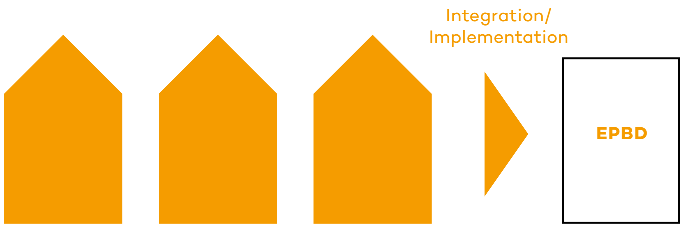
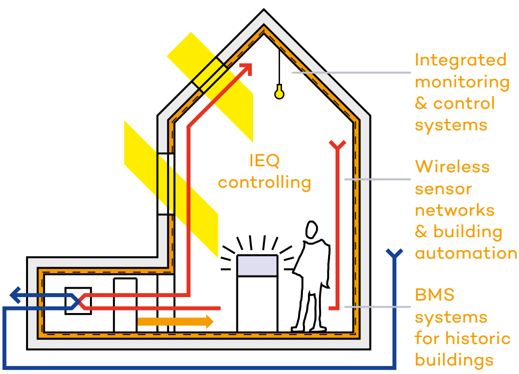


Fig 0.5: Integrations in present regulation framework

Other documents suggesting possible *integrations* and/or implementations of the *present regulation framework* for improving the energy efficiency of historic buildings in urban areas have been issued. Some of these most relevant are the Energy Performance of Buildings Directive (EPBD) in relation to historic buildings, the development of a pertinent standard with CEN TC 346 on cultural property, and EIA, the SEA directives and SUIT guidelines (see Fig. 0.4).

Fig. 0.6: Indoor Environmental Quality (IEQ)



Finally, 3ENCULT has defined a methodological approach on the integration of monitoring and control systems in a dedicated BMS system for historic buildings (see Fig. 0.5). This is to ensure the best *Indoor Environmental Quality (IEQ)* for the comfort of inhabitants, for avoiding deterioration of the building fabric, and for optimal conservation of valuable interiors with the lowest possible energy demand. Results are presented in Chapter 6.

Methodology

The technical developments within 3ENCULT are based on the analysis of built heritage and completed with dedicated work packages on quality assurance and design tools (see Fig. 0.7). Dissemination is at the top; it raises the awareness of stakeholders from policymakers to architects, businesses to the general public. The case studies finally accomplished all phases of the project, providing stimulus for the solution development as well as successful feedback on implemented measures and concepts.

Conclusion

Apart from the high number of specific solutions found and tools developed during the three and a half years of work in the project, two main conclusions can be drawn.

Firstly, including all stakeholders in the design process of the energy retrofit of a historic building is a base principle postulated by 3ENCULT, an approach which is also reflected in the multidisciplinary project consortium itself:

Conservation experts represent the demand side for the preservation of cultural heritage. They define the specific needs of historic buildings and provide other partners with criteria for interventions. Technical experts were chosen to cover all relevant energy efficiency issues. These include expertise on retrofit solutions for envelope and energy systems as well as answers to specific problems, e.g. moisture problems in beam, but also knowledge of potential damage mechanisms and integrated monitoring & control. Specialists for urban development transfer the developed solutions into the urban context. Moreover, within so-called Local Case Study Teams building owners, architects, and engineers in charge of the retrofit works and representatives from the offices for the protection of historic monuments as well as from other local bodies concerned (e.g. city council) are gathered.

Secondly, for each energy retrofit of a historic building the multidisciplinary exchange between all stakeholders starts with the comprehensive diagnosis of the status quo; it supports the development of solutions and selects the most appropriate one; it does not end before an integrated monitoring and control is in operation. This validates the process and guarantees quality outcomes.

Further information can be found on the project's website www.3encult.eu.

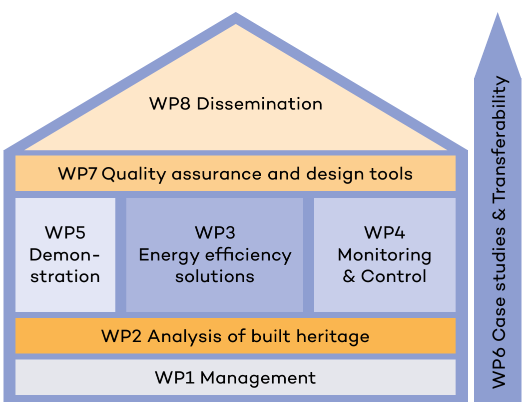


Fig. 0.7: Project structure

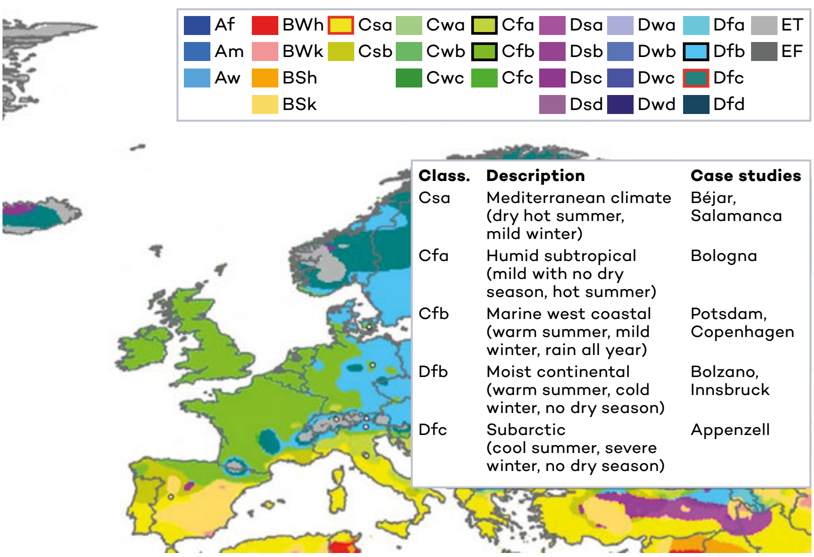
Alexandra Troi, EURAC research

The research activities were accompanied and inspired by different case studies, which at the same time assessed the solutions developed. The 3ENCULT project (3ENCULT) contributed to the diagnosis, supported the design and planning phase, and monitored and gave feedback. The project, however, could not contribute financially to the intervention itself; therefore it was important that the owners were committed to implementing dedicated solutions. The different time schedules of the case studies allowed focusing on different phases within the relatively short project duration.

Different kinds of applications: Case studies reflect typical applications in urban areas and range from residential use, to commercial and office use, to educational use such as schools and universities. In order to cover the preservation of cultural heritage collections in historic buildings, museum use is also covered.

Different kinds of building structure and eras: The buildings date from different eras, ranging from the Middle Ages (thirteenth century) to the twentieth century. Regarding building structure, the most common types, ranging from stone to masonry and clinker to wooden structures are covered.

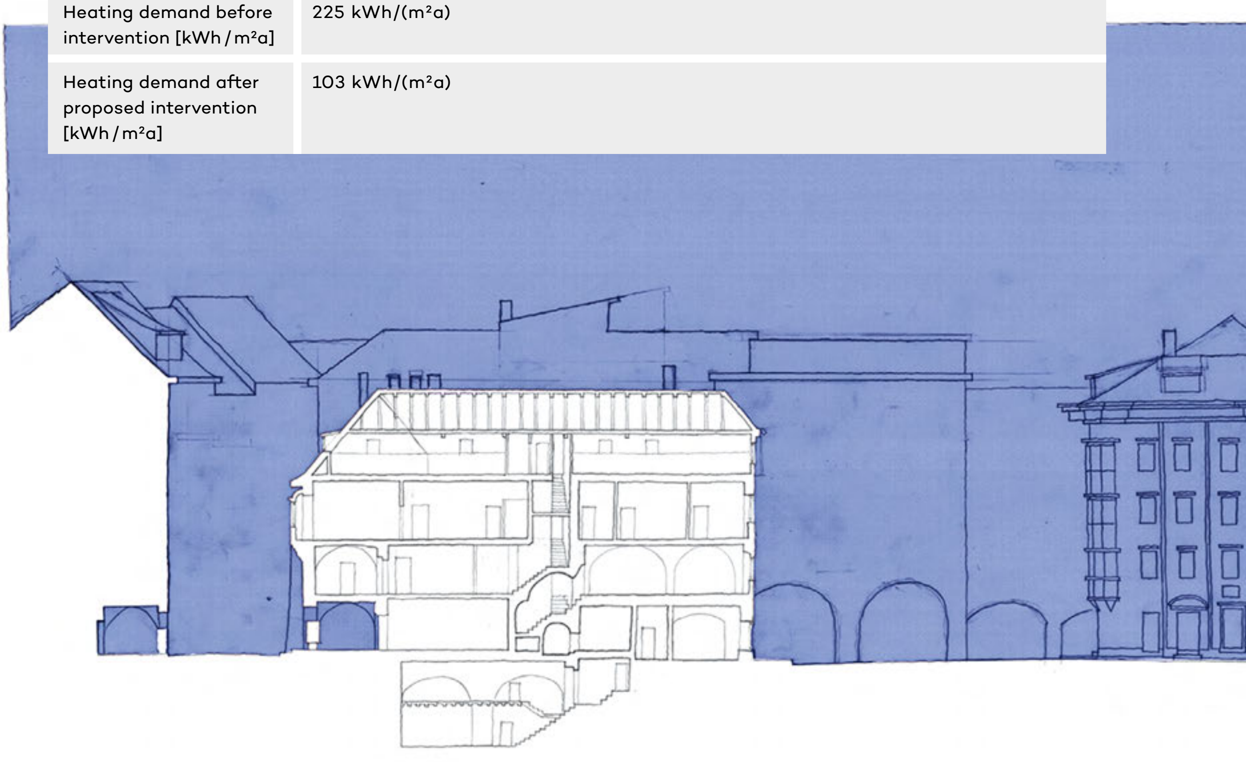
Different kinds of climate: The sites chosen cover all major European climates, from mild to severe winters and cool to hot summers (see Fig. 0.8).



Class.	Description	Case studies
Csa	Mediterranean climate (dry hot summer, mild winter)	Béjar, Salamanca
Cfa	Humid subtropical (mild with no dry season, hot summer)	Bologna
Cfb	Marine west coastal (warm summer, mild winter, rain all year)	Potsdam, Copenhagen
Dfb	Moist continental (warm summer, cold winter, no dry season)	Bolzano, Innsbruck
Dfc	Subarctic (cool summer, severe winter, no dry season)	Appenzell

Fig. 0.8: Map showing climates covered

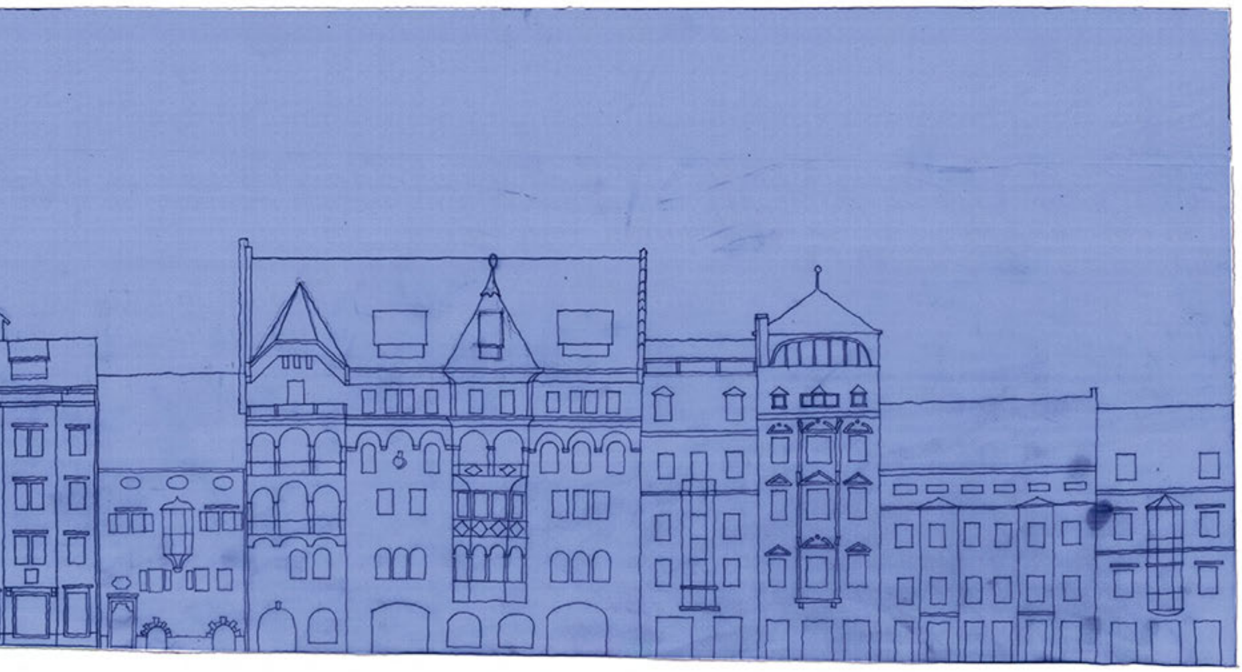
Name	Waaghaus
Location	Bolzano / Bozen, Italy (46°50'' 0', 11°35'' 5')
Date of construction	Thirteenth century
Architectural style(s)	Romanesque arcade building ('Laubenhaus')
Construction type / materials	→ Massive construction → Walls in natural stone and lime mortar with lime plaster → Vaulted ceilings and ceilings in wooden construction (inserted floor) → Saddle roof in timber rafters with wooden casing, and monk and nun roof tiles
Original building use	Seat of the Public Weigh House (Waaghaus) until 1780
Current / Future building use	**Current use:** presently uninhabited, previously apartments on the upper floors, shops and bar on the ground floor, storage in the basement. **Future use:** ground floor remains shops; upper floors for cultural purposes
Local case study team	→ EURAC research (scientific lead) → Local state office for historic monuments (conservation support) → Fondazione Casse di Risparmio (building owner)
Main interventions	→ Development and installation of a highly energy efficient, heritage compatible passive house window → Application of capillary active internal insulation in combination with wooden beam ceiling in a test zone of the building → Concept for passive energy refurbishment → Concepts for natural lighting and artificial lighting → Study on transferability of concepts to an urban context
Heating demand before intervention [kWh / m²a]	225 kWh/(m²a)
Heating demand after proposed intervention [kWh / m²a]	103 kWh/(m²a)



CASE STUDY 1

WAAGHAUS, BOLZANO, ITALY

Dagmar Exner, Elena Lucchi, Alexandra Troi, EURAC research



Building history and general description

The Waaghaus, a building of Romanesque origins, is located in the historic city centre of Bolzano. It is part of the Portici di Bolzano, which were built at the end of the twelfth century and formed the nucleus of the town. As is typical for this common medieval building type, the portico houses (Laubenhäuser) are lined up alongside each other down the length of the road, with narrow facades to the street. Around 4 m wide and 50 m deep, they are structured by atriums into a front, middle and rear house. This original urban system with its consistent structural appearance interspersed by the system of atria for the supply of air and light is still perfectly recognisable today. Buildings usually consist of a ground floor, up to three basement levels, three full upper storeys and an originally uninhabited top floor. The ground floor was and still is used as space for shopping, and is accessible via the characteristic arcade along the street front. The cellars were used to store goods, while the living space was situated on the upper floors.

The Waaghaus is part of the Portici di Bolzano, but it is separated from the continuous structure of arcade houses on both long sides by a narrow alley. Until 1780 the building was the home of the Fronwaage, an officially calibrated public set of scales. From 1780, the rooms were probably used for commercial purposes until the first half of the twentieth century when the building was converted into a dwelling and only the ground floor was used for business. By the 1990s the house was no longer in use. In 2009 it was sold by the city of Bolzano to the foundation Cassa di Risparmio (savings bank), on condition that it be used for cultural purposes. After a complete architectural and energy refurbishment it has become an exhibition space for photography.

Fig. 1.1: The Waaghaus

Fig. 1.2: The fresco by Albert Stolz on the arch over the alley shows the 'Fronwaage'.

Pre-intervention analysis

Prior to planning refurbishment interventions a complete survey of the building was carried out and documented using the Historic Buildings Information Model (hBIM) (see Section 3.2). The activities undertaken are shown in the following figures with more detailed captions than usual.

Historic evolution of the building

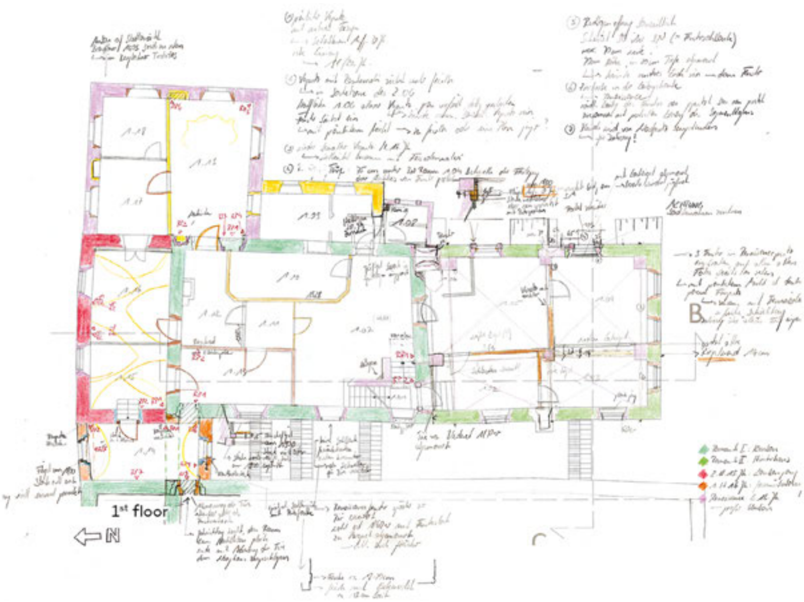


Fig. 1.3: Historical research confirmed Romanesque origins of the central part of the building and of the two basement floors (green). The arcades were added in the fifteenth century (red) and the bridge towards the neighbour building in the sixteenth century (orange). A major intervention at the end of the sixteenth century (pink) included making the window openings consistent, extending the building on the east and west side (over the bridge), and adding partition walls in the southern part of the second floor. More internal partition walls date from the twentieth century (brown).

Investigation of construction method and heritage value

WALLS:

All full storeys and the cellar are built in masonry of natural stones with lime mortar joints. Exterior walls have a thickness of about 60 to 80 cm. Except for the basement level, the stonework on both sides of the walls is covered in most parts with historic lime plaster and in parts with wall paintings and frescoes. Since the historic surfaces should remain the outermost perceivable ones, only a temporary installation of internal insulation in carefully selected parts of the building is possible, which has to be removable without leaving any trace on the existing walls. The existing layers of paint (even if not historic), the appearance of the historic plaster, and the uneven surfaces and edges should be preserved. The same applies to surfaces with mural paintings, which - even if covered by paint layers and only partially visible – are the most valuable surfaces and should be maintained as they are. The original proportions of the rooms and above all the symmetry of the stuccoed ceiling, should not be changed by the installation of internal insulation. Existing wooden pavement should be conserved.

ROOF:

The building has a saddle roof with wooden rafters and casing, roofing cardboard (bitumen) on the wooden casing, and above it tile cladding. In its current state, it is partially insulated with 8 cm of mineral wool between the rafters, covered with gypsum plasterboard. The roof has to be preserved in its actual form for two main reasons: firstly, the monk and nun roof tiles are historic and handcrafted in a unique way; and secondly, the roofscape of the historic city centre is visible from the surrounding mountains and its homogeneous appearance has to be kept. Down spouts should not be changed (e.g. by raising the roof covering for insulation) and profile and proportions of the roof-edge should be preserved. Insulation from inside, between and below the rafters is worth considering

WINDOWS:

Most of the original windows were replaced by box-type windows in the 1950s/60s; just a few original windows are from the late baroque era with thin wooden profiles and single glazing (e.g. the bay windows on the north facade). The uniform window size, dating from the sixteenth century, is typical of the baroque era, and the profiled sandstone frames also date from this era. Wooden window shutters are used to filter or block light. The casements on ground floor are from the last century with single or double glazing and mostly thin metal section frames, partially integrated into the plaster. The windows in the roof dormers are standard industrial insulation windows from the 1990s.
Since the box-type windows of the 1950s/60s are not of historic value, they should be replaced, reproducing the appearance of a historic window, the outer window being placed right behind the existing original stone frame and installed in the recess in a similar position. The late baroque windows should be preserved and repaired – and possibly improved with energy efficiency measures. The casements on the ground floor and the windows in the roof dormers are also not of historic value and could be replaced.

Tab. 1.1: Based on historic building research, on-site inspections, and non-destructive testing (NDT) like IR-thermography, the structure could be assessed and the historic, technical, and artistic value of the single building elements be determined, giving guidance on what may be changed or should be preserved, and to what extent.

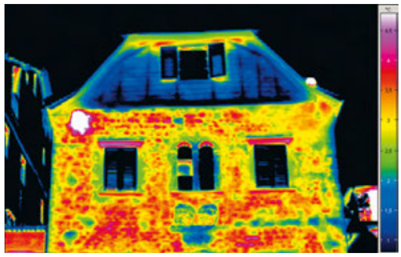


Fig. 1.4: IR-thermography of the south facade shows homogeneous brickwork in natural stones and material change at the exterior top floor wall.

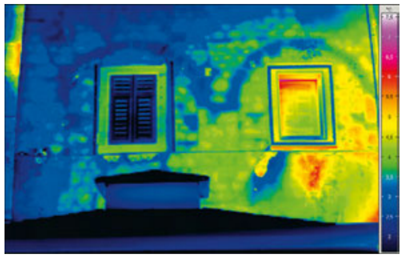


Fig. 1.5: IR-thermography of the east wall shows the difference between the heated and unheated part. In particular, it shows the presence of different wall thicknesses (of the parapet) and traces of arcs.

Physical properties of materials and construction details

Fig. 1.6: For several material samples (a core drill hole, painting and plaster samples from the exterior wall, material samples from the wooden beams and the filling of the ceiling density) the material parameters as specific heat capacity as well as thermal conductivity and the water absorption coefficient and porosity were determined.

Fig. 1.7: Several wooden beam-ends in the ceilings of the 1st and 2nd floor were exposed to visually diagnose their exact position, how they bear on the exterior wall, and what their condition is.

Tab. 1.2: For selected points of the thermal envelope, the thermal transmittance was determined with an in-situ heat flow meter (HFM).

Component	Exterior wall (north side)	Parapet under window (north side)	Ceiling over porticos (inserted floor ceiling)
Material / construction	Lime plaster, natural stone / lime mortar	Lime plaster, natural stone / lime mortar	Lime plaster and mortar, wooden slats, wooden beams, filling of earth, sand and pebbles
Thickness [m]	0.62	0.26	0.40
Measurement time [h]	96	96	120
Conductance [W/m²K]	1.36, (1.37)[1]	2.86	0.48
[1] U-Value corrected with thermal mass factor			

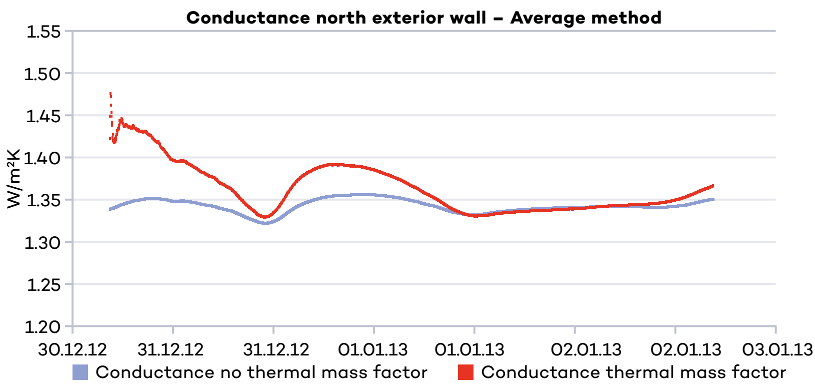
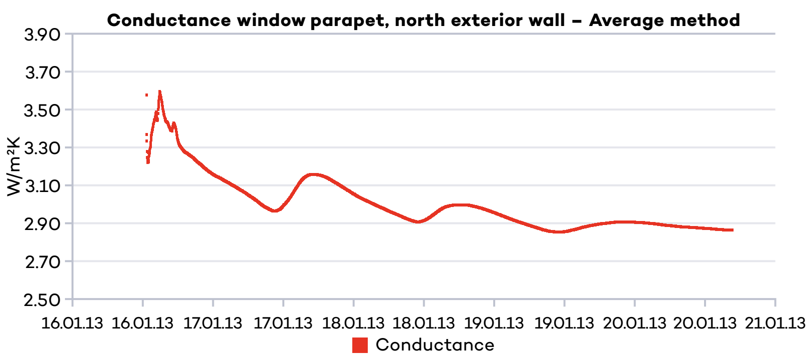


Fig. 1.8: Conductance of north exterior wall and window parapet: to provide a stable average of the U-value [Baker, 2008 and 2011] which takes into account the thermal inertia of the stone walls, instead of the standard 72 h period, the monitoring period was chosen to be 96–120 h, related to the thickness of the construction detail.



Airtightness and infiltration causes

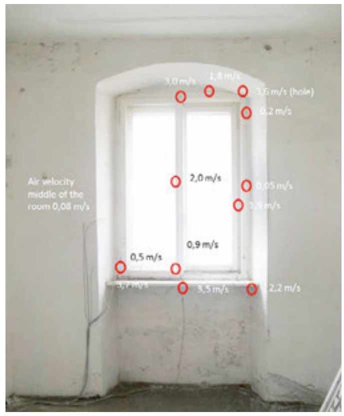


Fig. 1.9: Fan installed in the entrance door; gas overflow through window; measurement of air velocity at a pressure difference of 50 Pa at several points of the existing window. The blower door test for the building resulted in nearly 10 1/h, value extrapolated from measurements up to the maximum reachable pressure difference of 28 Pa. Single room testing at a pressure difference of 50 Pa demonstrated the causes of infiltration. Tracer gas overflowed mainly through the window.

Daylight potential

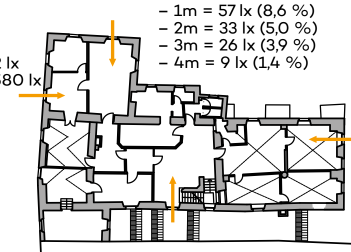
Distribution of daylight on the first floor

Outside
Vertical illuminance = 500 lx
Horizontal illuminance = 660 lx

Inside
- 1m = 57 lx (8,6 %)
- 2m = 33 lx (5,0 %)
- 3m = 26 lx (3,9 %)
- 4m = 9 lx (1,4 %)

Outside
Vertical illuminance = 282 lx
Horizontal illuminance = 580 lx

Inside
- 1m = 15 lx (2,8 %)
- 2m = 8 lx (1,4 %)
- 3m = 7 lx (1,2 %)
- 4m = 5 lx (0,9 %)



Outside
Vertical illuminance = 700 lx
Horizontal illuminance = 900 lx

Inside
- 1m = 65 lx (7,2 %)
- 2m = 60 lx (6,7 %)
- 3m = 21 lx (2,3 %)
- 4m = 10 lx (1,1 %)

Outside
Vertical illuminance = 60 lx
Horizontal illuminance = 206 lx

Inside
- 1m = 8 lx (3,9 %)
- 2m = 3 lx (1,4 %)
- 3m = 1 lx (0,5 %)

Fig. 1.10: Gradual reduction of the daylight coefficient in north, east, south, and west facing rooms on the first floor of the building. The daylight factor is often below 2%, which is the minimum value for an acceptable supply of daylight.

Energy simulation

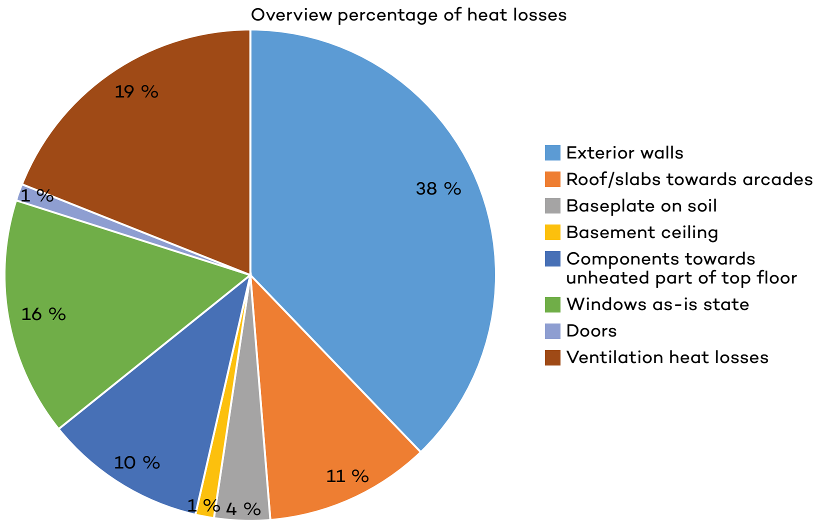


Fig. 1.11: The heating energy demand for the building (as-is state with top floor), calculated with PHPP is 225 kWh / m²a. It is striking that the low thermal resistance of the exterior walls causes 38% of the heat losses, followed by ventilation heat losses (19%) and windows (16%).

Identification of intervention needs

In pre-intervention analysis, the following problems were identified:

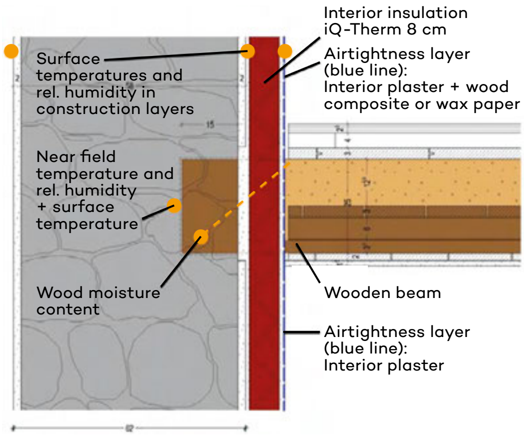
→ high transmission heat losses through wall and windows;
→ high infiltration heat losses mainly caused by leaking windows;
→ lack of daylight, particularly in north, east and west oriented rooms;
→ high relative humidity in basement floors (mould risk);
→ mould risk on weak parts of the envelope like window recesses and bay windows.

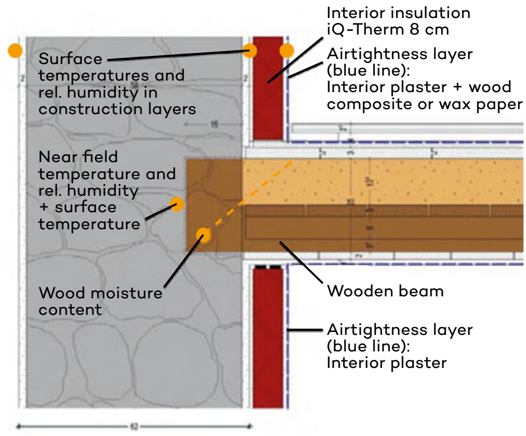
Description and evaluation of interventions

Based on the comprehensive study a retrofit concept was proposed, improving energy performance and thermal comfort while maintaining the architectural and aesthetic value of the building. The local case study team concentrated on passive architectural solutions that are independent from the building use, as the specific use for the single rooms was still not settled.

Insulation of opaque parts of the building

Since the historic plaster should remain the outermost visible layer, only a reversible internal insulation in some carefully selected parts of the building was proposed. Capillary active insulation (iQ-Therm λ=0,026 W/mK) fixed with clay-based glue allows residue-free removal of the insulation if it is required any time in future. Two possible solutions for the wall/ceiling connection have been developed that are transferable to similar situations and have both been hygrothermally studied using DELPHIN software. One is a continuous insulation and the other a non-continuous insulation.





VERSION I: 'CONTINUOUS' INSULATION	VERSION II: 'NON-CONTINUOUS' INSULATION
Continuous airtight layer (blue dashed line): the internal plaster connected with flexible airtight material around the horizontal wooden beam. Cracks in the wooden beam which pass through the airtight layer must be closed (e. g. by gluing wooden dowels).	**Continuous airtight layer (blue dashed line):** the internal plaster connected with flexible airtight adhesive tape to the horizontal wooden composite on the topside of the ceiling. On the underside of the ceiling, compression tape is applied between the insulation panel and the existing ceiling plaster. The continuous airtight layer is the internal plaster (wall and ceiling).
Advantages: lower heat loss, continuous airtight layer	**Advantages:** minimal impact to the ceiling construction, less work
Disadvantages: connection between wooden beams and internal insulation, higher impact on ceiling construction	**Disadvantages:** thermal bridge in the area of the ceiling, airtightness layer is interrupted at the transition to the next room (interior door)
	Risk for **possible damage** from diffusion and convection at cold parts (wall and beam ends) under investigation

Tab. 1.3: Comparison of two different applications of the internal insulation layer at the wall / ceiling connection

The behaviour of the conventional continuous insulation is already verified by tests, simulations, and reference literature. The non-continuous insulation solution is currently being verified through several simulations, tests and in situ monitoring (see Tab. 1.3). The two insulation types have been implemented in one room of the building after consolidation of the historic plaster. Both applications will be monitored and then compared and evaluated.

	EXTERIOR WALL
Construction as-is state	Natural stone, lime mortar joints, lime plaster
U-value as-is state	1.12 W/m²K
Intervention	8 cm of internal insulation (iQTherm); (λ 0,031)
U-value refurbished	0.28 W/m²K

Tab. 1.4: U-values before and after the application of internal insulation to the exterior walls

Replacement / enhancement of windows and building airtightness

The original windows from the late baroque period were given a second window layer, enhancing their energy efficiency, while the windows from the 1950s/60s should be replaced with new windows to fit the historic aesthetic better. In close collaboration, a local case study team, a window developer and a conservator developed a window that is energy efficient, of passive house standard, and also heritage compatible.

	Ug	Uf	Ψ INSTALLATION (WITHOUT PARAPET)	g-VALUE
Existing box-type	2.8 W/m²K	2.5 W/m²K	0.24 W/mK	0.77
Smartwin historic	0.57 W/m²K	0.97 W/m²K	0.16 W/mK	0.44

Tab. 1.5: Replacement of box-type windows from the 1950s/60s by a Smartwin historic (triple glazing plus additional historic glazing)

Despite the lower solar gains the window energy balance (thermal losses minus gains) improves by 70% (double glazing versus original window) or 80% (triple glazing versus original window). Looking at the building's total energy balance (starting from leaky untight windows and considering 14% window area and walls in natural stone), changing the windows may reduce the energy demand by up to 20%: 10% due to thermal performance increase, and 10% due to improvement in airtightness (need for indoor air quality considered, without heat recovery).

Insulation of other envelope parts

	ROOF	BASEPLATE TO GROUND	BASEMENT CEILING	SLABS TOWARDS ARCADES
Construction as-is state	Partly 8 cm rock wool	Concrete slab	Vaulted natural stone ceiling, lime mortar joints	Wooden beams; sand, earth and pebble filling; underside ceiling lime plastered; floor wooden substructure and boards
U-value as-is state	2.6 W/m²K / 1.4 W/m²K	2.7 W/m²K	1.0 W/m²K	0.44 W/m²K
Intervention	25 cm of insulation (λ 0,042), 11 cm between rafters, 14 cm from below	12 cm perlite (λ 0,05) in pavement structure[1]	12 cm perlite (λ 0,05) in pavement structure[1]	Substitution of existing filling material between beams with 18 cm insulation (λ 0,042), additionally a 3 cm continuous layer on the wooden beams
U-value refurbished	0.17 W/m²K	0.36 W/m²K	0.30 W/m²K	0.17 W/m²K

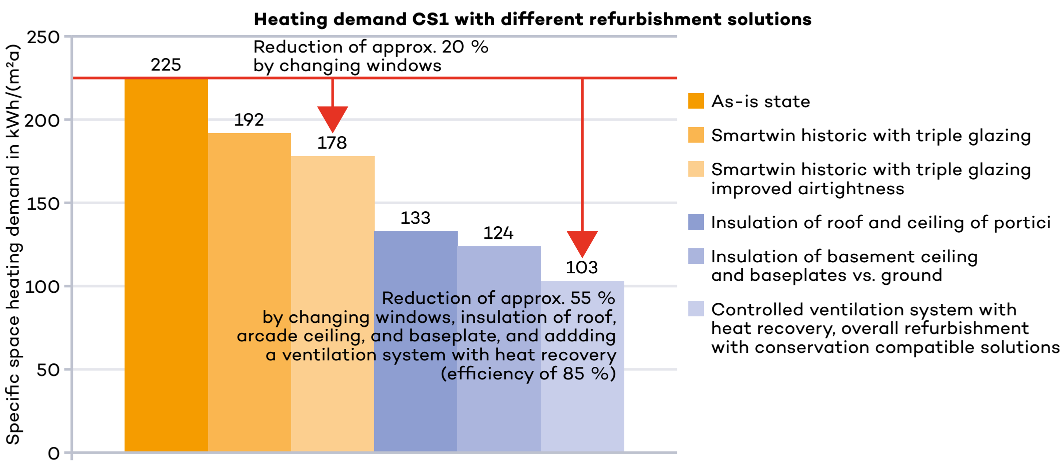
[1] Check thermal bridges caused by interior walls

Tab. 1.6: Energy efficient enhancement of opaque parts of the envelope

Fig. 1.12: Heating energy demand: Reduction of 20% by upgrading the windows, reduction of 55% by implementing all heritage-compatible interventions.

Together with the installation of a controlled ventilation system with heat recovery (efficiency 85%) to decrease the ventilation heat losses, the measures described in Tab. 1.6 show a possible reduction of the heating energy demand of more than 50%.

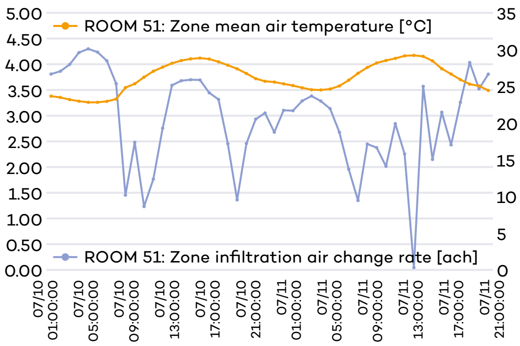
Figure 1.12 shows a reduction of 20% by upgrading the windows, a reduction of 55% by implementing all heritage-compatible interventions.



Ventilation

After improving the airtightness of the building, it is important to ensure a suitable level of air exchange for a healthy indoor environment, both for inhabitants and users, and for the building. For the Waaghaus several potential strategies were evaluated by the EnergyPlus building software and Airflow Network model, including heritage-compatible mechanical ventilation with heat recovery, managing windows for cross ventilation, and using existing chimneys to exploit the stack effect. The latter two solutions, while not using energy to operate, rely on the direct income of external air, which is a disadvantage in winter. In summer they can be more effectively used, but to avoid warm air entering the building the windows should be opened only during hours when the building is empty (corresponding to the coolest daily hours). Figure 1.13 shows the potential ventilation rate after implementing a system that has some windows open permanently and some automatically opening and closing when the zonal temperature is higher than the external and set-point temperatures.

Figure 1.14 shows the results of thermal comfort in summer achieved by ventilation. Open windows during the day did not always ensure optimal comfort: in May, the temperature was below the thermal comfort level.



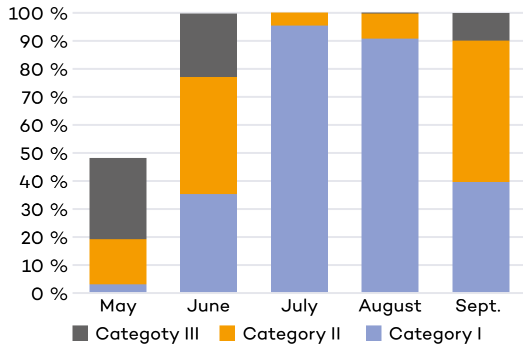


Fig. 1.13: Achievable air exchange with cross ventilation from windows and stack effect from chimneys, and relative temperature on hot days in July.

Fig. 1.14: Room 51 – Monthly average thermal comfort in compliance with EN 15251, using adaptation method Category I – Occupied Hours

To assess the potential use of underground cold air from the basement, a third ventilation strategy was modelled using the Energy Management System model. The basement is in direct contact with the soil that is used as cooling source for heat rejection, while the heat exchanger of the mechanical ventilation system cools the air that is distributed to the upper part of the building. Using this strategy it is possible to achieve the same comfort level without the automated window system.

As regards proposals for shading and daylight optimisation, please refer to Section 5.5.

Focus: Highly energy-efficient heritage-compatible window

As previously mentioned, most of the original windows are not of historic value from the conservator's point of view and should be replaced with a historic window reproduction. The aims of the devel-opment of this new window were to build firstly a highly energy-efficient window with Passive House qualities, and secondly a window that fulfils the aesthetic heritage demands of the building.

Window development

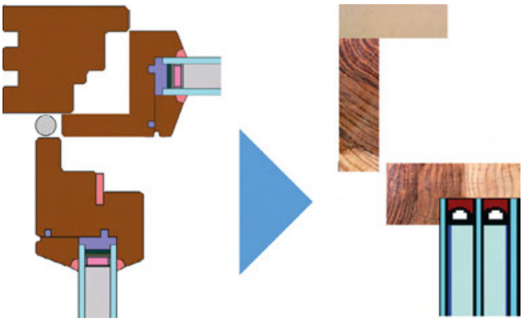
At the first workshop, the window developer and producer, the building physicist, the architect, and the conservator determined the aesthetic, formal and functional needs of the new window before starting the development of a concept. Typical characteristics of local historic windows and relevant recurrent problems of energy efficiency refurbishment of protected windows were considered in concept development (see Fig. 1.15). From the conservator´s point of view, two aspects of the original appearance of local historic windows should be adopted to the new window: the original proportion between glass area and sash bars and window frame and the appearance of original historic glazing.

Changing historic single glazing to double glazing changes the look of the facade because of altered reflection and mirroring caused by (i) convex or concave deformation of the glass pane through expansion and contraction of gas between the two glass layers, (ii) the different surface finish of modern flat float glass compared with traditional blown glass, and (iii) more regular reflection if subdivisions are no longer divided (therefore not causing different glass inclination).

In an expert workshop the overall window concept for the whole building was developed. For the original windows from the late baroque era, it was decided to consider energy efficiency enhancement by adding a second window layer, while the windows from the 1950s/60s should be replaced with new windows which better fit the historic context.

As there were no drawings of the original window available, the new window was based on a classic casement window with two sashes that both had two sash bars. The concept developed separated the demands and functions into two layers: the outer layer was the aesthetic reproduction of the original historic window and the inner layer was developed for high energy efficiency. In this way, it was possible to obtain the appearance of the original historic window from outside in terms of frame dimensions, sash bars and mirroring, without any negative effect on the energy efficiency. This outer layer became the weatherproof layer. The Passive House window with triple glazing was integrated into a second inner layer, making the window airtight. By rotating the frame cross section ninety degrees and by moving the centre of rotation of

Fig. 1.15: Originally, the wooden frames, impost, and sash bars were very fragile and thin, possibly moulded (a-b-c), while the appearance of the typical replacements is much broader (simple application of the IV68 standard, d-e-f).



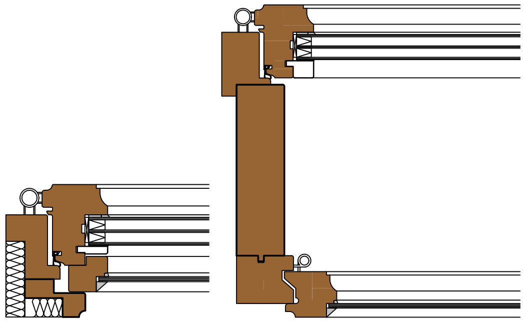


Fig. 1.16: Rotation of the frame cross section by ninety degrees

Fig. 1.17: Separation of functions into two layers to achieve a smaller frame: 'historic' window outside; integration of passive house window inside

the fitting, a smaller frame than the conventional solution was achieved (see Fig. 1.16). It is positioned in a way that its frame is not visible from the outside. Following this approach, both a box-type and a casement window are executable (see Fig. 1.17). It allows also preservation of the original window by simply adding the second energy-efficient layer on the inside or on the outside.

On the installed prototype of the casement window version, the conservator evaluated the fulfilment of heritage demands: the appearance of the outer single glazing and the appearance of the inner triple glazing, the proportions, subdivision and frame thickness, the evaluation of the division of functions, and the colour and profiling. Based on this feedback the prototype was developed further. During the prototype development, a building historian had discovered traces of imposts (in some cases where the outer sashes of the box-type window from the 1950s/60s were installed in an original baroque frame), the new prototype was also built with a horizontal impost and four window sashes (two above, two below). The existing window with an impost in the bay window served as model. The use of the very thin triple glazing (2/8/2/8/2), with the total thickness of a standard double glazing, made it possible for the frame proportion to be narrower and the appearance from inside was very similar to a double glazing (see Fig. 1.18).

Fig. 1.18: The latest prototype installed in the Waaghaus

The application of the concept and the implementation of the window prototype benefited from the flexibility, experience, and knowledge of the small traditional window producer, who was able to tailor its facilities to the production of this specialised window.

Window installation and building energy balance

Regarding the window to wall connection, as no application of internal insulation was possible for most parts of the case study the junction was optimised by studying the existing reveal on site and inserting an insulation layer of 4–6 cm around the window. This helped improve the Ψ (psi) values and thereby increase the surface temperatures at critical points to the required values (see Fig. 1.19).

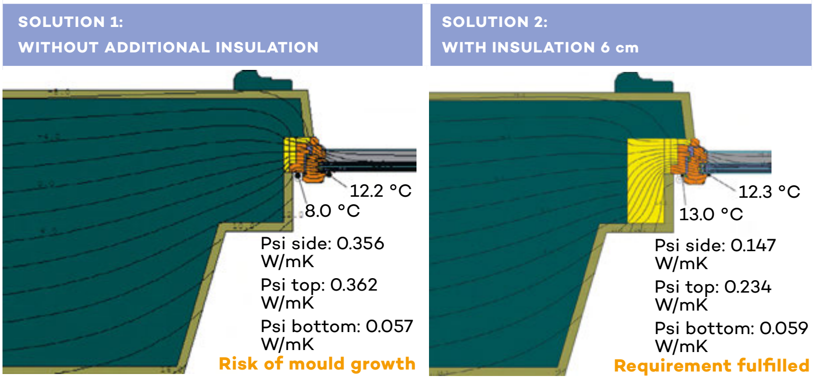


Fig. 1.19: Comparison of two window connections, with and without additional insulation

Flexibility of the SmartWin window concept

The flexibility of the newly developed window system allows its integration into an original window. In the case of the three baroque windows in the bay window, it is important to maintain the interior view; therefore the preference was for the additional layer to be added on the outside. The solution developed was to remove the external wooden frame that the shutters were fixed to and replace it with a second window layer, which takes over the energy-efficient function (the concept of the composite window prototype applied in reverse). The outer pane can be opened to the outside and is without the horizontal impost (only one sash). For the remaining three original windows, it was decided to install the second layer on the inside instead.

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Name	Palazzo d'Accursio
Location	Bologna, Italy
Date of construction	Thirteenth century
Architectural style(s)	Not one homogeneous architectural style, austere architectural language for the fourteenth century section, decorated and embellished features for the fifteenth century section
Construction type/ materials	The construction type is layered across different historic phases. The used materials are: → brick for the wall structure; → marble and sandstone for the decoration; → wood for roof structure, tiles and copper plates for the roof covering
Original building use	Initially a deposit for grain storage; from the fourteenth century seat of city government, then Papal Legation.
Current building use	The town hall of Bologna
Main interventions	The renovations allowed the reopening of the prestigious Sala Urbana as part of the Municipal Arts Collection and included: → thermal insulation of the building envelope; → installation of high performance windows; → installation of an energy saving lighting system; → installation of wireless sensors to monitor the internal climate.
Total heating measured, consumption before intervention: [kWh/m²a]	Average value (2007–2012): 106,01 [kWh/m²a] (27.583 estimated square meters)
Average electricity measured, consump- tion before intervention [kWh/m²a]	Average value (2010–2013): 106 kWh/m²a

CASE STUDY 2

PALAZZO D'ACCURSIO, BOLOGNA, ITALY

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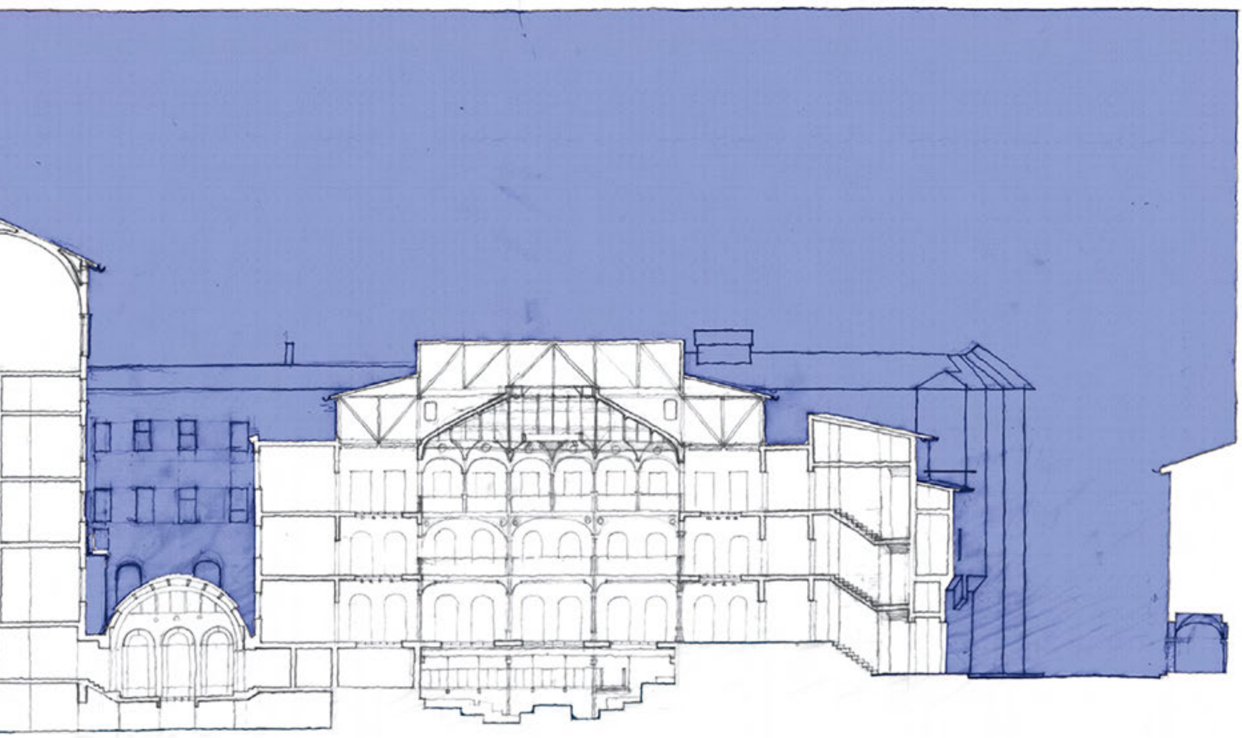


Building history and general description

Building history The actual structure of Palazzo d'Accursio is the result of several modifications: the original nucleus of the building was the Biada Palace, protected by a square perimeter wall and used for the storage of grain. This was expanded over the centuries to become the institutional headquarters of the city. In 1336 it became the residence of the Elders, hosting the city government. Between 1365 and 1508, it was renovated and expanded by architect Fioravante Fioravanti. Crenellated walls interspersed with towers were erected, together with the completion of the building facade in front of Maggiore Square and of the western body of the palace, with contributions from several architects including Donato Bramante. Between 1513 and 1886, renovation and further extensions included the completion of Cardinal Legate's private apartments and Galeazzo Alessi's chapel.

Constraints, conditions, and protection

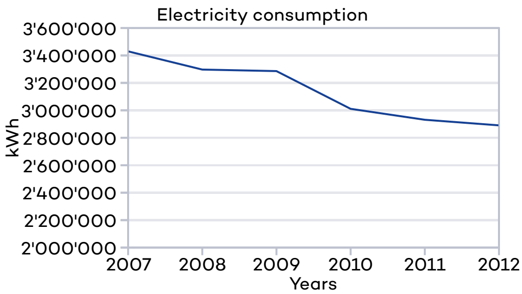
The building is qualified as a building of historic and architectural interest in the Urban Building Regulation Code; it is classified among the buildings protected by the National Law of Conservation of Historic Heritage. The regulation code admits only respectful interventions of renovation and maintenance. In particular, it requires preservation of the original integrity of every architectural, artistic and decorative element of a structure, such as:

- → consolidation with the substitution of irreparable parts without modifying the position and height of major walls, lofts, ceilings, stairs;
- → the insertion of essential technological installations, respecting the previously given constraints;
- → each intervention must be reversible.

Before, during, and after intervention analyses

Measured energy consumption

The diagrams in Figure 2.1 and Figure 2.2 show the electricity, gas, and Gecam (white diesel, an emulsion of water in oil) consumption for the whole Palazzo d'Accursio.



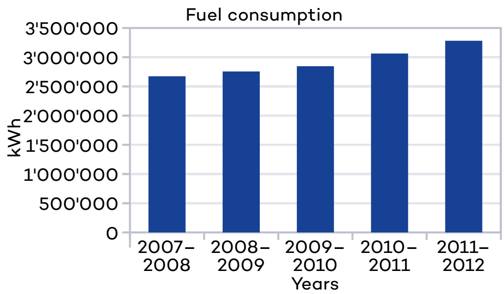


Fig. 2.1: Electricity consumption (lighting, air conditioning, office equipment, server)

Fig. 2.2: Fuel consumption (central heating plant)

The diagnosis was performed through a detailed analysis of the electrical systems and recorded during two surveys carried out at the beginning and the end of the project. During the first survey, conducted in November 2011, total consumption was 164.635 kWh / year, while in the second survey, conducted in November 2013, total consumption was 159.027 kWh/ year.

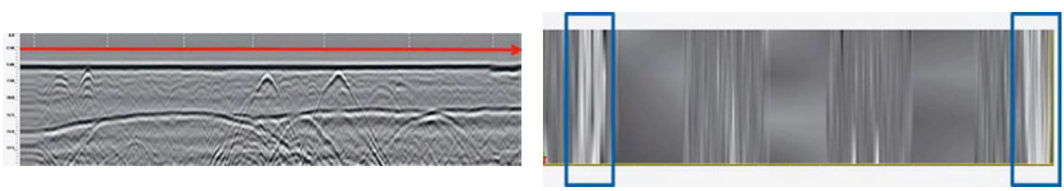
The high electricity consumption (106 kWh / m²) is mainly due to the use of individual air conditioners in summer and of small electric stoves to improve comfort inside the offices in winter. Use of this equipment is due to the current heating and cooling systems being inadequate. The decline of consumption from 2007 to 2013 is mainly due to a significant transition to the use of fluorescent lamps.

Analysis and non-destructive tests

Diagnoses before and during the intervention foresaw the combination of different approaches and several non-destructive techniques in the whole Municipal Collection area. The integrated structural and energetic approach developed by the Department of Civil, Chemical, Environmental and Materials Engineering (DICAM) at the University of Bologna included:

→ GPR radar tests for investigating the masonry construction stratigraphy;
→ Infra-Red Thermography (IRT);
→ blower door test;
→ U-value tests;
→ daylight test using photometric equipment.

Fig. 2.3: Left: 'Aemilia ars' room, radargram of the floor (vertical section) by a 900 MHz radar antenna along an E-W survey line, 12 m long. The vault thickness is visible. Right: Slice from a 3D set of radar data from the top part of the south wall in the Sala Urbana showing a vertical inner view with unknown chimney flues (blue squares)



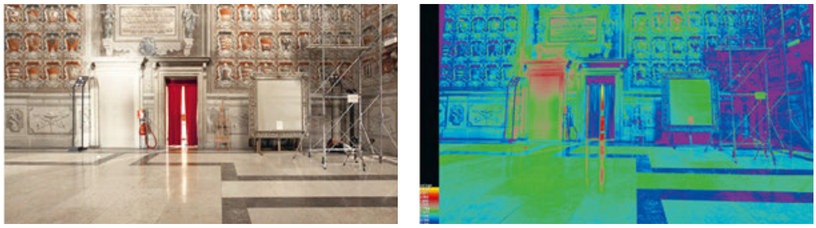


Fig. 2.4: Luminance test in the Sala Urbana

These tests showed the presence of thermal bridges in the ceiling and of cavities inside the walls (chimneys). The blower door test showed the locations of major air infiltrations (windows and ceiling). The daylight test revealed that the Sala Urbana was poorly illuminated and that luminance levels on the walls were below recommended levels.

Hygrothermal and environmental monitoring

Hygrothermal monitoring of the building was carried out through a Wireless Sensor Network (WSN) and an IEQ (Indoor Environmental Quality) audit for characterisation of micro-climatic conditions performed with portable instrumentation, both in the museum and office areas:

→ WSN monitoring went on from February 2011 to April 2012. The results obtained for air temperature and relative humidity inside the Sala Urbana and in its attic showed that the situation is not favourable for artworks conservation.

→ IEQ audits were performed in winter and summer. During the two monitoring activities, hygrometric, visual, and acoustic parameters were surveyed in each room. In the following phase, by processing these parameters the comfort indexes were calculated. Results concerning thermal comfort showed satisfactory values for winter in the Sala Urbana (PMV=-0,29, PPD=6,74). In order to better know the internal museum environment and that of its collections, in the Municipal Collection area the pre-intervention indoor climate conditions were repeatedly monitored by researchers of the University of Bologna in different seasons and with opened / closed windows /doors, by means of a digital thermo-hygrometer and analogue thermo-hygrographs to obtain psychrometric profiles and maps showing air temperature and humidity at different heights above the floor.

The climatic variations in Sala Urbana during and after the refurbishment intervention in the summer and autumn of 2013 were monitored by the University of

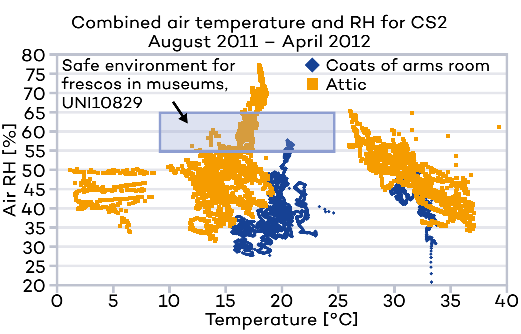


Fig. 2.5: Combined air temperature and relative humidty (RH)

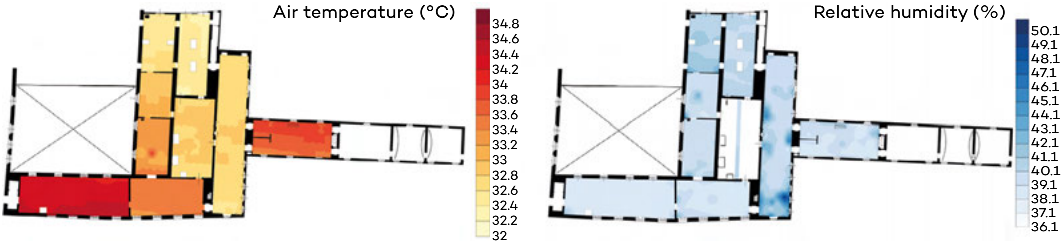


Fig. 2.6: Environmental data acquisition in the Municipal Collections on a hot August day with closed windows (right) and resulting T and RH maps (below).

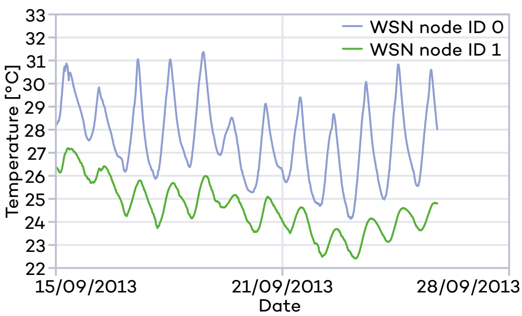


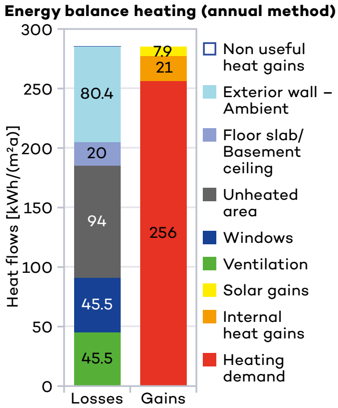
Fig. 2.7: WSN monitoring of microclimatic conditions during refurbishment works in Sala Urbana

Bologna by means of a WSN with two nodes strategically placed, one at the level of the roof and the other at the top of the internal scaffolding. Temperature, relative humidity, light, and vibration were recorded.

Energy simulations

Passive House Planning Package (PHPP) calculation results

A PHPP calculation was applied twice to the Municipal Collections rooms as one of the structurally homogeneous areas, and as representative of the whole building. Not surprisingly, the results evidenced that the Municipal Collections area falls far short of achieving the Passive House standard.



	Treated floor area	1015.0 m²		Requirements	Fulfilled?*
Space heating	Heating demand	273	kWh/(m²a)	15 kWh/(m²a)	no
	Heating load	124	W/m²	10 W/m²	no
Space cooling	Overall specif. space cooling demand	2	kWh/(m²a)	–	–
	Cooling load	19	W/m²	–	–
	Frequency of overheating (> 25 °C)	1.7	%	–	–
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances	543	kWh/(m²a)	120 kWh/(m²a)	no
	DHW, space heating and auxiliary electricity	439	kWh/(m²a)	–	–
	Specific primary energy reduction through solar electricity		kWh/(m²a)	–	–
Airtightness	Pressurization test result n_{50}	5.9	1/h	0.6 1/h	no

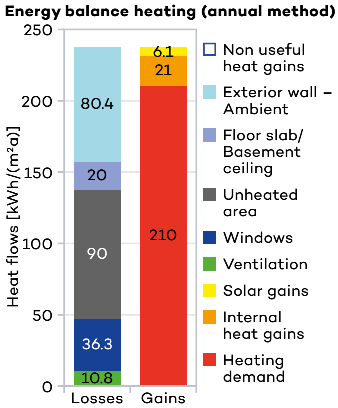
* empty field: data missing; '–': no requirement

Fig. 2.8: Pre-intervention energy balance

The results of the application of the PHPP analysis showed that the energy losses are distributed across the entire envelope with especially high losses in the unheated attic and through the external walls. The blower door test showed relatively poor airtightness with a mean air change rate of 5.9 1/h resulting in considerable infiltration heat losses. The transmission heat losses through the windows are also relevant, due to the presence of several large windows in each external wall.

Compared to the pre-intervention scenario, the results of the post-intervention PHPP showed that the losses in the unheated area (attics) and through the windows decreased in accordance with the implemented measure. Also ventilation losses decreased due to an improvement of the airtightness. Looking at the global assessment, the estimated heating and cooling demand decreased by 50 kWh/m²a (19%) and 1 kWh/m²a (50%).

Fig. 2.9: Post-intervention energy balance



	Treated floor area	1015.0 m²		Requirements	Fulfilled?*
Space heating	Heating demand	223	kWh/(m²a)	15 kWh/(m²a)	no
	Heating load	86	W/m²	10 W/m²	no
Space cooling	Overall specif. space cooling demand	1	kWh/(m²a)	–	–
	Cooling load	6	W/m²	–	–
	Frequency of overheating (> 25 °C)	1.0	%	–	–
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances	472	kWh/(m²a)	120 kWh/(m²a)	no
	DHW, space heating and auxiliary electricity	370	kWh/(m²a)	–	–
	Specific primary energy reduction through solar electricity		kWh/(m²a)	–	–
Airtightness	Pressurization test result n_{50}	2.5	1/h	0.6 1/h	no

* empty field: data missing; '–': no requirement

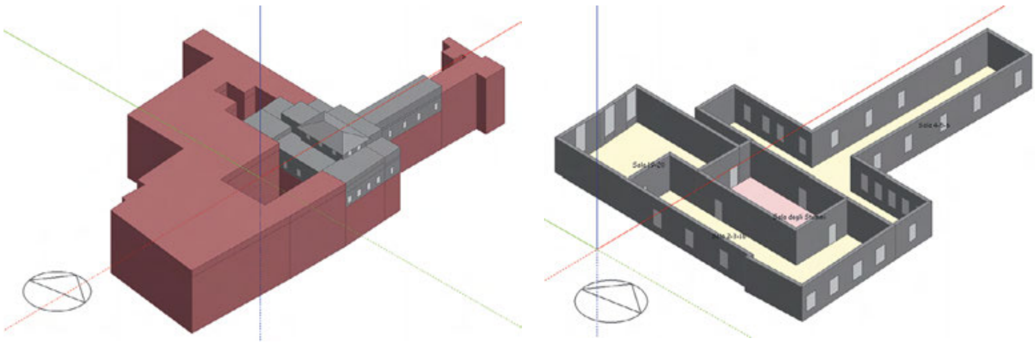


Fig. 2.10: 3d energy model of the building (left) and of the PHPP area (right)

Design Builder modelling (as-is state)
An energy model of the Municipal Collections area was elaborated using the dynamic building simulation software Design Builder (DB). Modelling and analysis were performed in seven steps, from digital rebuilding of the examined area, to the simulation of the thermal and physical characters of the building components, ending with the definition of the kind of HVAC and the type of regulators in the model. Using DB, the solar gains, internal gains, energy losses through the building envelope, and ventilation for both winter and summer were calculated, estimating the energy need for heating in winter and for cooling and lighting in summer.

Description and evaluation of the intervention

Methodological procedure and project

An intervention in the Sala Urbana of the Bologna Municipal Collections was essential to stop the decay of the ceiling frescos due to rainwater infiltrations through the deteriorated roof covering. The local authority was convinced to combine the necessary renovation measures with energy efficiency improvements. These met the following requirements:

→ improving internal comfort in the room in winter and in summer, and without airconditioning in summer;
→ protecting the fresco decorations on the walls and ceiling from direct sunlight by significantly reducing ultraviolet radiation and providing protection from infrared radiation.

The required interventions and expected retrofitting for the Sala Urbana are varied in process, each one essentially corresponding to the specific choice of the materials to be used.

Work primarily focused on the replacement and waterproofing of the roof and replacement of the existing windows. After evaluating each energy retrofit measure individually, an effectiveness analysis in dynamic conditions was carried out with alternative solutions and their relative impact in the building.

Interventions

The following works were carried out in the Sala Urbana:

→ *Roof refurbishment:* substitution of the existing roof by a ventilated roof with wood fibre insulation;

→ *Seismic improvement:* the perimeter walls were consolidated by inserting new bricks in the section portions in which the pre-existing chimneys had weakened the structure, and the perimeter structure was reinforced by a banding of metal bars. A wooden truss was stabilised by inserting metal bars and epoxy resins;

→ *Window replacement:* installation of wooden / aluminium window frames and double glazed with low-E glass;

→ *Automation and control of the Sala Urbana:* with a domotic system that automatically controls windows and curtains adjusting the light intensity depending on the current room use;

→ *Plaster replacement:* substitution of the present external plaster layer with a traditional lime-based plaster;

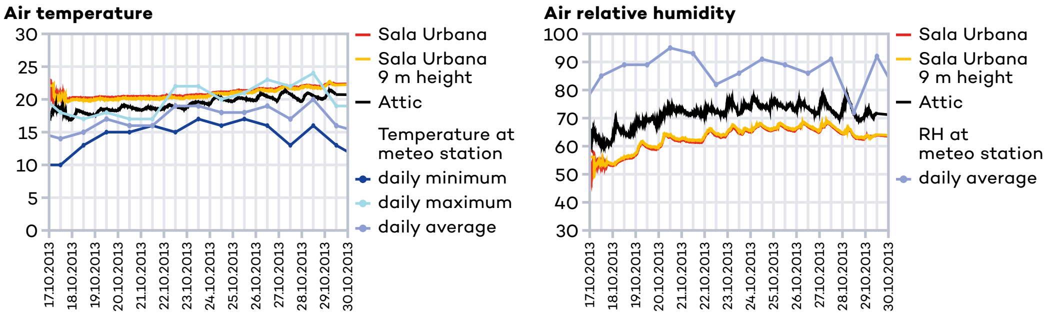
→ *Frescoed ceiling renovation:* insertion of an insulation layer at the extrados of the frescoed ceiling using natural plaster containing resins. Preparation of the paint surface with Japanese paper and subsequent cleaning;

→ *Artificial lighting:* refurbishment of the artificial lighting with a LED wall washer system for improved efficiency.

Fig. 2.11: Images of the roof refurbishment, structural consolidation, and ceiling renovation

Post intervention monitoring

WSN monitoring: Sala Urbana was monitored during the period 17/10/2013–21/11/2013. The results were compared with those acquired in the period 28/10/2011–08/11/2011 to verify the effects of the renovation works, especially the ones resulting from the installation of the new high performance windows. Some monitoring results are shown in Figures 2.12 and 2.13.



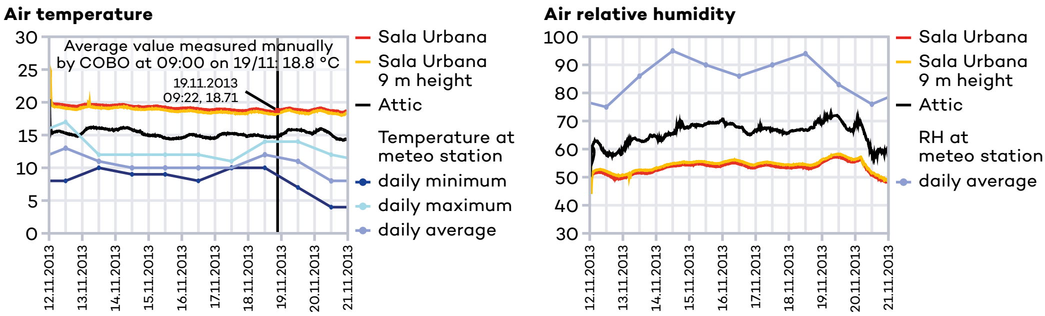


Fig. 2.12: Graph of air temperature and relative air humidity, before intervention

Fig. 2.13: Graph of air temperature and relative air humidity, post intervention

It can be seen from this monitoring session that after the installation of the new windows and the construction of the new roof, daily oscillations have been reduced and the internal micro-climate is less prone to follow the trend of the external one, thus obtaining a more stable environment.

New window frames and artificial lighting system

Substituted window frames

The frames have been provided with automatic openers activated on the basis of the ratio between the internal and the external temperature. By opening the windows on summer nights the chimney effect can be used for natural cooling.

Fig. 2.14: External window before and after the interventions

Motorising, automation, and control

The windows and curtains have been equipped with an automated opening system. The curtains are moved automatically and synchronised with the opening and closing of the windows. The system has the capacity to adjust according to different scenarios, such as indoor temperature and moisture, and automatically closes in the case of rain and strong wind. The control unit installed is based on the Konnex domotic system. This system guarantees the correct microclimate for the preservation of the wall paintings.

Pre-intervention monitoring with a WSN

Before any energy efficiency measures are implemented in a historic building, a sufficiently long period of monitoring should be undertaken in order to evaluate the seasonal oscillations of the internal environment and their relationship with the external climate. This, however, is a costly operation and could involve some invasive interventions like mounting sensors and / or other equipment. A WSN is recommended as it requires no cabling and is cheaper compared to a traditional wired system.

Experimental artificial lighting system

The main goal of the energy efficient lighting installation in Palazzo d'Accursio is to provide visual comfort to visitors viewing the frescoes and to preserve the materials. The lighting system is based on LED wall washers that are placed around the decorative cornice at 8.5 m above the floor. The project idea is to hang an I-beam from the two available anchorage points represented by the narrow openings in the decorated ceiling through which the chandeliers supports used to pass. These were found during the refurbishing of ceiling frescoes. The bar will carry the 3ENCULT wall-washers (www.projektleuchten.de). This installation is a good balance between perfect illumination and conservation considerations (i.e. reversibility) and offers visual comfort as it is glare-free and has well balanced lighting levels on the walls and ceiling. The luminaire itself is nearly invisible because of its small dimensions and its specific light intensity distribution. The transition from the existing lights which used halogen lamps to a system of wall wash LED lighting has reduced the electricity consumption by about 53%.

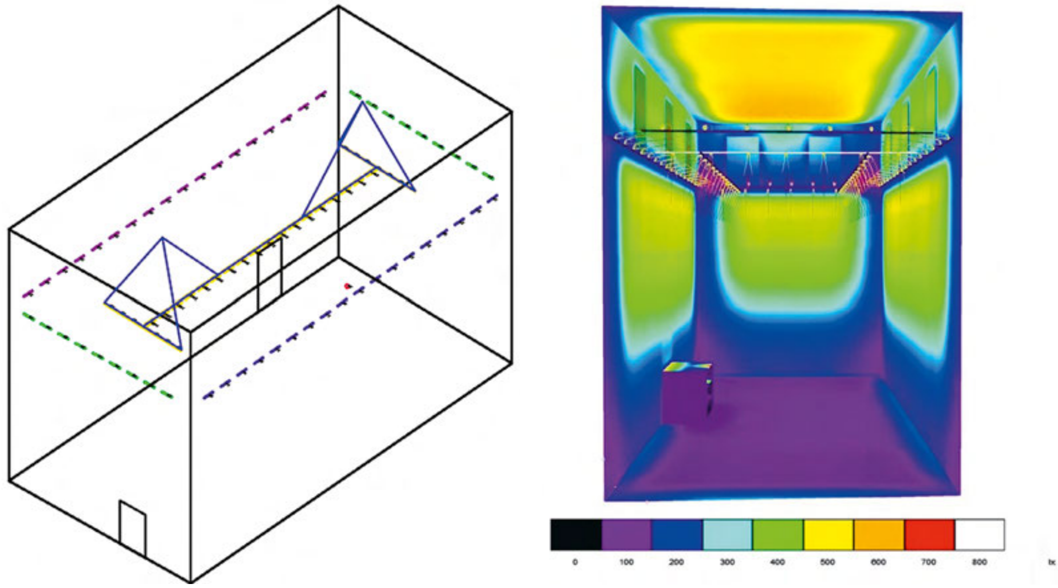


Fig. 2.15: Artificial lighting simulations

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Ori, 1976 Ori, A. S., *Bologna raccontata. Guida ai monumenti, alla storia, all'arte della città*, 1976.

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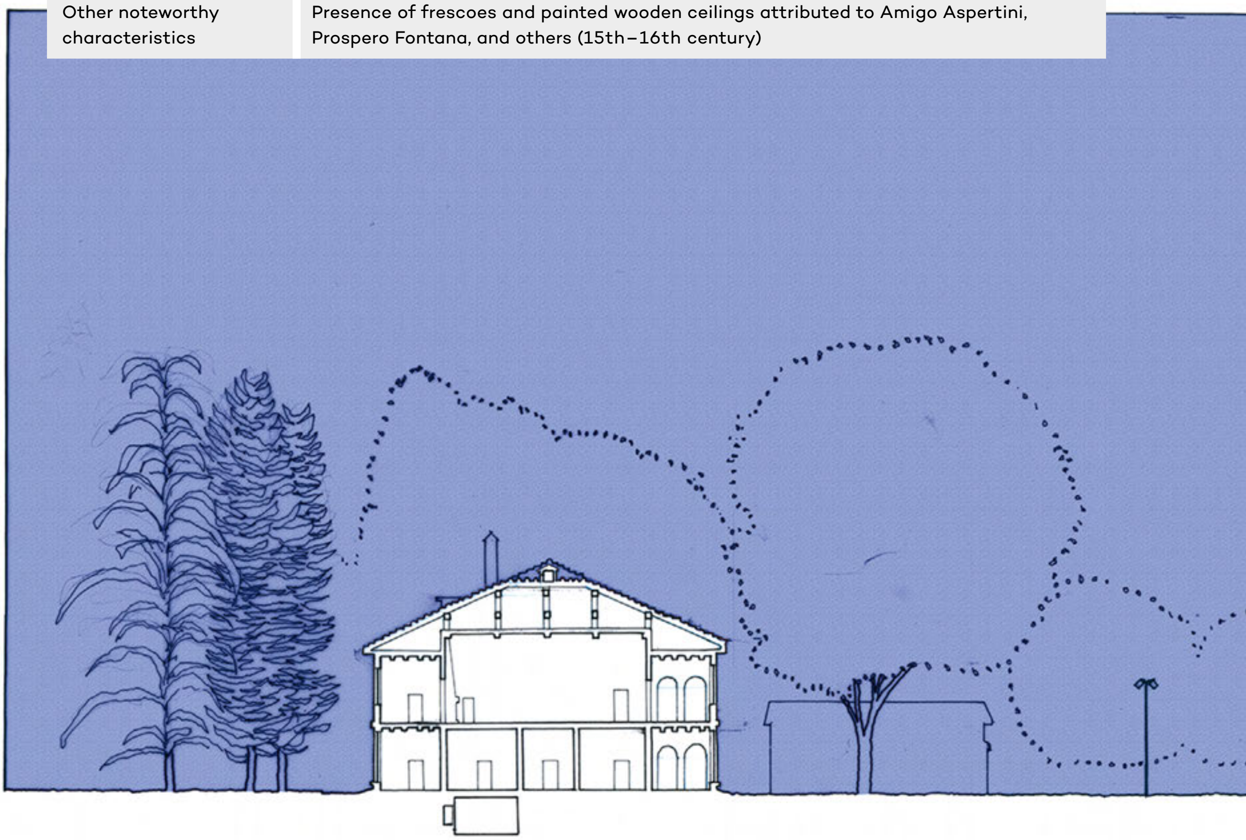
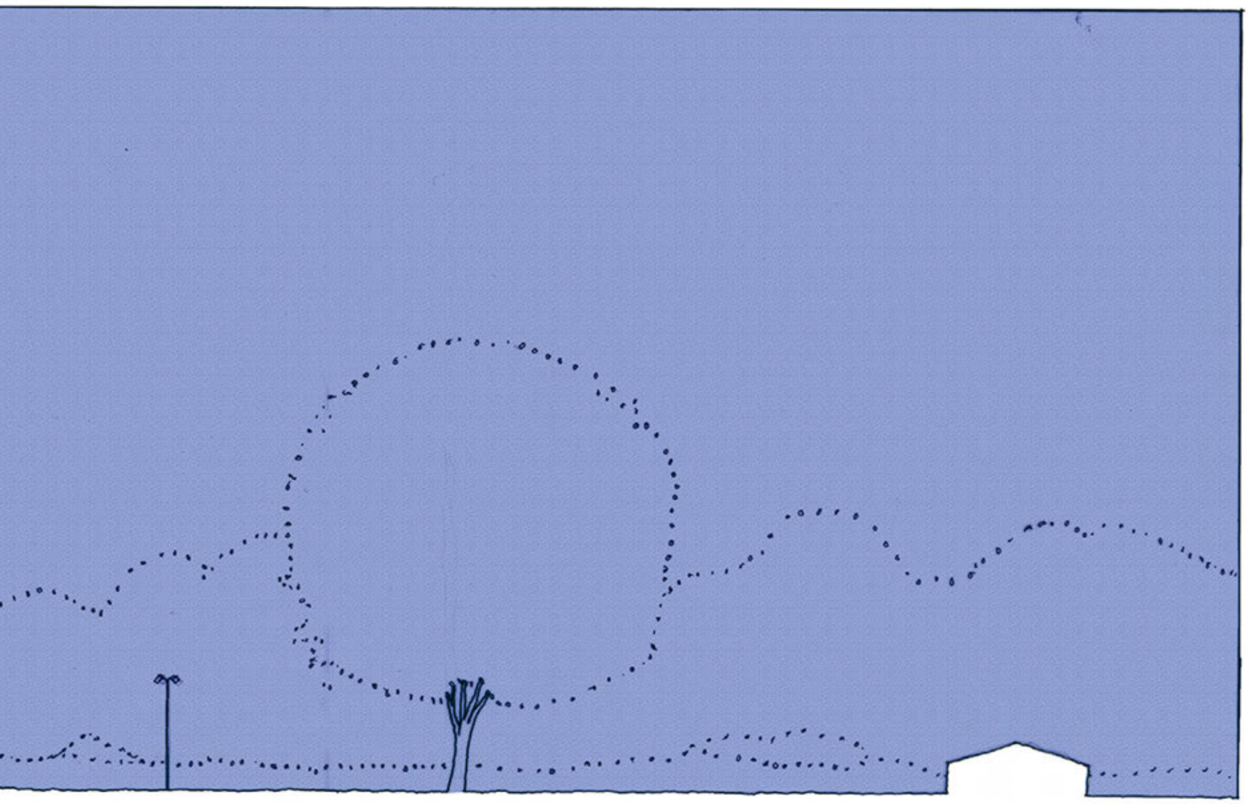
Name	Palazzina della Viola
Location	Via Filippo Re 2, 40126 Bologna, Italy (Lat N 44° 29' – Long E 11° 20')
Date of construction	1497 by Giovanni II Bentivoglio
Architectural style(s)	Renaissance
Construction type / materials	Lightweight-masonry building with ceilings made of timber beams or more recent concrete and brick elements, steel beams
Original building use	Hunting lodge and leisure activities
Current building use	Since March 2012, International Relations Dept, University of Bologna
Main alterations	VRF system, DOAS with heat recovery, restoration of windows and floor, solar film on glazed surface of galleries
Heating demand / consumption before intervention [kWh/m²a]	Calculation using PHPP protocol: 278 [kWh/m²a]
Heating demand / consumption after intervention [kWh/m²a]	Calculation using PHPP protocol: 264 [kWh/m²a]
Other noteworthy characteristics	Presence of frescoes and painted wooden ceilings attributed to Amigo Aspertini, Prospero Fontana, and others (15th–16th century)



CASE STUDY 3

PALAZZINA DELLA VIOLA, BOLOGNA, ITALY

Camilla Colla, Elena Gabrielli, Marco Giuliani, DICAM Department, University of Bologna / Giacomo Paci, DEI Department, University of Bologna



Building history and general description

The Palazzina della Viola, which owes its name to the violets once blooming in the surrounding meadows, was built in 1497 by Giovanni II Bentivoglio on the edge of the city for his son Annibale as a hunting lodge and leisure retreat. In 1540, the building was bought by Cardinale Bonifacio Ferrerio and it became a student residence until 1797 when it was expropriated during the Napoleonic era. In 1803 the Palazzina was passed on to the Italian Government and later it became the headquarters of the Agriculture Faculty of the University of Bologna with the adjacent Botanical Gardens. The building has undergone many alterations, redesigns and renovations throughout its existence (i.e. in the 17th century, at the beginning of the 20th century, and after the Second World War) and it has also suffered periods of abandonment, the most recent period lasting almost ten years, until the start of the refurbishment work in 2011. During the 3ENCULT project, the Palazzina was subjected to preservation measures that included extensive restoration and interventions aimed at improving its functionality and seismic resistance (January 2011 to January 2012). It now accommodates the headquarters of the Department of International Relations of the University of Bologna.

This unique listed building, a 'jewel of Renaissance art', has a square floor plan (four floors, 300 m² per floor, around 4240 m³ total volume). Three façades have a lighter appearance due to a double open gallery. It is a load-bearing brick masonry structure with wooden or concrete-and-metal ceilings and it is enriched on the ground-floor and first-floor level by frescoes and painted wooden ceilings (15th and 16th centuries), attributed to Amico Aspertini, Prospero Fontana, and others.

Fig. 3.1: Front view in 1906 (left); site aerial view (right)

Pre- and mid-intervention analyses

During a comprehensive diagnosis consisting of a multi-phase combination of innovative non-destructive tests and manual and wireless sensors, monitoring techniques were implemented that take the specific features of this case study into account, including the materials used, the construction types and the historic value of the building. This methodology was repeated in the different phases of the intervention, applying diagnostic and monitoring techniques to analyse the structures and the energy use. This section focuses on the analyses carried out prior to and during the interventions, while the activities carried out after the renovation work are described in the section 'Description and evaluation of interventions'.

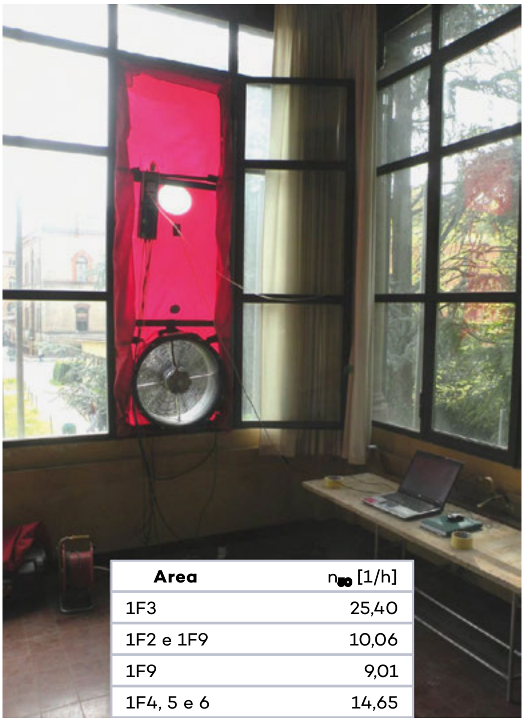
Non-destructive tests

The extensive diagnostic approach enabled the integrated and innovative application of several non-destructive diagnostic techniques in order to obtain useful information, both from a structural and an energy-based perspective, without causing any damage to the structure or artefacts.

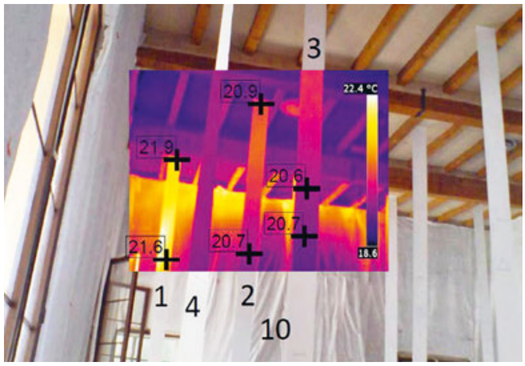
Among these techniques, it is worth mentioning the blower door test, which is usually applied to determine the airtightness of new buildings. There is no standardised procedure for its application in historic buildings such as this one, which is characterised by large volumes and relatively low airtightness caused by air losses, for example through the wooden elements of the ceilings, the window frames, etc. Thus, to achieve measureable pressure differences, the BDT was carried out in sub-areas of the Palazzina. Findings were obtained by appropriately dividing the volumes and examining a few rooms for each test. For this, similarities of ceilings, floors and window frames were taken into account. In addition, the sources of air losses resulting from the state of neglect of the building rather than from the specific characteristics of the building structure, such as broken window panes or openings in the ceiling, were sealed. Moreover, for a more complete diagnosis, the BDT tests were coupled with IR thermography and hand-held anemometer measurements to locate and evaluate the air losses (see Fig. 3.2, left). This way it was not only possible to determine the overall air change rate n_{50}=10 1/h, but also to identify the exact location of air leaks. Specific types of windows, ceilings and floors (i.e. those constructed of timber planks) are particularly prone to leaking.

Other energy-related aspects, such as the air fluxes between adjacent rooms in absence of heating/cooling systems, were studied by means of an innovative, non-destructive procedure developed especially for this purpose [Colla; Corradetti, 2012].

By measuring the air temperature at specified times via IR, using paper strips mounted on the ceiling, it was possible to visualise warm and cold air fluxes along vertical and horizontal sections of the room (see Fig. 3.2, bottom, right). Based on time sequences of two-dimensional temperature maps (both horizontal at different levels from the floor and vertical), the movements of the air can be tracked and valuable information affecting comfort and energy levels can be gathered.



Area	n_{50} [1/h]
1F3	25,40
1F2 e 1F9	10,06
1F9	9,01
1F4, 5 e 6	14,65



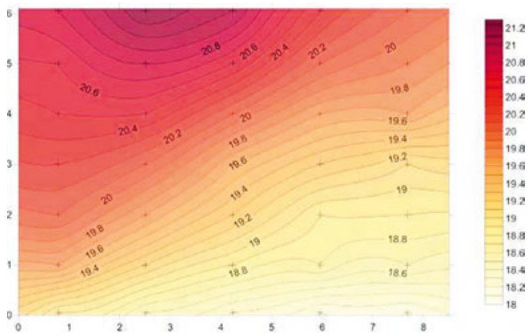


Fig. 3.2: BDT pre-intervention (left); IR-thermography analysis of air fluxes (top right); example of temperature distribution in plan view at a particular time (bottom, right).

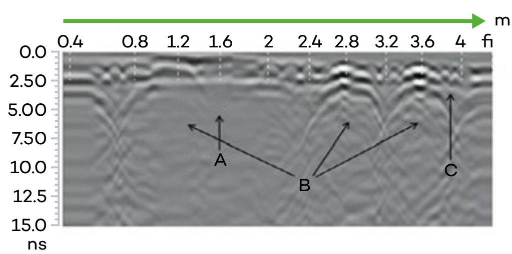


Fig. 3.3: Investigation of ceiling build-up by GPR (left), 2D radargram showing the elements of the ceiling (right)

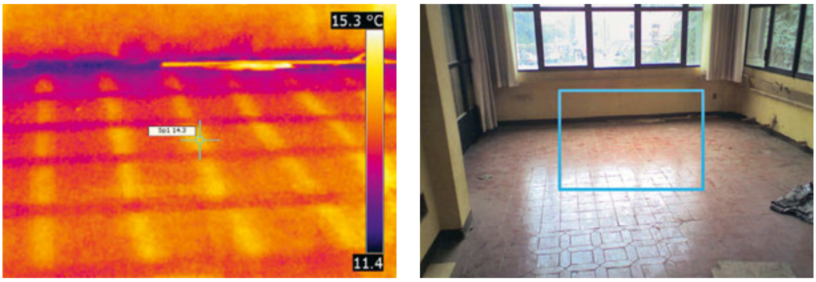


Fig. 3.4: IR investigation of ceiling structures and thermal bridges: IR image (left) and corresponding visible field (right)

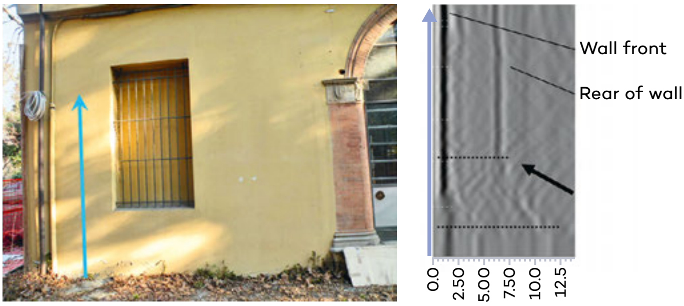


Fig. 3.5: GPR radar for moisture detection: vertical survey line on a masonry wall (left) and corresponding radargram with interpretation of levels of moisture (right).

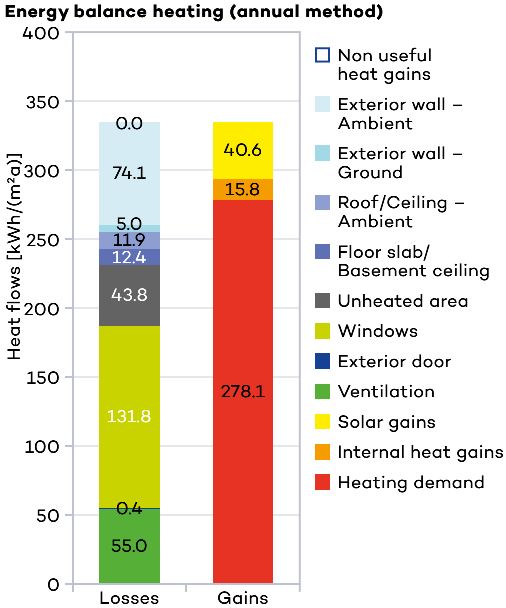
Extensive investigation carried out by means of GPR radar with medium- and high-frequency antennas and by IR thermography (see Figs. 3.3 and 3.4) allowed the determination of structural characteristics such as the ceiling build-up or the masonry walls' composition, as well as information about existing thermal bridges or moisture problems. For example, by surveying with GPR antenna along vertical profiles, sections of the walls (radargram) can be obtained that show different moisture content at various heights in the wall thickness and the maximum level of rising damp (see Fig. 3.5). In the radargram, the arrow indicates the highest level of rising damp.

Energy analysis, pre-intervention

The thorough analysis of the building structure, as shown in the section before, made it possible to estimate well the energy balance of the building with PHPP. Figure 3.6 shows that the main energy loss is due to the windows. The losses through exterior walls, the attic and due to infiltration are, however, also considerable. A state of comfort during summer is provided only by ventilation through the windows, with an air change rate of 0.6 1/h. This level guarantees that overheating will remain below the 10% acceptable limit for PHPP. The cooling demand is 12 kWh/(m²a).

Fig. 3.6: Energy balance pre-intervention

Energy balance heating (annual method)



Space heating	Heating demand	286	kWh/(m²a)
	Heating load	113	W/m²
Space cooling	Overall specif. space cooling demand		kWh/(m²a)
	Cooling load		W/m²
	Frequency of overheating (> 25 °C)	9.1	%
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances	355	kWh/(m²a)
	DHW, space heating and auxiliary electricity	355	kWh/(m²a)
	Specific primary energy reduction through solar electricity		kWh/(m²a)
Airtightness	Pressurization test result n_{50}	10.0	1/h

Description and evaluation of interventions

The refurbishment of Palazzina della Viola included structural consolidation, preservation of frescoes and artworks and the modernisation of the facilities. The main restriction on energy efficiency improvement was the specification that the windows along the galleries were not to be replaced. The only intervention concerning these windows – with iron frame – was the installation of solar protection film. The other windows – timber framed – were restored and double glass panes installed. At ground level, most of the floors were rebuilt after the consolidation of the foundations and an impermeable layer was added. Water radiator systems with boilers were substituted with variable refrigerant flow, direct expansion heat pumps, assisted by the ventilation system for the control of the air quality. This technology provides heating and cooling with a reduced impact on the distribution network on the building.

The pipes were installed behind a plasterboard panel along the walls in the galleries and the parts of the floor that were reconstructed. The ventilation system was installed in the attic, an unheated area controlled by the variable air volume system using heat recovery. The extensive use of LED technology has considerably reduced energy consumption for lighting.

WSN monitoring

After the refurbishment works, a newer version of the WSN developed for 3ENCULT was installed, with 36 motes collecting data from 144 sensors. Previously, the building was monitored using a smaller and earlier 3ENCULT WSN version with 18 motes. The data collected comprised air temperature, humidity, light intensity, and acceleration. This network has been continuously collecting data since March 2012 and is still carrying on.

The data collected until now has been used to analyse the environment climate condition of the building, generating temperature and humidity distribution maps that can highlight overheating and dry zones (see Fig. 3.8).

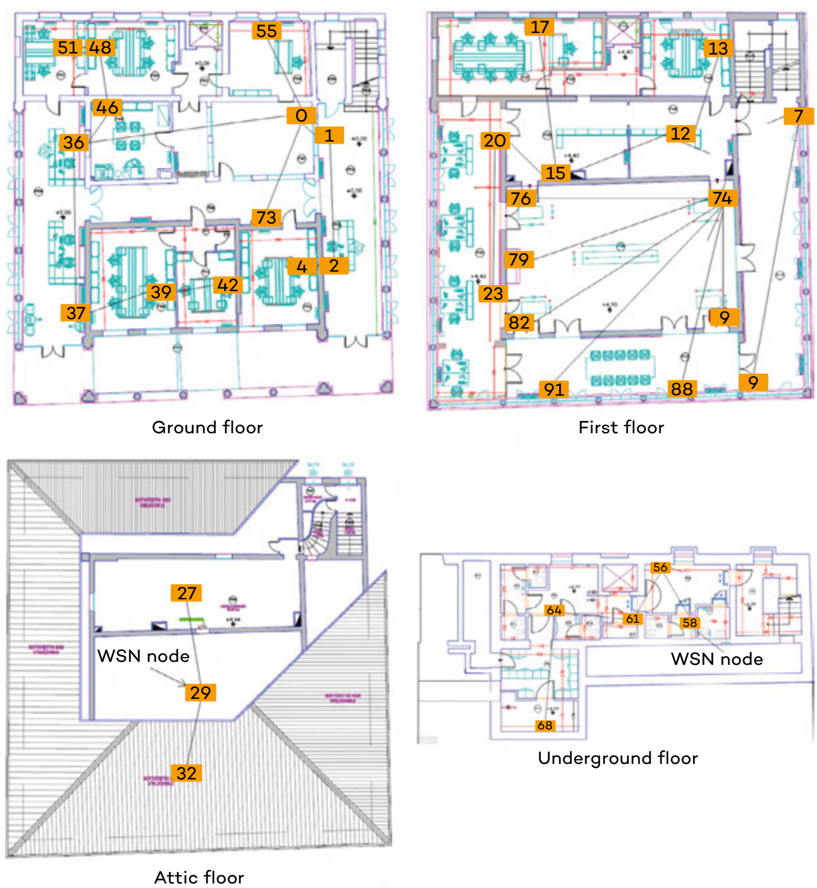


Fig. 3.7: After refurbishment instalment of 3ENCULT WSN monitoring system

Moreover, the data has been used to analyse dangerous climate conditions for cultural heritage objects, such as the fresco in the central room on the first floor. Previously, humidity levels were too high in the room containing the fresco before and during refurbishment (see Fig. 3.13), while after refurbishment the relative humidity was too low (see Fig. 3.9). This clearly shows the need to integrate a humidifier into the HVCA system.

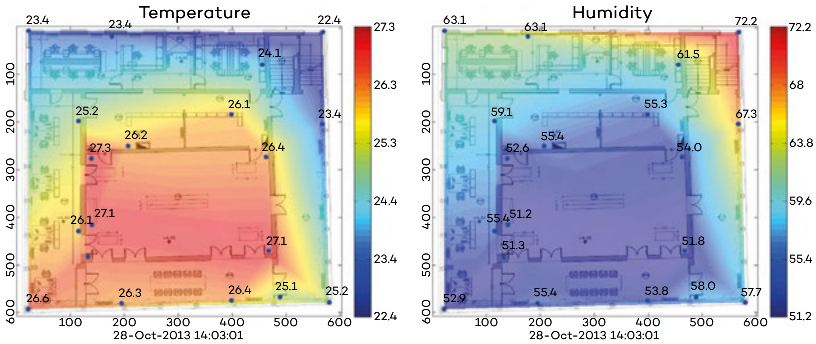


Fig. 3.8: Air temperature and relative humidity maps from experimental monitoring data on the first floor of Palazzina della Viola

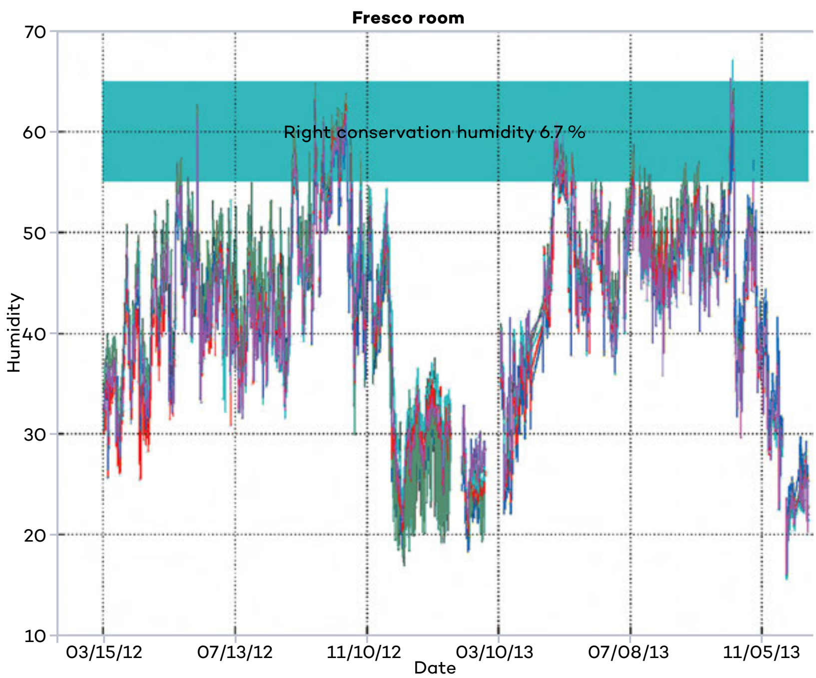


Fig. 3.9: Large hall, first floor of Palazzina, relative humidity post-refurbishment

NDT evaluation and WSN dynamic climatic monitoring

The comprehensive diagnosis of this historic building was repeated after the completion of refurbishment work, with the exception of the blower door test. In addition to the information recorded by the climatic WSN monitoring described in section 'Focus':

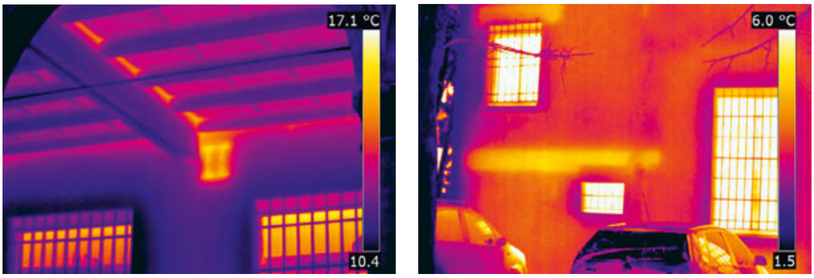


Fig. 3.10: Post-refurbishment NDT of thermal bridges by IR thermography: steel beam ends 'visible' from outside beneath the plaster, under the porch (left) and concrete stair landing (right) showing thermal bridges

WSN monitoring, several non-destructive techniques such as IR thermography were applied (see Fig. 3.10) in order to evaluate the current state of the Palazzina. Moreover, some 'movable' WSN nodes were used for innovative, dynamic, environmentally focused monitoring. Results of distribution maps of light, air temperature and relative humidity, at various levels from the ground, are useful for evaluating the risk to cultural heritage and the level of protection needed for delicate artefacts, as well as the potential discomfort of working conditions [Paci et al., 2012]. For example, it was shown that UV filters on the glass panes of windows or textile curtains both reduce the risk of frescoes being exposed to excessive direct sunlight as well as the risk of glare due to reflection from glass meeting tables, which are part of the new furniture.

Energy analysis post-intervention

The PHPP calculation was also repeated after the building retrofit in order to evaluate which improvements were generated by the selected intervention in terms of energy. The focus of the project manager was more on the conservation of the building, but some of the energy efficiency aspects were taken into account. PHPP was performed initially in the 'pre-intervention' configuration and later the interior load was changed to correspond to the 'post-intervention' configuration. This calculation allows the evaluation of the improvement of building performance. Comparing scenario 'Pre-Intervention-b' with 'Pre-Intervention', the ventilation through the windows should be increased to guarantee the same level of comfort (air change rate from 0.6 to 1/h). The internal gain is increased in agreement with the new functional schedule of the building. The losses through the windows, exterior walls and attic remain consistent. The ventilation levels drop due to the reduction of the infiltration. The air change rate per hour at 50 Pa drops from 10 to 5. In terms of the overall assessment, the heating demand is increased by 3.6% while the cooling demand is reduced by 19%, from 14.3 to 12 kWh/(m^2a). Calculations performed do not refer to space cooling because PHPP only shows the frequency of overheating when the cooling system is not present. Overheating during the summer is prevented by the installation of a cooling system. Primary energy is the sum of consumption of the entire building, taking into account equipment, systems and auxiliary. The presence of a cooling system increases the use of primary energy.

Focus: WSN monitoring

The Palazzina della Viola has been monitored by a new Wireless Sensor Network (WSN) system prototype developed in the context of the 3ENCULT project. The WSN is composed of several small boxes, each one able to collect data from environment sensors and to send them via radio. The data are collected in a database and employed both to monitor and control the environment climate. The 3ENCULT WSN is specifically designed for cultural heritage building monitoring and preservation and therefore meets with the specifications and constraints of easy installation, small size, environmental sensors and long-term monitoring without maintenance (several years of service before battery replacement).

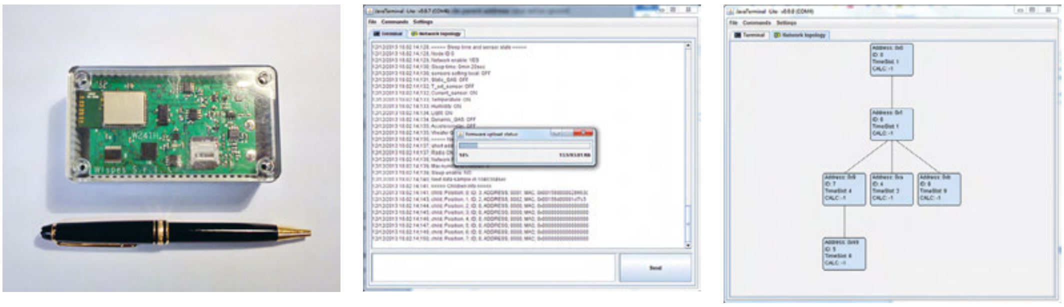
The refurbishment work on the Palazzina was undertaken from January 2011 until January 2012, allowing the building environment conditions to be monitored before, during and after intervention in the time frame of the 3ENCULT project. There are now offices and meeting rooms inside the building that are used almost every day.

The WSN monitoring of the Palazzina had a twofold target. The first target was to test the new 3ENCULT WSN in a real situation. The second one was to collect distributed environment data before, during and after intervention in order to find out about any environment conditions that might be critical for cultural heritage objects and to analyse how it is possible to raise the human comfort levels in accordance with the preservation laws. The analysis of the data collected makes it possible to define and test algorithms and procedures for improved management of the HVAC system, while still respecting the cultural heritage and human comfort issues. For instance, it is possible to implement improved air conditioning in order to reduce strong humidity fluctuations that can damage cultural goods. Moreover, the 3ENCULT WSN can be connected with the control system of the HVAC to apply realtime management algorithms.

System: The 3ENCULT project developed a new Wireless Sensor Network designed for cultural heritage buildings: a network of small electronic boxes capable of collecting environmental data and sending them via radio. The system is called 3ENCULT WSN, it is based upon the Wispes Srl W24TH motes and firmware and can be obtained from the University of Bologna.

Hardware: The Wispes W24TH mote was chosen as a hardware platform due to its high computational power, the ultra-low power capability (8μA), SD card reader, and several environment sensors on board. In particular, the W24TH has a 32bit 32Mhz microcontroller, 128Kbyte of RAM, battery recharger, 802.15.4 radio transceiver, accelerometer, temperature sensor, humidity sensor, light intensity sensor, gas sensor connector, and expansion connector. Everything is enclosed in a 98×54×29 mm box and powered by two AA batteries (see Fig. 3.11, left).

Fig. 3.11: Wispes W24TH mote (left), Java Terminal application (centre and right)



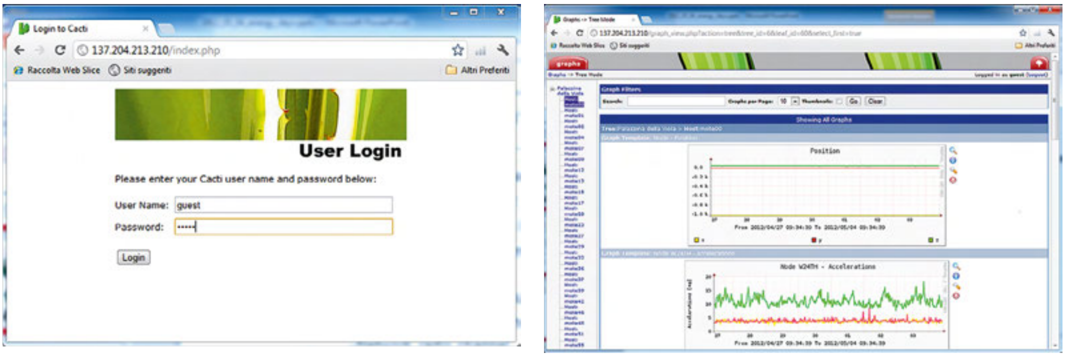
Sensor Specifics:

- → Temperature: 14bit codification, 0.01°C resolution, ±0.3 accuracy, -40 to 125°C operative range.
- → Humidity: 12bit codification, 0.04% RH resolution, ±2% RH accuracy, 0 to 100% RH operative range.
- → Ambient light sensor: 0.23 to 100,000 lux operative range, ±15% accuracy.

3ENCULT WSN software: the software has been designed to completely satisfy the specifications required to monitor a heritage building, such as ease of installation, long monitoring period, low maintenance, remote control, remote maintenance, remote setting, remote software update, high data collection reliability, system compatibility, large network support, and long battery life. It is able to manage the entire network, from its installation and configuration to the data collection and visualisation.

With a Java terminal application (see Fig. 3.11, centre and right), which is able to run on several platforms like PC, tablet, PC board and smartphone, the user can install, configure and send data to a remote database or web server. The data collection and visualisation is made from a web server using the 'Cacti' interface (see Fig. 3.12).[1]

1 The reader can view the data from the url http:137.204.213.210 (user: guest, password: guest)



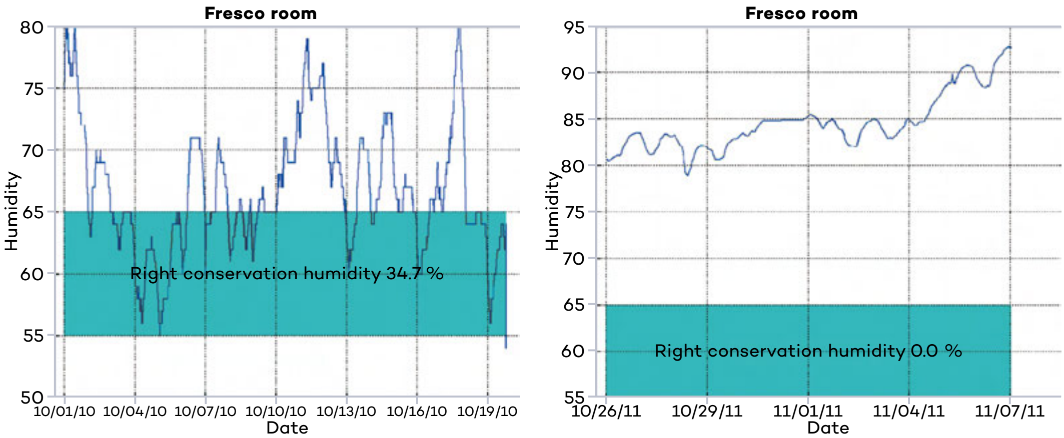


Fig. 3.12: Web visualisation interface

Fig. 3.13: Data of relative humidity collected in the main hall, before (left) and during refurbishment (right)

Employment: The 3ENCULT WSN was employed in the Palazzina della Viola before, during and after refurbishment (see Section 4.1). This report contains, for example, some results specifying air relative humidity data, collected before and during interventions in the large fresco hall on the first floor (see Fig. 3.13). According to the results, at that time the humidity levels were mostly higher than the required conservation threshold due to the climate in Bologna.

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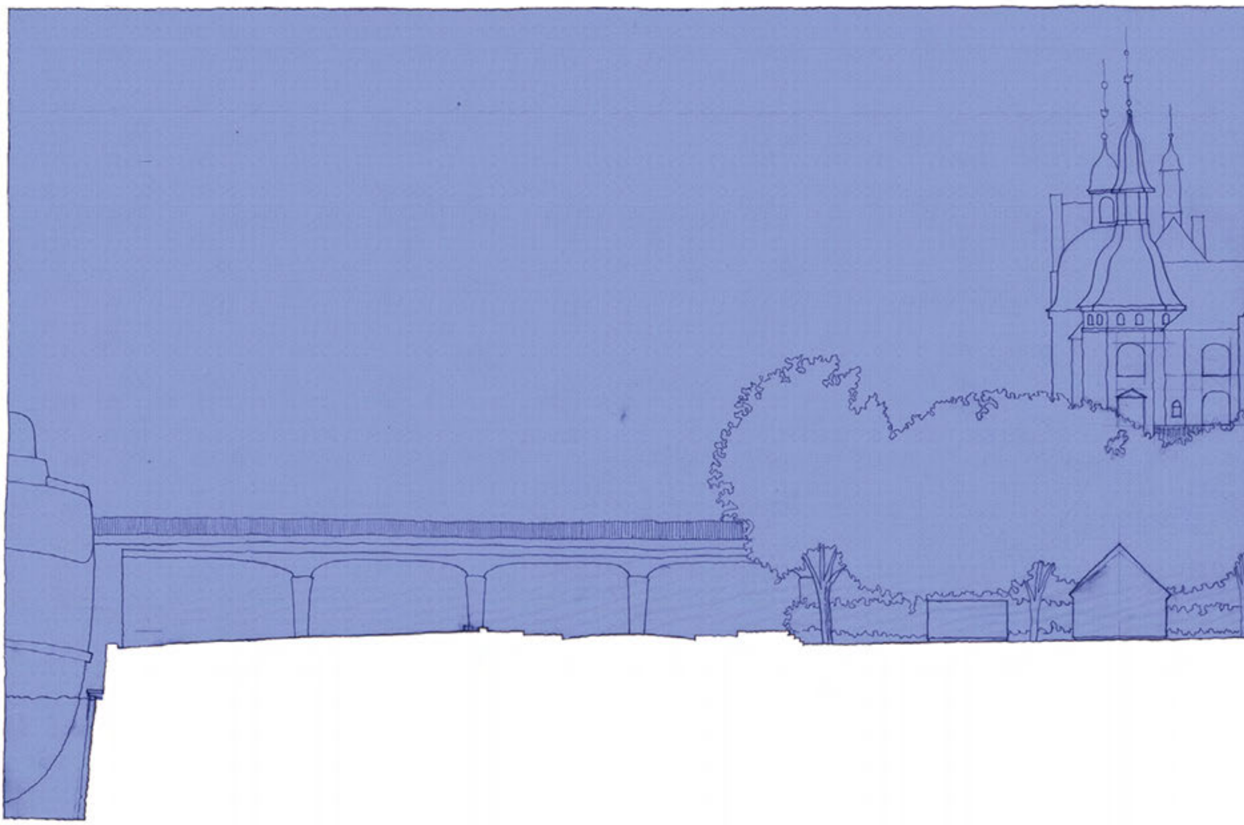
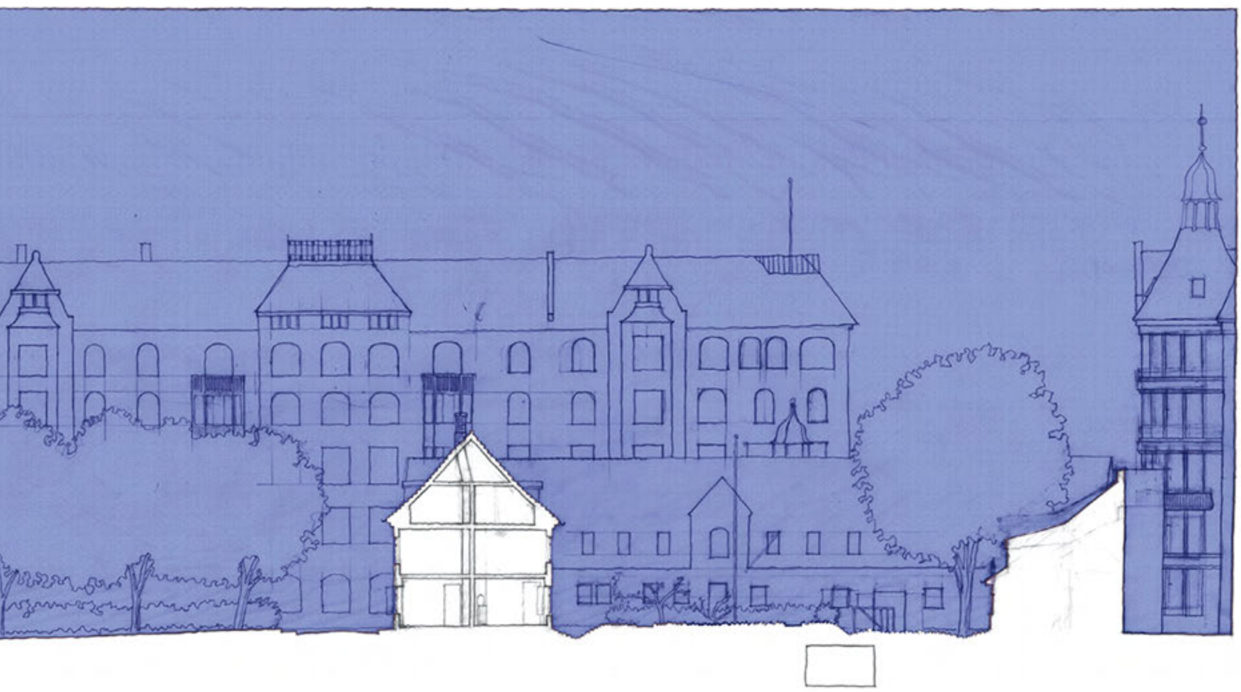
Name	The Material Court of the Fortress
Location	Frederiksholms Kanal 30, 1220 Copenhagen K, Denmark
Date of construction	1768
Architectural style(s)	Neoclassical
Construction type / materials	Brick house
Original building use	Warehouse
Current building use	Office
Main interventions	New coated glass in the inside frames; increased building airtightness; cooling and heating with fan coils; decentralised hot water production; Building Management System (BMS) control of lighting, heating and cooling systems; floor insulation
Heating demand / consumption before intervention [kWh/m²a]	151 (calculated value)
Heating demand / consumption after intervention [kWh/m²a]	130 (measured value)



CASE STUDY 4

THE MATERIAL COURT OF THE FORTRESS, COPENHAGEN, DENMARK

Christoffer Pilgaard, Torben Dahl, Ola Wedebrunn, The Royal Danish Academy of Fine Arts



Building history

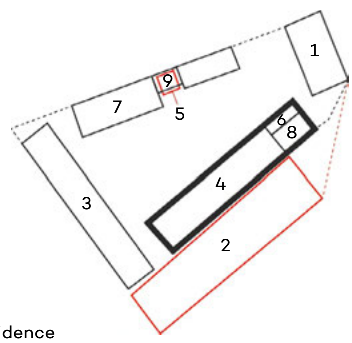
The Material Court of the Fortress is an ambitious restoration project, aiming at reducing the building's energy consumption and CO_2 emissions without violating the heritage value of the buildings. The restoration was done by teaming up different building advisors. Together they developed a process plan which made it possible for everyone to provide input from their respective professions; building physics, heritage value, architecture, energy consumption, and CO_2 emissions. The private foundation Realdania Byg has owned the building since 2007 (see Fig. 4.1).

Fig. 4.1: Material Court of the Fortress

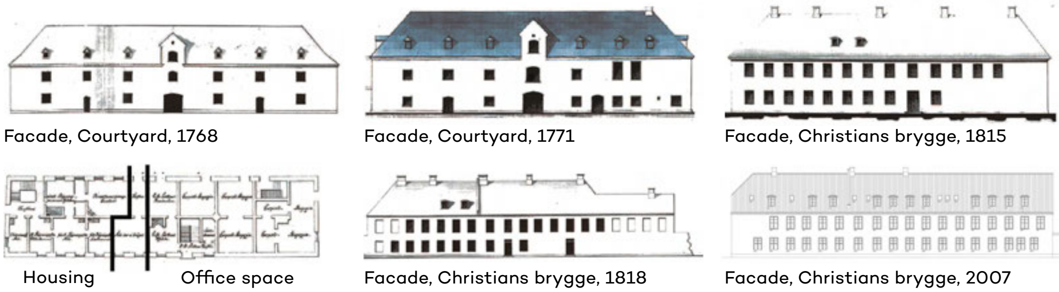
The Material Court of the Fortress consists of four very different buildings. The one analysed in the 3ENCULT project is building four, including the additions six and eight. Building four was built in 1768 to replace an earlier warehouse from 1683 that was demolished to make space for the King's Brewery. The new brick warehouse (building four) was built in neoclassical style with two floors, a hipped roof, and with a hoist centred on the facade to the courtyard. In the original building there were niches in the masonry to save bricks. This construction has kept the building relatively uniform as it has dictated the position of future windows. Today, the chimneys in the building are not in use. There has been district heating in the house since the 1940s (see Figs. 4.2–4.4).

Fig. 4.2: Material Court of the Fortress, building context

Fig. 4.3: Diagram, The Material Court of the Fortress



1 Keeper's residence
2 Site of former warehouse
3 Warehouse
4 Warehouse
5 Site of former lime pit
6 Extension
7 Warehouse
8 Extension
9 Middle building



Facade, Courtyard, 1768 | Facade, Courtyard, 1771 | Facade, Christians brygge, 1815

Housing | Office space | Facade, Christians brygge, 1818 | Facade, Christians brygge, 2007

Fig. 4.4: Building history

Pre-intervention analysis

Process

Using an advisory team to perform a multidisciplinary analysis influenced the processes of 3ENCULT. The multidisciplinary process was used as part of the 3ENCULT methodology (see Section 4.1.) and is a fundamental approach to projects combining cultural heritage and energy consumption.

Conservation / culture assessment

Context value

The Material Court of the Fortress was built in the Frederiksholm area, an artificial islet constructed around 1670 in order to strengthen the fortifications of Copenhagen. Frederiksholm appears on maps ninety years after its completion. Between the streets there are five construction areas. The Material Court of the Fortress and the Civil Service Materials Court together make up the area furthest to the southwest. In this area the plot ratio was made smaller compared to the other areas in order to make space for storing materials. The Material Court of the Fortress still has the same courtyard today. It is unique in its context regarding density and is an oasis in a modern city of high density.

Cultural value

The Material Court had been placed by Nyboder, near the citadel, but the new location by the western rampart was handy for future extensions against Amager, the island east of Copenhagen. Hence, the Material Court has played an important role in the history of Copenhagen and its value as part of the city´s fortifications is high. The Danish King Frederik III initiated the plan for the area south-east of Slotsholmen Frederiksholm. Henrik Rüse, a Dutch fortress engineer and architect, came to Denmark in 1661 to help with the fortress expansions. The plan for Frederiksholm included 224 rectangular sites and was influenced by the Dutch style with deep gabled houses and courtyards. In the final plan there were only eighty sites.

Architectural value
The facade is plastered and minimally decorated with only a simple cornice. The building is ochre yellow while the cornice and window frames are white. The roof surface is covered by red tiles. Towards Christians Brygge the building has green painted shutters on the ground floor. Due to the building's construction based on the recesses the facade has a defined pattern. However, on the roof the pattern is not followed by the dormers. This reveals the building's historical development. Details inside the building such as panelled doors, brass door handles, panelled windows, wall bases, stucco, and old locking mechanisms in the windows have architectural value as they have relation to and coherence with their context.

Energy assessment

Consumption before interventions
Until 2007, the building was owned by the Danish Ministry of Defence. The Ministry was very thorough in logging its consumption of electricity, water, and heating, and there were accurate consumption data on the building from 1995 to 2007 from energy bills. The annual consumption during that period was
→ Heat: 97.09 MWh, 83.8 kWh/m²
→ Electric equipment: 71.65 MWh, 61.8 kWh/m²
→ Electric lighting: 25.20 MWh, 21.7 kWh/m²

These data were relevant for an analysis of the effects of the following interventions, but the data were also used for the simulation models.

Simulation tools
To simulate the building energy consumption, different software programmes were used such as the BuildDesk Energy Program (Be06), a simulation tool for the building's energy consumption, including heating, hot water, cooling, ventilation, and electric light. In the multidisciplinary process described below (see p. 272), the Building Simulation (BSIM) software was used to simulate the thermal indoor climate and natural ventilation. Later in the process the Passive House Planning Package (PHPP) programme was used, which analyses similar parameters as Be06, but with a greater level of detail. This simulation is done in order to obtain a more precise theoretical analysis of the energy consumption before and after the restoration job, and also to make a broad analysis of all the case studies in 3ENCULT.

Airtightness
A blower door test was made to investigate the building's airtightness. This was done by creating a pressure in the building of 50 Pa,

Fig. 4.5: Blower door test

Fig. 4.6: Thermographic photography

corresponding to a wind speed of 10 m/s. Further investigations of airtightness were done in the areas where there was reason to suspect leakage or low U-value of the external wall by using thermography. The study concluded that there were leaks by the windows and in the attic (see Figs. 4.5 and 4.6).

Description and evaluation of interventions

Design process

The objective of the project was to effect a restoration with interventions that focused on reducing the building's energy consumption. A multidisciplinary approach was used with advisors from different fields; building physics, heritage value, architecture, energy consumption, and CO_2 emissions. To make the process more efficient the different partners in the group had to focus on themes related to their profession:

→ Building owner: Impact on rental opportunities;
→ Heritage authority: Conservation perspective;
→ Architects: Shapes, appearance, functionality, and interior design conditions;
→ Structural engineer: Impact on existing construction and risk assessment;
→ Services engineer: Energy consumption, CO_2 emissions, and indoor climate.

This process is described in more detail on the following pages.

Interventions

Interventions decided by using the multidisciplinary process were included in the detail of the project. A description of each intervention is listed below.

Fig. 4.7: New coated glass, inside frame

New coated glass in the inside frames

The windows already had double glazing from an earlier renovation, therefore there was not much to gain in relation to the building's windows. In any case, it was not an option to replace the windows with new ones because of historic and architectural qualities of the old ones. BSIM calculations showed that coating the double glazing would have a positive impact on the building's energy consumption (see Fig. 4.7).

Increased building airtightness

Gaskets were attached on the inside window frame, and a new vapour barrier was placed in the space under the eaves in the attic. These changes were done based on results from the blower door test.

Fig. 4.8: Natural ventilation from windows

Natural ventilation by opening windows

It was not an option to have visible ventilation or suspended ceilings because of the building's heritage values. Since the rooms in the building are relatively small, natural ventilation was an option and a comfortable way to have individual control in each office room (see Fig. 4.8).

Cooling and heating with fan coils

A goal of the restoration was to achieve an indoor climate at Level C, DS 1752, which is the lowest accepted rating in Danish legislation. That means an indoor temperature during the summer season at 24.5°C plus / minus 2.5°C. BSIM calculations of different rooms indicated occurrences of indoor temperatures above 27°C, making cooling necessary. The combined fan coils for both heating and cooling were encased in specially made wood panels to fit the existing house (see Figs. 4.9 – 4.11).

Fig. 4.9: Cooling and heating by convectors

Decentralised hot water production

Decentralised hot water containers were considered more efficient, whereas in a centralised system the hot water pipes would be long and heat loss would occur.

BMS control of lighting, heating and cooling systems

The electricity for the BMS system runs through cables under the floor. A critical point is that it is hard to get to the cables if repair work is needed.

Fig. 4.10: New piping and cables under the floor

Floor insulation

Since the wooden floor had to be replaced on the ground floor, it was convenient to insulate the new flooring.

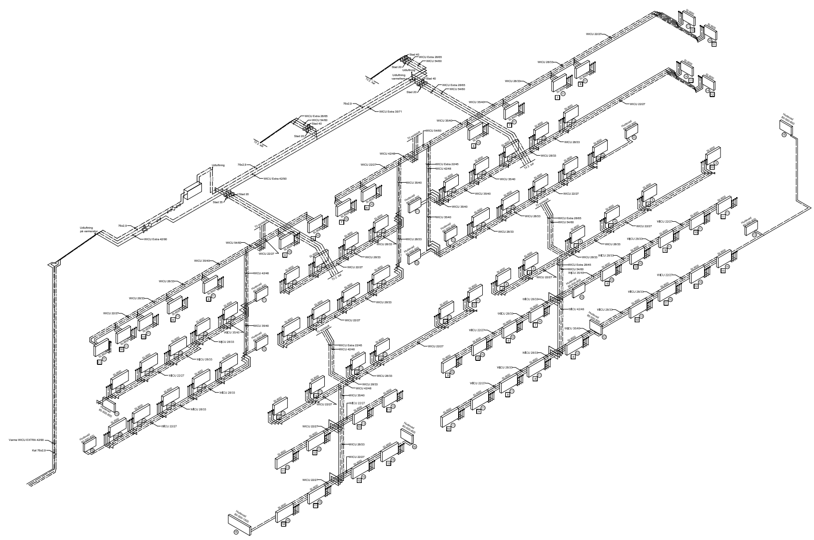


Fig. 4.11: Isometric drawing of fan coil pipelines

Post-intervention analysis

The interventions selected in the multidisciplinary process improved heat loss, with a CO_2 saving of 26.08%, but had a negative effect as consumption of electric lighting and cooling was increased respectively to 3.74% and 21.88%. Cooling was needed to achieve better indoor climate. The total CO_2 savings are expected to be 4.29%. Copenhagen Energy supplies district heating in the form of steam, where one ton of CO_2 corresponds to 6.8 MWh. Dong Energy supplies electricity, where one ton of CO_2 corresponds to 1.9 MWh. That is how the energy consumption is converted to CO_2. A post-intervention PHPP calculation shows savings at a specific space heating demand of 14%.

Consumption after implementations, and readings

Due to limited time and facilities for monitoring post-intervention consumption the results are few and insufficient, but so far these measurements confirm the simulated data:

→ Reading 21.12.12: 44.30 MWh;
→ Reading 15.3.13: 121.19 MWh;
→ Consumption from January, February and March due to the readings: 77 MWh;
→ Calculation with degree days: 153 MWh (77 MWh*2906/1465 = 153 MWh);
→ Degree days for a standard year in Denmark are 2906. Degree days for January, February and March are 1465.

This gives a heat consumption at approx. 132 kWh/m².

Focus: multidisciplinary process, balance of culture and energy

A multidisciplinary approach was adopted in the restoration of the Material Court of the Fortress.

Initially the service engineer made a total list of all possible interventions: windows and shading, insulation and building airtightness, ventilation, heating and cooling, electricity, solar thermal panels and photovoltaics, as well as behavioural changes.

First workgroup meeting: rough sorting of total list

At the first workgroup meeting, the advisors reviewed the service engineer's list. From the perspective of their professions, they commented on each individual intervention. This was reported in an evaluation form which each advisor completed.

The heritage agency in particular did not accept many of the interventions, because of the building's cultural heritage value. Interventions like replacement of windows, installing sun collectors, and photovoltaics were not accepted.

Second workgroup meeting: multidisciplinary analysis

The service engineer made a computer model of the building based on its geometry, orientation, materials, and existing energy use. This model was used in the multidisciplinary process to establish the energy savings of each intervention.

Each intervention that passed the first group meeting was individually inserted into the computer model to observe its energy effect. For each intervention an element card was made. The data was presented to the multidisciplinary team in the second workgroup meeting (see Fig. 4.12).

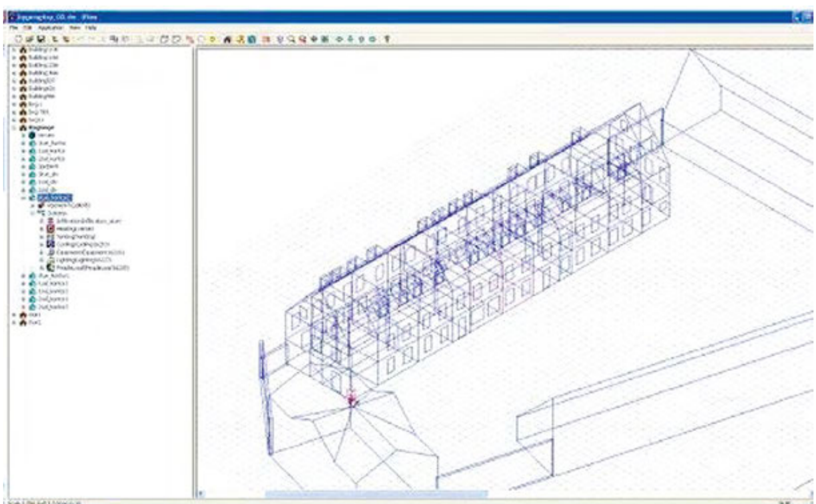


Fig. 4.12: BSIM computer model

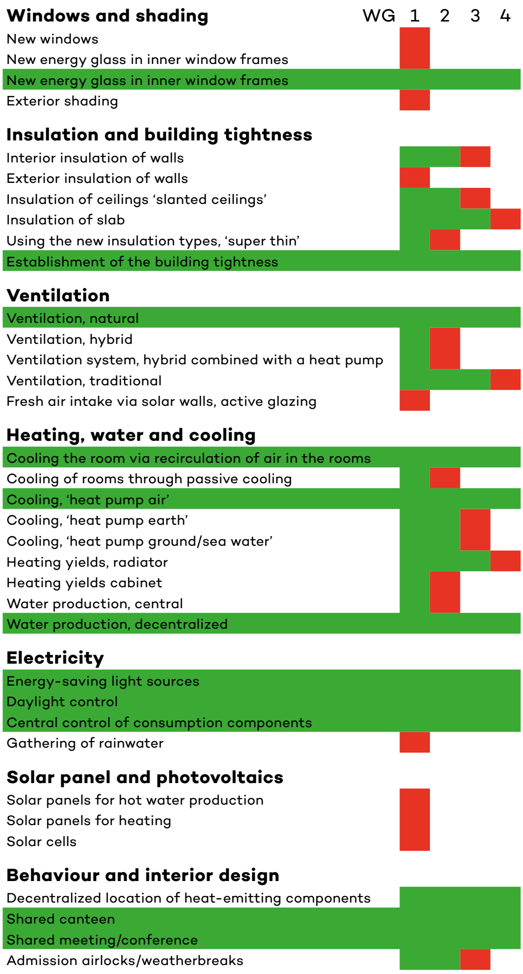


Fig. 4.13: Total list

Third workgroup meeting: directional selection

The different interventions had an impact on the building's energy consumption and CO_2 emissions, and also on the building's indoor climate. This aspect was included in the simulation. It was decided that the indoor climate should adhere to Level C, DS 1752 (European indoor air quality standard EN15251). The building's room temperature was added to each element card.

Fourth workgroup meeting: review and amendment

Finally a joint simulation was performed, including all the selected interventions. A review of the model, including the total CO_2 savings, energy conservation and indoor air impacts was presented to the workgroup (see Fig. 4.13). The combination of cultural heritage and sustainability affects different professions; restoration consultants such as conservators, architects and structural engineers, and for energy projects, service engineers and electrical engineers. A multidisciplinary approach is essential as the two fields relate to many of the same building elements, but from fundamentally different perspectives. A service engineer would, for example, want to insulate the inside of a wall, but this would be unthinkable from a conservator's viewpoint if the wall surface was of special cultural heritage quality. The Material Court of the Fortress demonstrates how such a multidisciplinary process takes place – a process in which the different aspects are balanced.

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Varming Varming, Jens Christian, *Fæstningens Materialgård,* Realdania Byg, Copenhagen, 2008.

Name	Hötting Secondary School, Innsbruck
Location	Fürstenweg 13, 6020 Innsbruck, Austria
Date of construction	1930
Architectural style(s)	Early modernism
Construction type / materials	Mixed structure - brickwork 58%, rammed concrete 42%, reinforced concrete less than 1%
Original building use	State school
Current building use	State school
Main interventions	→ New ventilation concept: active overflow ventilation with central heat recovery unit → Two different solutions for minimal invasive internal insulation (capillary-active materials) → Enhanced daylight autonomy by daylight redirection → New artificial lighting: highly efficient LED luminaires and innovative control → Optimisation of heating control → Improvement of the room acoustics without reduction of the usable thermal capacity
Heating demand / consumption before intervention [kWh/m²a]	Measured heating consumption before refurbishment is 130 kWh/(m²a). Calculated heating demand before refurbishment is 129.34 kWh/(m²a).
Heating demand / consumption after intervention [kWh/m²a]	Calculated heating demand after refurbishment is 38.49 kWh/(m²a).
Other noteworthy characteristics	Area/Volume: 1,790 m² / 19,180 m³ Classrooms: 65 m² / 225 m³ Window area per classroom: 16 m² Gymnasium 12×25 m

CASE STUDY 5

HÖTTING SECONDARY SCHOOL, INNSBRUCK, AUSTRIA

Rainer Pfluger, University of Innsbruck

Building history and general description

In 1928 the municipalities of Hötting and Innsbruck announced an architectural competition for the planned new school building. The architects Franz Baumann and Theodor Prachensky won it with a design that was strongly influenced by the architecture of Peter Behrens and the Bauhaus.

The building complex is outstanding on account of its treatment of space and for construction details typical of its period. This led to it being declared a historic monument in 2008 under Section 2 of the Austrian monument protection act [DMSG].

The original design concept strictly follows the principles of functional architecture. Well-proportioned volumes with a horizontal emphasis on the north-western part of the plot rise towards a slightly offset tower at the north-western corner. This forms a landmark in the street, announcing the entrance and marking the most important section of the building. This part of the building contains the entrance hall and main staircase, the offices on the first floor, and the biggest classrooms, which are used for major school events.


Fig. 5.1: Hötting Secondary School, Innsbruck

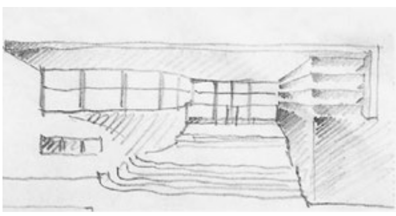
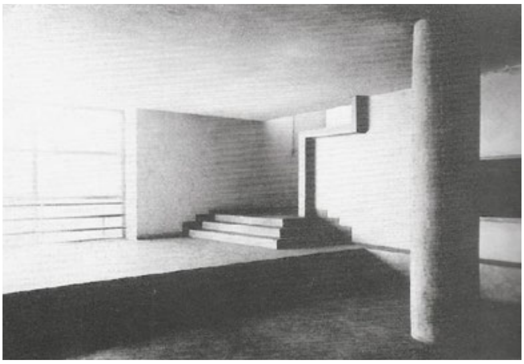



Fig. 5.2: Sketch by Franz Baumann (left) and photo (right) of the main entrance


Fig. 5.3: View from Furstenweg (left: as built in 1931, right: status quo in Jan. 2011). In the years following WW2, the school was enlarged on the eastern side.



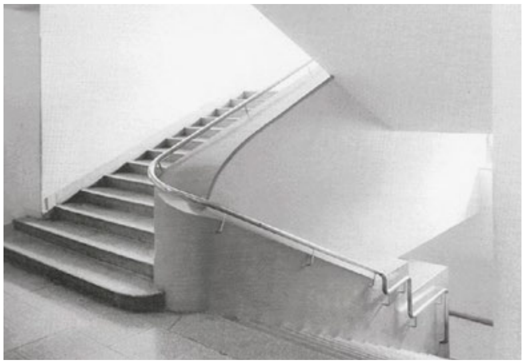


Fig. 5.4: Entrance hall and main staircase

The architects intended to enclose the schoolyard with two nearly rectangular wings to the northwest and northeast and a smaller, one-storey gym building to the southwest. The schoolyard is open to the recreation area in the south alongside the River Inn. The views out are arranged so as to frame landmarks such as the mountain ranges of the Nordkette (visible from the entrance and the classrooms in the northwest) and the Patscherkofel, while the river Inn can be seen from the hall and main stairway. This strong interaction between the buildings and the surrounding landscape is characteristic of early modern architecture in Tyrol.

All of the classrooms are open to the outside with horizontal window strips that let light and air into the classrooms. The central hallways with classrooms on both sides were also quite innovative at the time.

The architectural composition is rather stringent and pragmatic, an impression that is matched by the surviving original colours and surfaces (exterior: pedestal and gym walls in bush-hammered concrete; walls and ceiling in light grey; wooden furniture; white-painted window frames). Together they create a restrained, slightly cool, but relaxing and open atmosphere for pupils and teachers. Owing to the economic crisis in 1928, only the main wing on the north-western side, along Fürstenweg, and the gym to the south-west were built – between 1929 and 1932.

Fig. 5.5: Rural environment (school at left of photo), viewed from south-east and site plan

Pre-intervention analysis

The first stage of work on the case study was an intensive analysis of the current state of the building, from the points of view of preservation, architecture and building physics. In addition, the thermal comfort inside the classrooms was measured according to ISO 7730 and the indoor air quality was evaluated in terms of CO_2 concentration.

The acoustics (reverberation time) and visual comfort (daylight coefficient and artificial light distribution) were measured as well. Figure 5.6 shows a luminance measurement of a classroom before intervention, with poor artificial lighting (on two-thirds of the desks only 150 lux were measured, see also [Pfluger, 2011]).

Fig. 5.6: Luminance measurement in the classroom in artificial light (left) and blower door measurement (right)

A blower-door test was performed in order to quantify the overall air leakage rate, as well as to detect the most important leaks. The result of the pressurisation test was an n_{50}-value (air change rate at 50 Pa) of 4.8 1/h (+/- 20%) for the school building and 2.8 1/h (+/- 9%) for the gym. In order to see the influence of leakage at the original windows, the blower-door was mounted in a classroom: the result was n_{50}= 5.8 1/h (+/- 6%).

About 40% of the building's overall heat transmission pass through the exterior walls.

The energy balance calculations with PHPP, together with measurements and analyses of building details, provided a good overview of the major energy consumption categories.

IRT diagnosis helped to find energy-efficient solutions for all of the interventions, while giving high priority to their compatibility with conservation requirements (see also [Franzen, 2011]).

Description and evaluation of interventions

The main issue in the discussions between the owner, the architect and the cultural heritage authorities was the appearance of the restored school building. Any restoration plan would have to find the right balance between adaption to the needs of an up-to-date

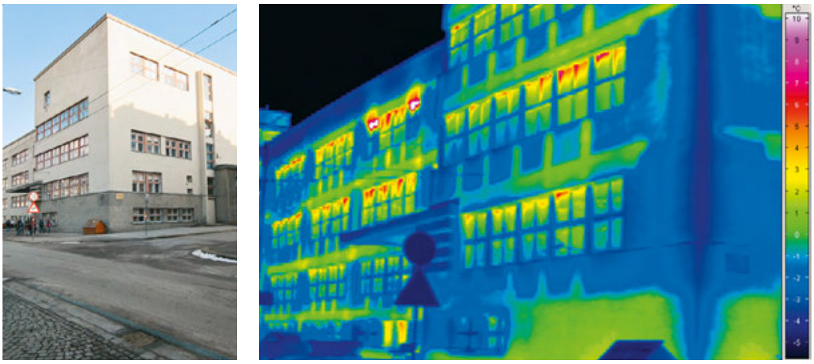


Fig. 5.7: View from west (left). The IR images were taken at night (31 Jan 2011) at an ambient temperature of around −5°C. All of the rooms were heated to an indoor air temperature of around 25°C.

school on the one hand, and preserving the specific atmosphere and characteristics of a building of the 1930s on the other.

In the framework of 3ENCULT, different intervention options were discussed with the Austrian Authority for Cultural Heritage, the building owner, and the architect. The main focus here was on preserving the building and improving its energy efficiency. For the user, the major advantages of the proposed measures were the improvement of thermal comfort and air quality and the enhancement of lighting, shading and acoustics.

Figure 5.8 shows the annual heat demand of different combinations of measures and interventions and the corresponding possible reductions of energy consumption [Sevela, 2014].

A maximum possible saving of 74% in annual room heating demand can be achieved by combining all measures.

This evaluation demonstrates that the biggest reduction can be achieved by insulating the walls and improving the airtightness. A heat-recovery ventilation system is necessary for better indoor air quality, thermal comfort and moisture control.

All of the interventions described hereafter were carried out as prototypes and tested in two classrooms, as shown in Figure 5.9 and Figure 5.12.

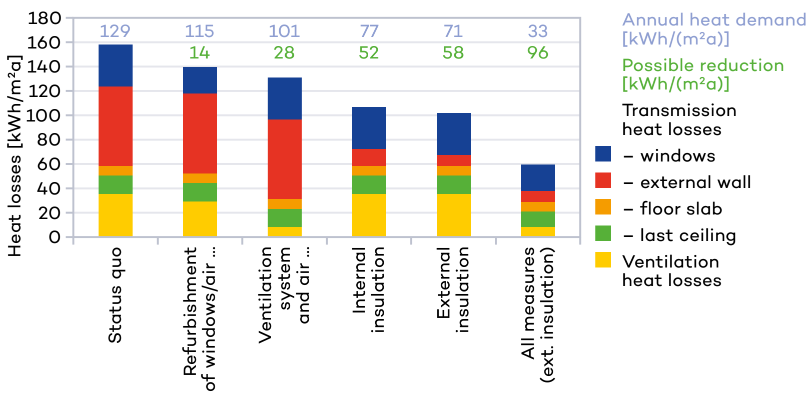


Fig. 5.8: Annual heat demand and possible reductions for different combinations of interventions

Classroom 1

→ Wall insulation: capillary-active internal insulation (Remmers iQ-Therm);
→ Original windows enhanced with low-e glazing and sealing lips;
→ Shading and daylight-redirection lamellae integrated in box-type windows;
→ Artificial lighting using LED technology with variable colour temperature and automatic dimming;
→ Sound absorber made from organic fibre;
→ Ventilation air distribution via laser-perforated textile diffuser.

Fig. 5.9: Prototype measures in classroom 1

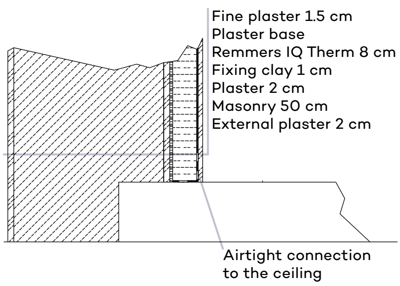


Fig. 5.10: PU-foam insulation (thermal conductivity 0.033 W/mK) with integrated silicate wicks and vapour-permeable plaster affixed to the wall with capillary-active clay (for reversibility)

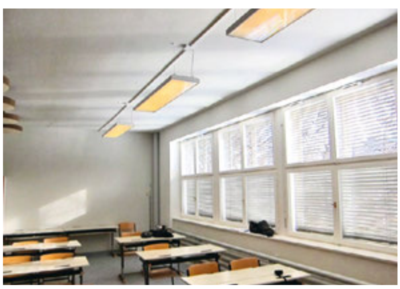


Fig. 5.11: Daylight redirection to the ceiling by the upper part of the blinds and sun-blocking by the lower part help to enhance daylight autonomy without glare problems

Classroom 2

→ Wall insulation: internal insulation with cellulose fibre;
→ Original windows restored and painted;
→ Shading by textile screens integrated in box-type windows;
→ Artificial light from highly efficient fluorescent lamps with glare suppression;
→ Sound absorber with integrated artificial light;
→ Ventilation air distribution through homogeneously perforated textile diffuser.

Fig. 5.12: Prototype measures in classroom 2

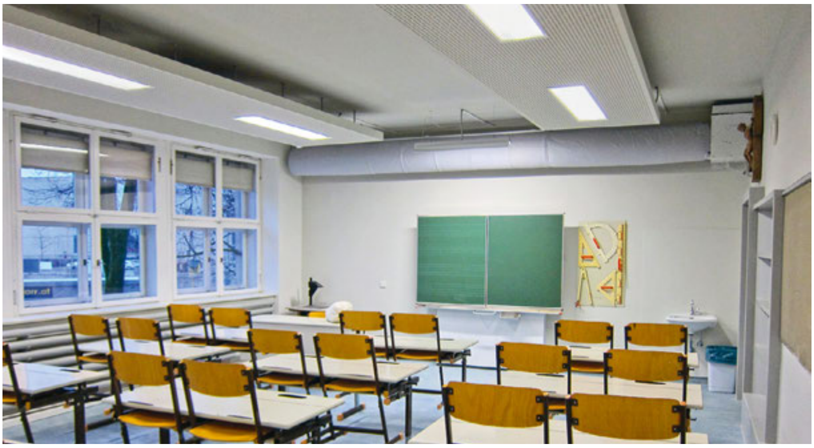


Fig. 5.13: Interior insulation with cellulose fibre (thermal conductivity 0.04 W/mK) and clay boards with clay finishing

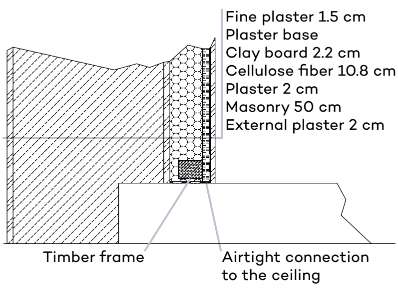


Fig. 5.14: Silencer and fan-box prototype manufactured by ATREA

Focus: Active overflow ventilation – testing the concept in a listed school building

The active overflow principle enables the building to be vented with a minimum of ductwork. The supply air from the heat recovery system in the roof space in the attic flows via the staircase and the corridors to the classrooms. The extract air is ducted from the toilets and changing rooms back to the counter-flow heat exchanger to preheat the ambient air. The control strategy is very simple and cost-effective: if the CO_2 concentration in the corridor rises, the air flow rate of the central fan in the heat recovery unit rises in order to keep the CO_2 level constant at around 600 ppm. The active overflow fans of the classrooms start operation one hour before the start of the lessons. They are switched off by presence-detector sensors.

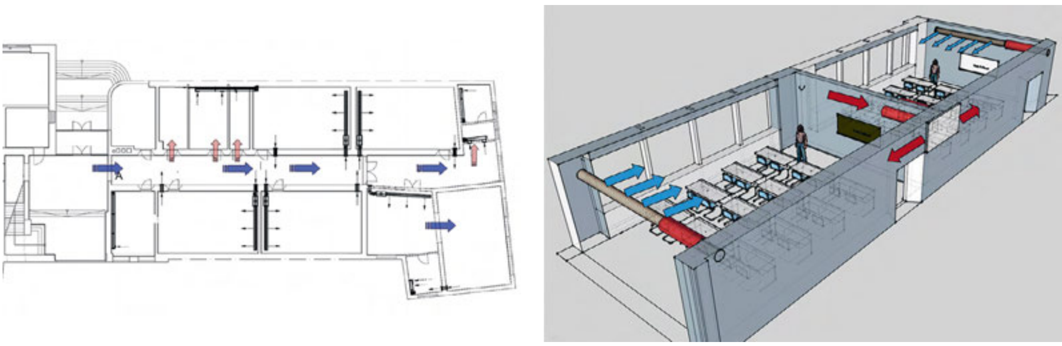


Fig. 5.15: Active overflow principle (supply air from corridor is distributed to the classrooms, extract air is vented back to the corridor via silencers)

Conclusion

A new type of ventilation system for historic school buildings, based on the active overflow principle, was analysed via measurements on prototypes installed in two classrooms, as well as by dynamic simulation. The ventilation efficiency of an active overflow system is lower in comparison to cascade ventilation, because the supply air and extract air mix in the corridor. The electrical efficiency is higher, however, and the control mechanism for the central fans and the active overflow fans is rather simple and effective. From the viewpoints of architecture and preservation, the active overflow system is preferable, because the ductwork is kept to a minimum [Längle, 2013].

Fig. 5.16: Mounting of the fan box (left), the textile diffuser (middle) and the overflow silencer (right)

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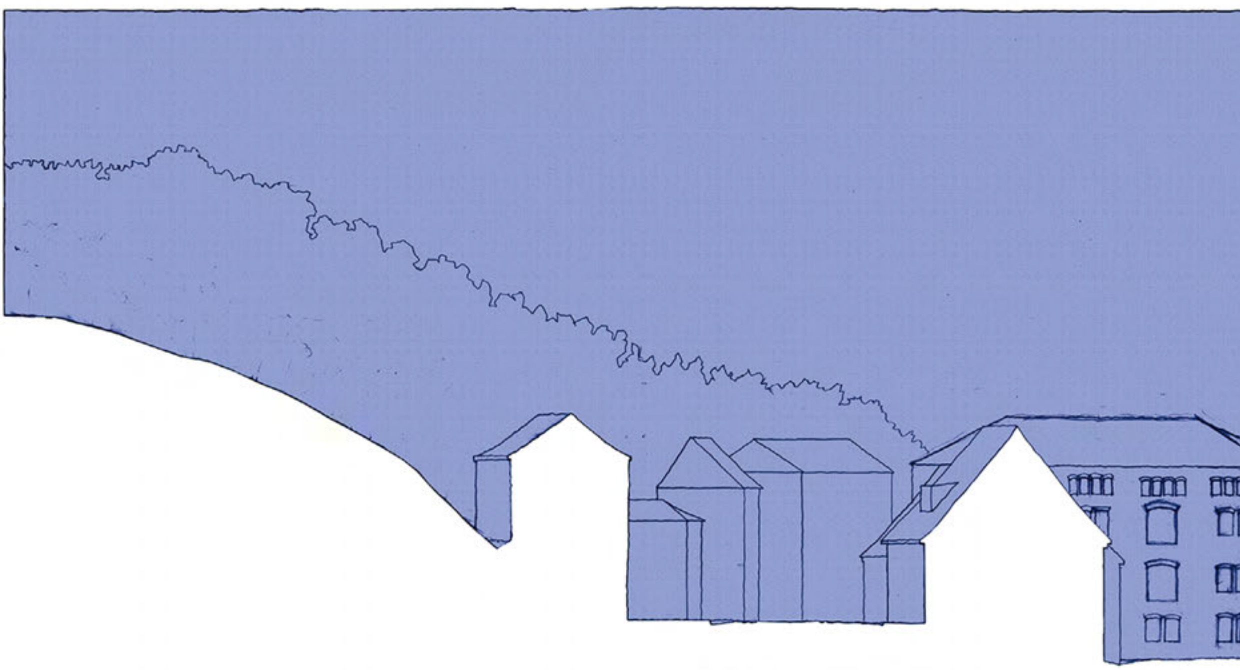
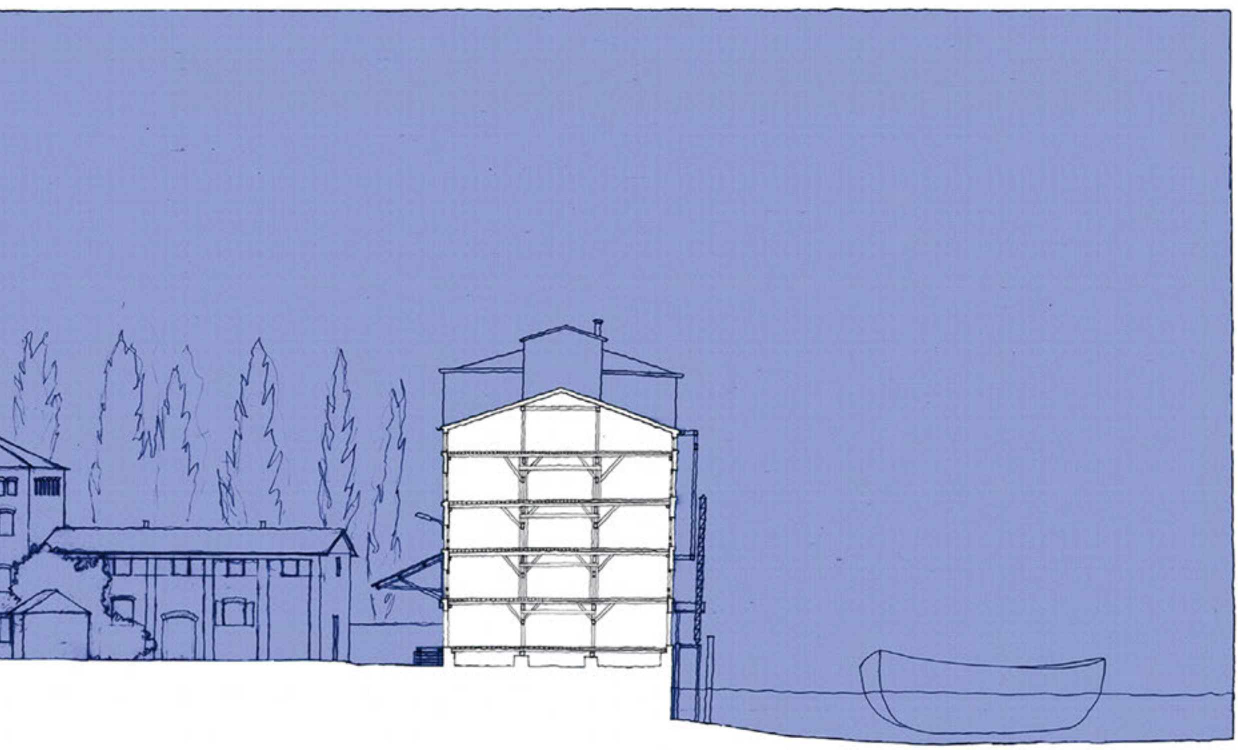
NAME	WAREHOUSE CITY BUILDING	WILHELMINIAN VILLA	BAROQUE BUILDING	RENAISSANCE BUILDING
Location	Potsdam, Germany	Dresden, Germany	Görlitz, Germany	Freiberg, Germany
Date of construction	1834	1890	1714	1518
Architectural style	Neoclassical	Wilhelminian	Baroque	Renaissance
Construction type / materials	timber frame	masonry natural stone	masonry natural stone	masonry brick
Original building use	storage	residential	residential	residential
Current building use	residential	residential	residential	residential
Main interventions	interior insulation loam-cork	interior insulation iQ-Therm	interior insulation TecTem	interior insulation calcium silicate
Heating demand before intervention [kWh/m²a]	approx. 380 kWh/m²a	approx. 400 kWh/m²a	approx. 180 kWh/m²a	approx. 400 kWh/m²a
Heating demand after intervention [kWh/m²a]	approx. 80 kWh/m²a	approx. 90 kWh/m²a	approx. 20 kWh/m²a	approx. 20 kWh/m²a



CASE STUDY 6

WAREHOUSE CITY AND OTHERS, GERMANY

Rudolf Plagge, Ayman Bishara, Christian Conrad, Dresden University of Technology



Case Study 6 covers four different kinds of historic building structure and eras, as well as architectural styles. The neoclassical Warehouse City of Potsdam from 1834, a Wilhelminian villa in Dresden from 1890, a Baroque building in Görlitz from 1714 and a Renaissance building in Freiberg, constructed in 1518, are the test buildings. Within Case Study 6, the main focus is on the analysis and evaluation of four different capillary-active interior insulation systems, which are both innovative and already commercially available. These are: Calcium Silicate Climate Board (from Calsitherm), TecTem Insulation Board Indoor (from Knauf Aquapanel), Loam-cork-diatomaceous earth plaster (from Haacke Insulations) and PUR-based iQ-Therm board (from Remmers Baustoffe). (see Section 5.1, p. 122) Below are photos showing their surface appearance.

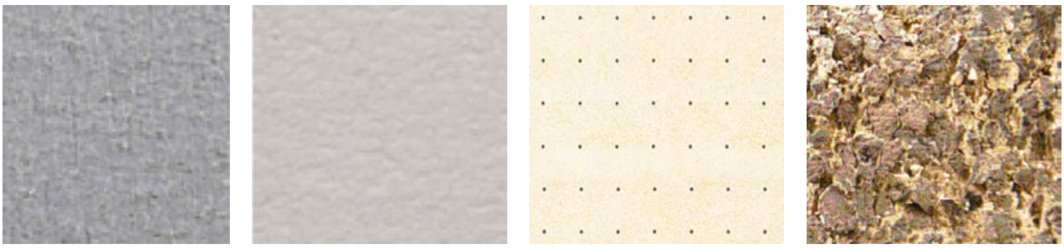


Fig. 6.1: Photos of the tested capillary active interior insulations systems

These four different interior insulation systems were investigated in the buildings of this case study. Beside the respective insulation component, each system comprises specially adapted adhesive mortar and a moisture-regulating plaster finish. These systems are listed in Table 6.1, together with profiles of the respective test buildings.

Warehouse City building

Building history and general description

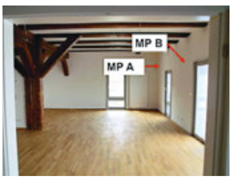
The Warehouse City is located in the centre of Potsdam and was built in 1688. It was used to supply the Prussian army with cereals and other food. It creates the genius loci, which is among the best places along the shore, with prestigious addresses and tradition.

Fig. 6.2: Warehouse City Building in Potsdam, a timber-framed construction, open joints on the outer facade

The pre-intervention diagnosis and analysis includes an assessment of the energy balance, a report on moisture status, an evaluation of the horizontal structural waterproofing and an analysis of construction details: all prerequisites for retrofitting. Since the energy-use has been reduced by 28%, more than is required by law, the focus turns to possible condensation and critical moisture contents in the wood construction and the risk of mould growth. Furthermore an analysis and evaluation of driving rain protection on two of the building's brick facades was done, based on adaptive hydrophobic impregnation. A hygrothermal examination of the construction details was therefore carried out in order to serve as the basis for the selection of an interior insulation system. Figure 6.5 below clearly demonstrates the moisture problem in the interior timber-framed construction and the defective joints in the outer skin.

Monitoring

Two measurement sections were installed in the building in order to evaluate the renovation measures. The first one is located in the west-facing wall, which is heavily exposed to driving rain, and the second one is set up at the corner of a wall to analyse thermal bridge effects and measure possible condensation.



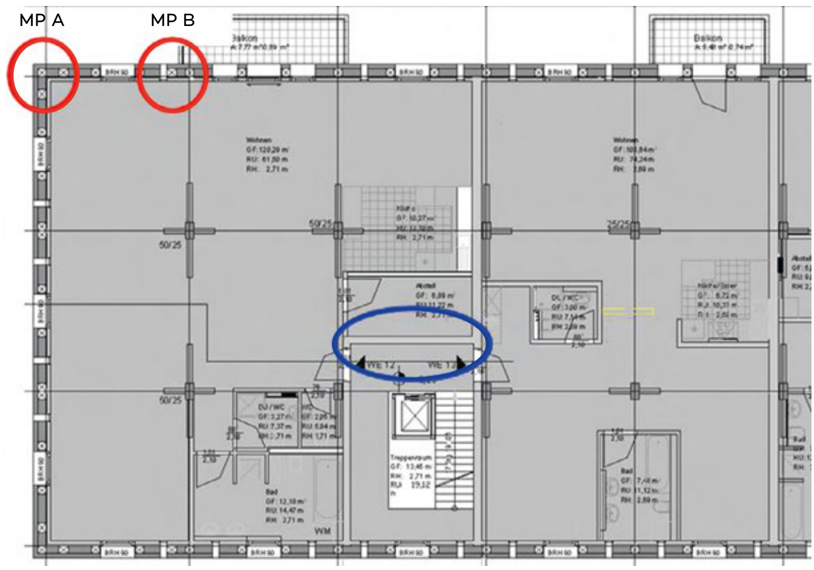


Fig. 6.3: Schinkelspeicher, Potsdam, monitoring system: second floor, location of the test sections and the data logger, measurement points MP A and MP B

Hygrothermal simulation

The following figures clearly demonstrate the hygric situation for both the existing status and the insulated status. Insulated wall structures are relatively dry close to the inner wall surface, but the humidity increases towards the outside. The interior insulation allows less heat loss through the construction, whereby evaporation is reduced. Figure 6.5 demonstrates that the moisture content of the wooden beam along in the western facade is above the

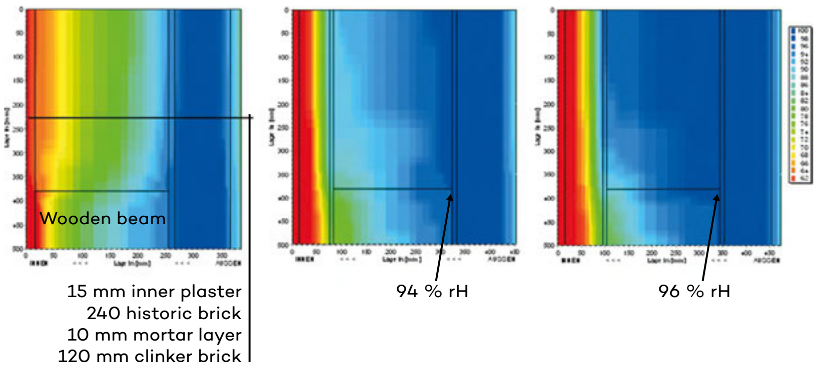


Fig. 6.4: Schinkelspeicher, range of relative humidity at the time of maximum moisture load simulated by DELPHIN with consideration of driving rain load, centre with 60 mm and right with 80 mm loam cork clay insulation

critical limit, whereas the water content of the wooden beam along in the eastern facade is below it. The cause of this difference is the high penetration of the west facade by driving rain. Driving rain enters it through the mortar joints of the masonry (see Fig. 6.5).

Hydrophobic impregnation

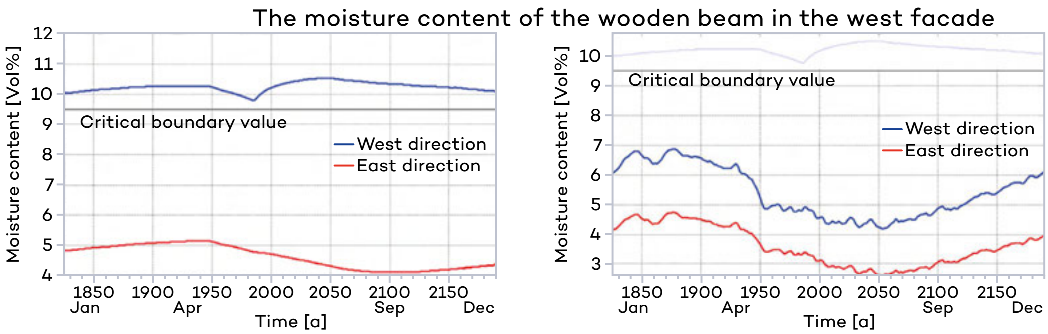


Fig. 6.5 Moisture content of wooden beam, west and east facades, before (left) and after (right) hydrophobic impregnation

before and after hydrophobic impregnation makes clear that driving rain protection can be essential to keep a structure intact. Since the eastern outer wall is exposed to a lower rain load, the hydrophobic impregnation of this wall is not necessary in this case.

Wilhelminian building in Dresden

This listed Wilhelminian-style building in Dresden was most likely built in 1870; it was altered in 1912. In 1980 the first floor and the first and second attic floors were inhabited, as well as part of the basement. The arrangement of rooms suggests that the house was originally designed for one family: it had three grand floors connected by open stairs, service rooms in the basement and servant bedrooms on the attic floors. Traces of this first design were found during the reconstruction work. On the first floor the three rooms

Fig. 6.6: Wilhelminian style building in Dresden, before and after renovation

looking onto the road originally opened into one another through an alignment of double doors.

Pre-intervention analysis

The guidelines for the reconstruction of the building required the original built substance to be preserved and its structural needs to be respected. This meant that the building should continue to be used as a residence. Owing to the large usable floor area (between 120 and 140 m² without stairs) each floor was to be turned into a single apartment. The structure of the house would thereby be retained. This meant rooms of similar size facing the street, plenty of interior doors and a large hallway. The structure of the house allows a more open interior design on the attic floors. The basement was mostly not designed for residential use, but it is available for the apartments as additional living or storage space.

The structural measures for energy-efficient renovation

The challenge was to insulate the facade to increase the thermal protection of the listed Wilhelminian building. This could only be achieved by using interior insulation. It was therefore necessary to find a vapour-permeable, capillary-active interior insulation product. The choice fell on iQ-Therm Insulation Board, a high-performance insulation material using new technology. The PUR panels with capillary pervasions ensure capillary moisture transport through the wall to retain its drying capacity (see Fig. 6.7). In order to be sure that the structure is protected against damage, critical connections with the interior insulation, e.g. bearing walls, ceiling beam bearings, were analysed. The hygrothermal behaviour of the walls was monitored continuously for a number of years by sensors. The application of sensor techniques enabled the collection of important hygrothermal performance parameters, such as the heat flux and temperature, to evaluate thermal transmission gains or losses.


Fig. 6.7: Wilhelminian building, wall-heating surface, application of iQ-Therm insulation system to the outer wall

Monitoring

Three measurement sections for analysing hygrothermal conditions were installed in the house. The first section analyses the end of the wooden beam in combination with the interior insulation and the suspended ceiling. The second section measures thermal bridges at bearing walls and window-reveal effects in the western wall. The third section is located in the bathroom, where the moisture load in the tiled walls is a subject for analysis in comparison to a plastered wall. The floor plan in Figure 6.8 shows the positions of the three measurement sections and the data-logger (left); the installation of sensors at the wooden beam head is displayed on the right.

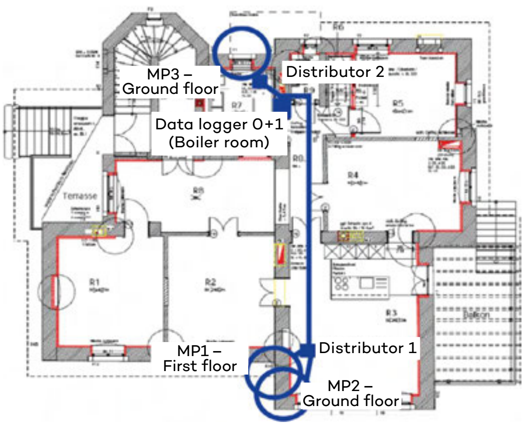


Fig. 6.8: Arrangement of the measurement section on the first floor as well as the insulated sensors at the end of wooden beam

One very important measurement section is installed on the cold side of the insulation in order to evaluate the hygrothermal situation in this critical area. Figure 6.9 shows the arrangement of all sensors in the wall construction of the building: temperature and heat flux sensors on the inner surface, temperature and relative humidity sensors in the condensation area.

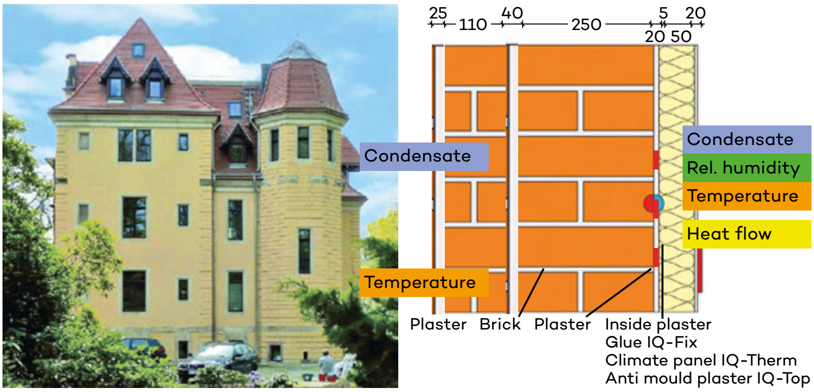


Fig. 6.9: Arrangement of sensors in the construction cross section

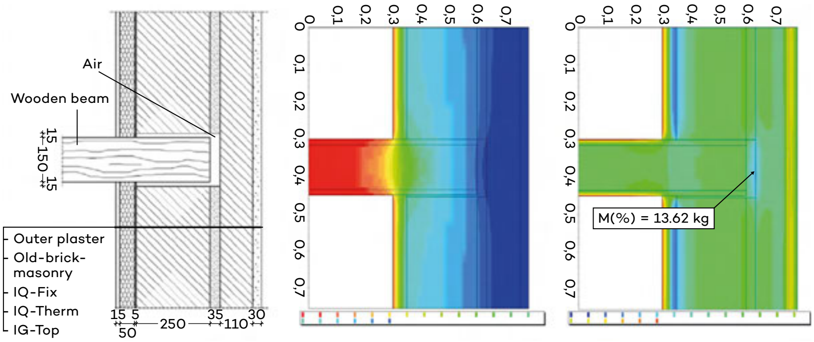
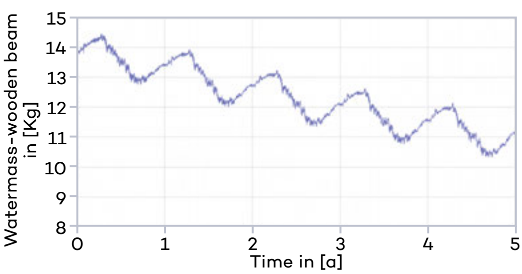


Fig. 6.10: Wooden beam construction, temperature and relative humidity distribution around the wooden beam construction in 2D on 3rd February of the second calculation year

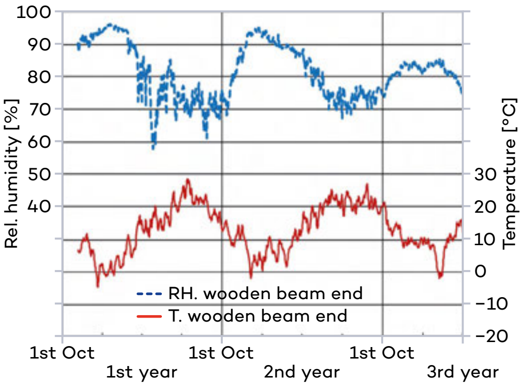
Hygrothermal simulation

The evaluation of the two-dimensional wooden beam end construction is carried out by numerical simulation using DELPHIN program code. All simulations are calculated for minimum heat protection according to DIN 4108-2 (German standard 4108-2) and to real climate conditions (test reference year). Figure 6.10 shows a detail for the design and dimensioning of the interior insulation at the wooden beam end (left), with the distribution of temperature and relative humidity simulated exemplarily for 3rd February (centre and right diagrams).

Fig. 6.11: Curve of the water content for five years at the critical point of the wooden beam end



DELPHIN also simulates the moisture content of wooden beams for five years. Figure 6.11 identifies that the wooden beam can dry fast. The moisture content of the most critical point at the beam represents 13.6 kg during the second year, and decreases in the course of five years to 11 kg.



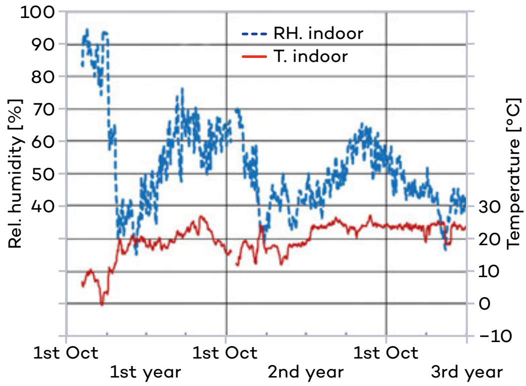


Fig. 6.12: Relative humidity and temperature measured for three years – critical point of the wooden beam end and inside the living room

Shown here are the real data measured at the critical point of the wooden beam end in the course of three years. It is clear that the wooden beams dry rapidly. The relative humidity decreases to 80% in the third year of measurement.

The measurement data of the interior climate show high relative humidity and a low temperature during the first year, when the building was still under construction and not in use (i.e. not heated). Once it is in normal use, the construction stabilises, the moisture load decreases and the data indicate a damage-free construction.

Baroque building in Görlitz

The listed historic building stands in the oldest quarter of the German city of Görlitz in Saxony. The main structure dates from 1250, but in 1726 the building was gutted by fire, so the rest had to be rebuilt. As it is now, the building presents a plain plaster facade and a regular window grid on three axes at the front and back. To the right is the entrance with a segmental arch, while to its left on the ground floor there is only one window. The construction of the outer walls consists of plastered masonry and the ceilings are supported by wooden beams.

Fig. 6.13: Baroque building in Görlitz, before and after renovation

Energy measures and maintenance work contribute to the sustainable refurbishment of protected monuments as well as to their preservation. They are a prerequisite for continuing use of these historic buildings, so long as the current requirements are met. The historic building is thus saved from decay. Its appearance after energy-efficient refurbishment corresponds to the original period.

In this case study, the necessary building repairs were combined with thermal insulation measures. The overall heat transfer coefficients before the renovation are listed in the table below. The U-values of the structure in general are very high, leading to very poor thermal protection and thus to a very high energy demand.

Tab. 6.1: Thermal insulation data before renovation

COMPONENT	DESCRIPTION	U-VALUE [W/M²K]
window	wooden composite window	2.5
outer wall	mixed brick masonry – plaster exterior	1.0–2.5
roof	false ceiling – unheated attic	1.0–1.2
ceiling above ground floor 1	vault	0.7
ceiling above ground floor 2	false ceiling	1.0

The new highly insulating box-type windows have a low U-value of 0.75 W/(m²K) owing to the use of double glazed solar-insulating glass (U = 1.3 W/(m²K) and g = 0.76). The profiles were designed to be typical of the nineteenth century. Since external insulation was not accepted as a solution by the building conservation office, vapour-permeable capillary-active interior insulation (calcium silicate climate board) was combined with conventional insulating plaster on the first two storeys above ground level. The use of insulating plaster reduces the risk of condensation on the cold side of the interior insulation.

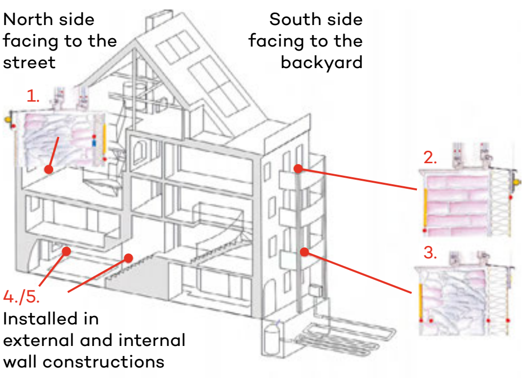


Fig. 6.14: Monitoring system installed in the building, measurement sections located in different wall positions

The hygrothermal behaviour of the construction and the entire building are affected by the following parameters: air temperature, relative humidity or partial pressure of water vapour, direct and indirect radiation, diffuse sky radiation, driving rain, and air pressure. The quantification of these external climatic parameters is required for building component analysis and building design. To this end, a meteorological station was installed on the roof of the building.

The indoor climate was measured in every room by a temperature/humidity sensor. Over ten measuring sections were installed in the building in different parts of the construction. As an example, the measuring section through the mixed masonry with interior insulation is shown, with an exterior view of the north side at second floor level (see Fig. 6.14).

A selection of the measurement results are given in the figures below. The mixed masonry wall was improved with interior insulation (5 cm of calcium silicate climate board) and conventional 3 cm of outdoor thermal insulation plaster. To monitor humidity and temperature conditions in the wall and to analyse the condensation zone, miniature sensors (humidity, temperature, heat conductivity and pyranometer) were installed. No condensate was detected in the construction using these measurement techniques. The relative humidity on the cold side of the insulation was at its maximum of 85% in January. Although the outside temperature fluctuates greatly, the temperature is almost constant on the cold side of the insulation (see Fig. 6.15 below). Apparently the higher relative humidity at the cold side of the interior insulation can dry through the permeable structure and reaches the indoor level of relative humidity in July. During an extreme heat wave between July 15th and July 20th, the temperature on the cold side of insulation is seen to be lower than the room temperature. This means that even in the niche, where the wall is less thick, the mass of the building is still sufficent to buffer the indoor temperature.

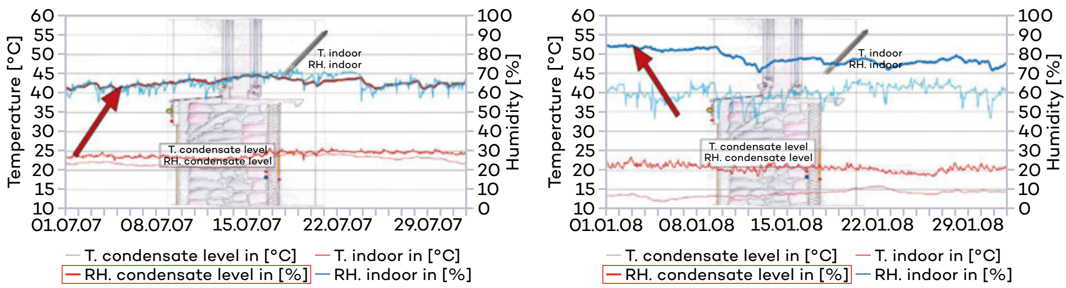


Fig. 6.15: Temperature and humidity of the indoor climate, humidity and temperature conditions in the wall, kitchen on the second floor

Renaissance building in Freiberg

This Renaissance building in Freiberg is a listed building and was constructed in the sixteenth century. It is situated in the oldest quarter of Freiberg, in Saxony, Germany. It is a typical example of the mediaeval buildings in the historic city centre. The building comprises different types of construction, as parts of it were built at different times. The basement was built during the Middle Ages, while the ground floor dates from the Renaissance. The first floor and the roof are more recent. The street facade and a small part of the rear facade have a Renaissance appearance. The main structure consists of masonry in natural stone (gneiss) and plaster, wooden beam ceilings and a wooden roof construction (see Fig. 6.16).

Fig. 6.16: Renaissance building in Freiberg, before and after renovation

The renovation objective in this building was to turn a 500-year-old listed building into a house with almost zero energy consumption, in order to create an attractive residence in the historic city centre. This was also meant to demonstrate the feasibility of energy-efficient retrofitting while preserving the historical appearance of the building.

Various diagnoses and analyses were undertaken in the building in order to arrive at suitable solutions. These were: visual inspection, geometric survey, window frame survey, measurements of temperature and relative humidity of the indoor climate, U-value measurements, survey of openings in ceilings/floors, blower door test, and hygrothermal simulation. The interesting aspect of this reconstruction project was the broad preservation of built substance while satisfying today's demands for energy-saving construction and living. Two methods that were already known from passive house design were implemented. The following figure shows the potential for saving energy through a comparison with various building sector standards.

Fig. 6.17: Heating energy consumption before renovation of the building – Donatsgasse 21

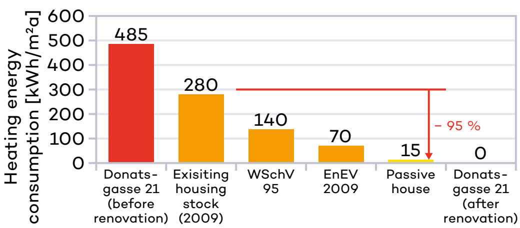
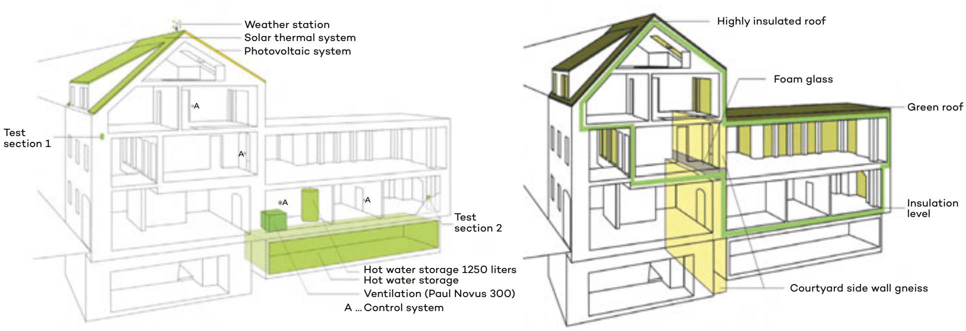


Figure 6.17 reveals that if the Passive House standard could be reached, that would mean saving about 95 % of the prior energy consumption of the building in Freiberg. In order to achieve this goal, a complete set of technical systems was installed in the house: solar thermal system, photolytic system, hot water storage, ventilation system and control system, as well as a weather station and various measurement sections (see Fig. 6.18 left). Windows of Passive House standard with insulation glazing ($U < 0.7$ W/m²K), which matched the old window openings, were used in the whole building. The existing old roof structure was retained.

Fig. 6.18: Overview of technical measures (left), wall insulation and windows



Adding exterior insulation to the gneiss window reveals with Renaissance embrasures would have been unthinkable from the conservation point of view. The facade was therefore preserved in its original form by creating a kind of buffer zone. This zone is used both as an entrance and a stairwell. The buffer zone also reduces the heat loss of the building. The insulation of exterior walls was consistently implemented up to U <0.1 W/m²K. Capillary interior insulation with calcium silicate climate boards and TecTem insulation panels were used in some parts. The roof structure was improved by creating a double-layer roof, with insulation both above and between the rafters (see Fig. 6.18 right).

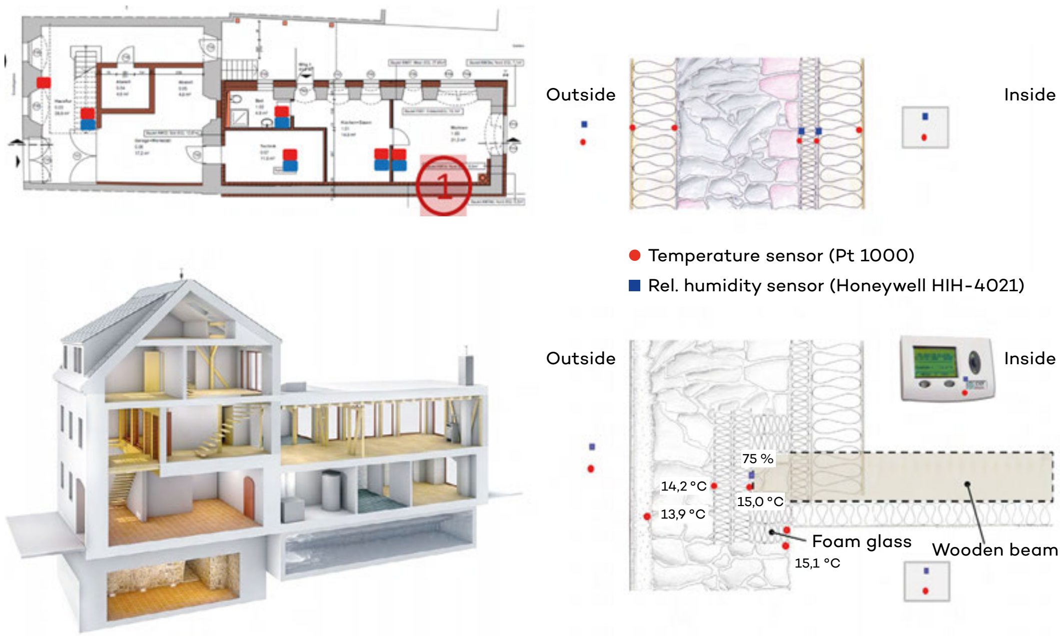


Fig. 6.19: Monitoring system: measurement sections on plan and in section, arrangement of sensors in the wall construction and at the wooden beam end

As in some of the other buildings, a monitoring system was installed to evaluate the hygrothermal behaviour and the energy consumption after renovation. Figure 6.19 shows the measurement sections on the ground floor, as well as the arrangement of the sensors installed at the wooden beam end and in the wall construction. Figure 6.20 shows the real measurement data for heating energy consumption in the years 2011/2012. The overall figure of 3400 kWh after renovation corresponds to 20 kWh/m²a.

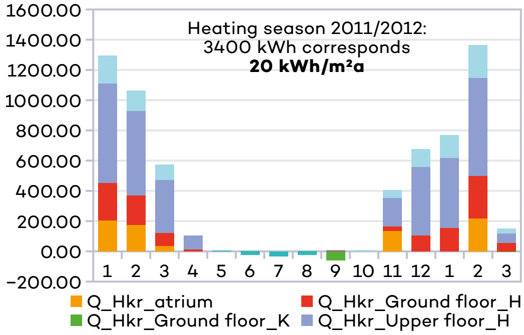


Fig. 6.20: Measured heat consumption after renovation in 2011/2012

The heat energy consumption was also calculated by PHPP. The calculated annual heat energy demand amounts to 4140 kWh/a equivalent to 19.8 kWh/m²a (see Fig. 6.21). In addition to this, there is a hot water requirement of 2226 kWh/a (warming from 8°C to 50°C, 25l/person/day, for five people, the total heat consumption would be 6366 kWh/year.)

The calculated heat energy consumption corresponds very well to the measured data. Both methods, calculation and measurement data, verify that the heat energy consumption after renovation approaches that of a passive house. This means that the intervention made it possible to save approx. 95% of the energy previously consumed by the building in Freiberg.

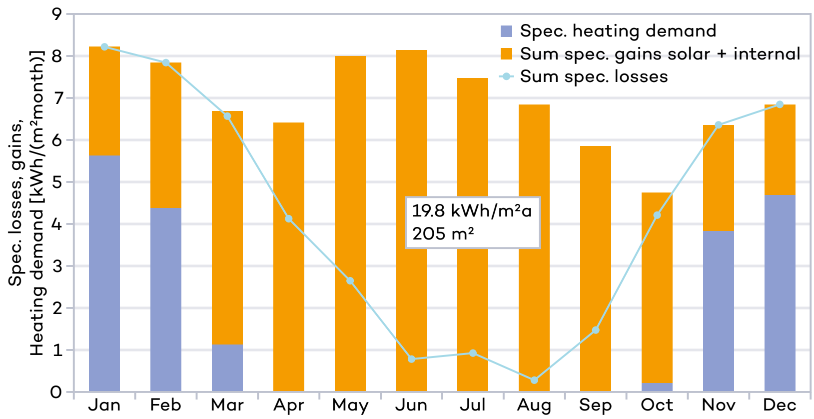


Fig. 6.21: Annual heat consumption calculated by PHPP

Summary und conclusion

Energy-efficient renovation and the sensitive treatment of our architectural cultural heritage can work together. The uses of new materials and technologies in historic monuments have, however, to be accompanied by advanced evaluation methods such as physical testing and the use of modern simulation tools. Interior insulation in historic buildings represents a challenge in several aspects and it raises many questions that have to be answered:

→ Are new materials compatible with the existing building and does it make any sense to install insulation everywhere?
→ What is the energy potential of retrofitting?
→ What risk is there of causing damage thereby, how probable is it and what might its extent be?

Energy-efficient retrofitting and conversion offer a way of giving valuable and culturally relevant buildings a new lease of life. The examples given in Case Study 6, with a focus on interior insulation, show that the following topics are significant in planning this: the selection of interior insulation and its dimensioning, the natural moisture load of the structure (e.g. in driving rain), and the alteration and creation of construction details (e.g. in respect of thermal bridges). A successful project uses

→ special measurement technology: e.g. laboratory tests, diagnostic measurements and sensors: (radar, thermographic camera, water uptake experiment, etc);
→ numeric simulation and calculation methods: e.g. coupled moisture and heat transfer (DELPHIN), building energy calculation and simulation (PHPP, Design Builder, e-plus, etc).

In this manner, complex geometric details, such as the joints at windows or suspended ceilings, can be evaluated and optimised, while condensation risks, thermal bridges, mould growth, and other sources of damage can be avoided with confidence.

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Name	Industrial Engineering School of Béjar
Location	Béjar, Salamanca, Spain (40° 23' 6.756', -5° 45' 39.48')
Date of construction	1968
Architectural style(s)	Constructivism
Construction type / materials	Reinforced concrete, brick and zinc panel
Original building use	Academic: University
Current building use	Academic: University
Main interventions	Lighting and HVAC: Control algorithms
Heating demand / consumption before intervention [kWh/m²a]	Electricity demand: 23 kWh/m²a (only lighting) Heating demand: 70 kWh/m²a
Heating demand / consumption after intervention [kWh/m²a]	Electricity demand: 18 kWh/m²a (only lighting) Heating demand: 70 kWh/m²a
Other noteworthy characteristics	Lattice

CASE STUDY 7

INDUSTRIAL ENGINEERING SCHOOL, BÉJAR, SPAIN

José L. Hernández, Miguel A. García, Roberto Sanz, Álvaro Corredera,
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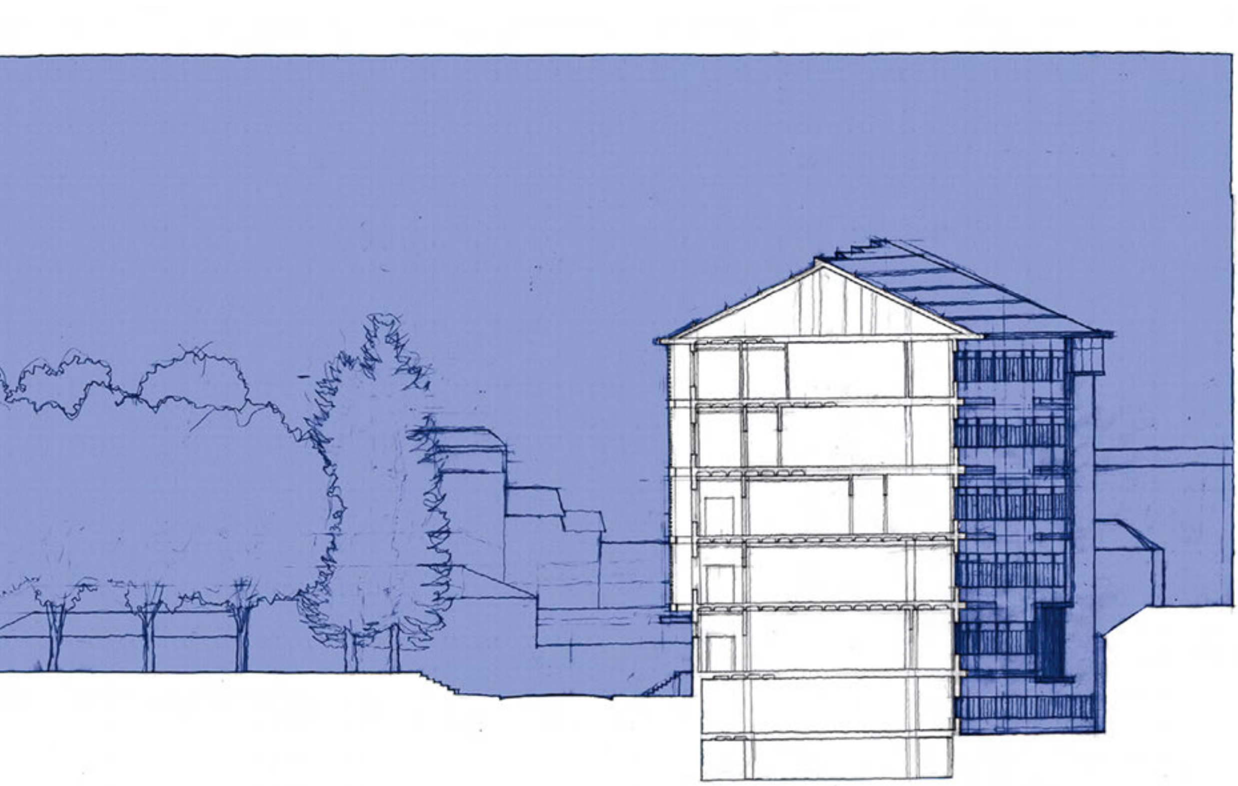


Building history and general description

The Industrial Engineering School of Béjar was founded in 1852 by Queen Isabel II. It came to be known as the Industries Superior School, and initially, textiles, mechanics and electricity were studied. Between 1880 and 1948, the school was managed by the church: originally by San Gil Church and then in 1903, when this church became too small, the San Francisco Monastery took over the university's administration. After the end of WWII, the university constructed a new main office building.

The current main office building, designed by architect Manuel Blanc Díaz, was built between 1968 and 1972. The construction of the building broke with the traditional architecture of the region in this period, using minimal, geometric, and industrial design that is functional, influenced by the Constructivists and the Modern Movement. To optimise the building for the local climate, minor aspects of the design were influenced by regional architecture. In the words of Díaz, 'the aesthetic solution of the building is based on function and the environmental and climatic conditions'.

Fig. 7.1: Main facade of the building

Fig. 7.2: Plans of the building

The building has a net built area of 136,245 m² and a net usable area of 9,467 m² distributed across two basements, the ground floor, and four floors above the ground floor. The main material in the structure is reinforced concrete used for the columns and slabs. The columns and slab fronts have no thermal insulation and are embedded in the walls, independently of the brick facing causing the greatest problems (thermal bridges, leakage, etc). The walls do not have insulation material, but between the two faces there is a non-ventilated air gap of 5 cm, so that the thermal transmittance of this construction is U = 1.50 W/m²·K. The roof is made of zinc plate with a transmittance of 1.75 W/m²·K. The window frames are metallic and have large horizontal strips with thermal bridge optimisation f and double glazing 4/20/4 with a transmittance of 3.45 W/m²·K and a g-value of 0.76. The overall transmittance of the building is 2.10 W/m²·K. The building orientation is north-south on the longitudinal axis, and the biggest facades are east-west oriented with large glazed surfaces. The concrete lattice is in the west (main) facade, whereas the east facade includes some cantilevers to protect the wall from solar radiation. In fact, the lattice is one of the most peculiar characteristics of the building. It covers almost the entire main facade which protects the building from wind and rain. The architect based his design on regional architecture by reinterpreting the facades of the traditional houses of Béjar that were made with roof tiling for protecting the most exposed facades against strong winds and rain, common in this region. Besides this protection, the lattice provides shade to the internal rooms by avoiding the solar radiation during the periods of the day with the highest radiation.

Although it is not a heritage-listed building, its cultural value lies in its formal character and in its social and economic impact on the region, because it was the first building of the University of Salamanca in this area of the Province. This has assisted the development of the textile industry in the area of Béjar.

The building is well preserved although there are some problems with the projecting concrete slabs due to moisture. The main problems, however, are related to the low comfort conditions (both thermal and lighting) as well as to the high electricity consumption with an average of 230,000 kWh/a. Other characteristics of the building are the heating days and heating degree days (HDD), 240 days and 1804 HDD, respectively. The heating system is composed of two gas oil boilers (a main unit and a support unit) and radiators for distribution. The main boiler's actual output is 581 kW with efficiency of 88.5%, while the support boiler's actual output is 418.6 kW with efficiency of 88.1 %. The library contains an HVAC system with three external fan-coil units and two splits in the offices, which was the reason it was chosen as the test room. The building is equipped with artificial lighting systems with fluorescent tubes.

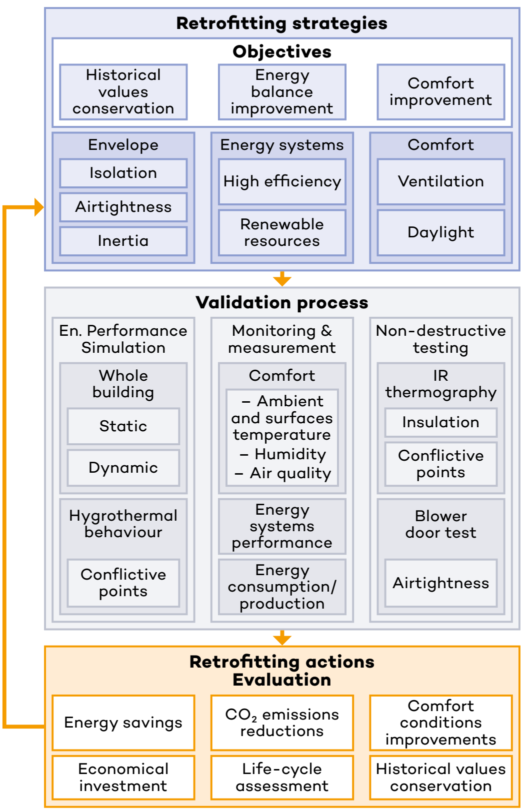
Pre-intervention analysis

Diagnosis is the first step in determining the problems and inefficiencies of a building to ensure that interventions are focused on historic values of conservation and on improving energy balance and comfort. The validation process methodology was to combine energy performance simulation, monitoring and measurement processes, and non-destructive testing of the building, as shown in Figure 7.3. The benchmark is based on the energy savings, CO_2 emissions reduction, comfort improvement, economic investment, life-cycle assessment, and conserving the building's historic values.

The original building underwent two interventions before this analysis which must be taken into account. In both the roof was changed and in the second intervention, all external windows were replaced with conventional double glazing and thermal-bridge-optimised frames. The lighting was originally grouped in circuits that are not appropriate for the use of the building as their alignment is perpendicular to the facade. In the initial diagnosis, the following problems were detected:

- → overheating during the warmer months, especially on the east facade;
- → deficient heating distribution system with only two circuits, leading to significant temperature differences and comfort issues;
- → manual control strategy for cooling system elements causing low comfort levels in cooled areas;
- → oversized lighting system in corridors and halls;
- → inefficient lighting system due to the incorrect distribution of lighting circuits in classrooms and laboratories;
- → under-utilisation of daylight and solar radiation;
- → low level of insulation; leakage.

Fig. 7.3: Methodology validation process



Simulation

Different simulations were carried out in order to determine the behaviour of the building from the energy and lighting points of view.

Energy performance simulation

Two energy performance simulation tools were used for simulation of the thermal behaviour of the building and the annual heating and cooling demand: Passive House Planning Package (PHPP) and Transient Systems Simulation (TRNSYS).

In this case study, the cooling system is limited to a very small cooled area of 150 m², representing only 2% of the heated area. In summer periods the occupancy level of the building is very low; therefore, the simulations are focused on the heating system energy demand. In heating mode some critical thresholds arise when outdoor conditions during some part of the day are above the indoor set point. However, this is not the case with the climate in Béjar, where the winter is very cold; therefore the static and dynamic simulations should give reasonably similar results.

Table 7.1 summarises the results of annual heating demand for both simulations, which are quite similar. Further study of the disaggregated losses and gains, however, shows there are substantial differences: transmittance losses (30% less in PHPP) and ventilation losses (30% less in PHPP), while solar and internal heat gains are increased by 81% and 40% respectively in TRNSYS compared to PHPP. This is because TRNSYS summarises losses over the whole year whereas PHPP only summarises results for the heating period.

Tab. 7.1: Energy performance simulation results

HEATING ENERGY BALANCE	PHPP (kWh/m²a)	TRNSYS (kWh/m²a)
Ventilation losses	**17.90**	**25.70**
Transmittance losses	**94.70**	**154.89**
Windows	34.60	
Floor / slab basement	13.20	
Roof	11.90	
Ext. wall (ground)	2.30	
Ext. wall (ambient)	32.70	
Solar gains	**11.60**	**62.72**
Internal heat gains	**13.00**	**22.23**
Convection		12.26
Radiation		9.97
Annual heating demand	**88.00**	**95.64**

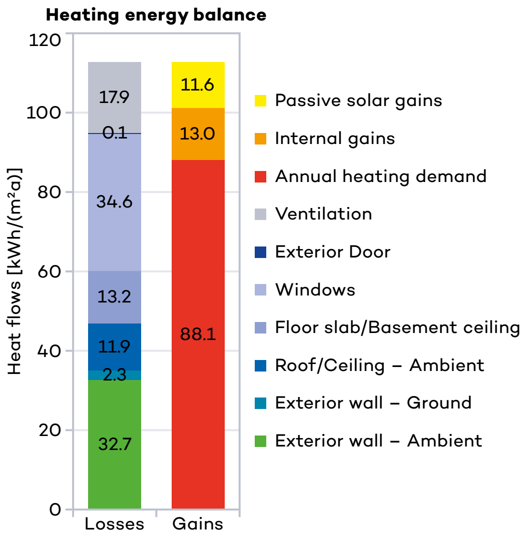


Fig. 7.4: Heating energy balance

With regard to the heating energy balance, Figure 7.4 displays the total balance of heating energy divided into the components considered in the simulation.

Lighting simulation

As previously mentioned, inefficiencies in the lighting system had been detected; therefore, a simulation with Dialux was carried out in order to evaluate the lighting values. The test room chosen is the physics laboratory because it has windows on both the east and west facades. Figure 7.5 shows the isobars of the light levels in the room as well as the measurement values in different conditions (lights off, all lights on, and selected lights on) for the lux level. The simulation results indicate the comfort level of 500 lux is not reached in all zones of the room. With selected lights on, measurements almost achieve the comfort conditions at the workplaces in the room: with all the lights on the lighting level is too high, whereas with all the lights off it is too low in all areas.

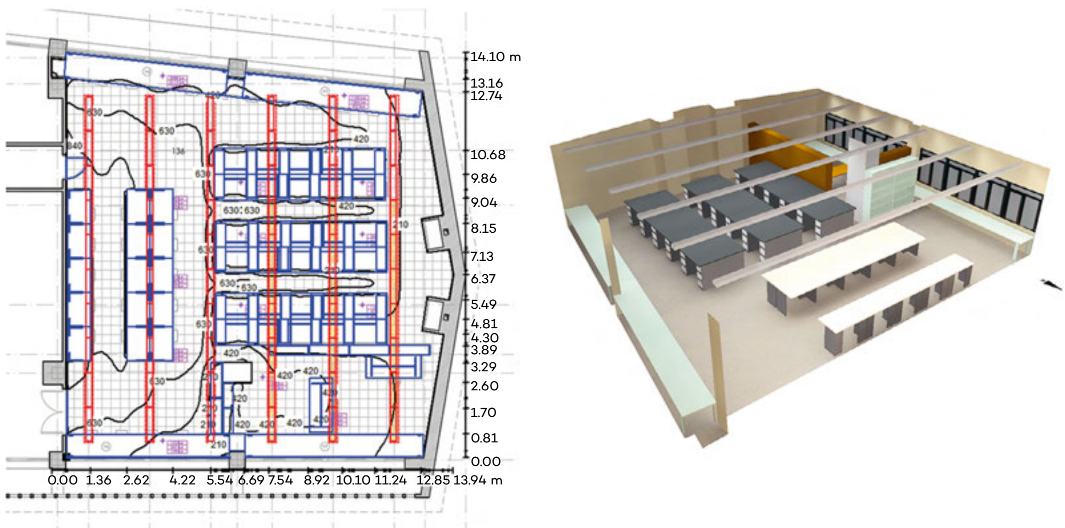


Fig. 7.5: Dialux simulation results

Blower door test

In all building energy performance simulations, it is necessary to quantify the median annual air exchange rate through leakages in the building envelope. This is normally very different from the estimated values used in the initial calculations, which are almost always optimistic. The tests were completed in the two test rooms in the building, which are the physics laboratory and the library. Also, a complementary IR thermography was carried out for the detection of physical infiltration points. The results show that the building envelope presents a very low level of airtightness ($n_{50} \approx 8.9$ 1/h), due to three main points of air entrance:

- → In the external walls, the different rigidity of the structural elements made of reinforced concrete (columns and slabs) and the brick walls without anchoring elements caused longitudinal cracking in the joints.
- → The joints of the windows and blind boxes are not sealed. In this type of historic building this is due to the degradation of the sealing material but, as the windows in this building were replaced recently, it is reasonable to assume that it is due to a construction deficiency.
- → There is circulating air coming from the ceiling void. This is a problem for neighbouring heated and non-heated rooms.

Monitoring

The final diagnosis phase was comparison of the actual measurements of the building conditions, both as input for the first analysis and as baseline for the evaluation of the results. The purpose of the monitoring system was to develop a baseline for energy performance indicators, such as comfort parameters and energy measurements, and the integration of further control strategies. For the comfort parameters, the library and physics laboratory were the test rooms. In these rooms, temperature, humidity, and luminance level sensors were installed together with occupancy sensors (see Fig. 7.6) in order to analyse the occupancy patterns and establish the most adequate control strategies. Electrical and thermal energy meters were installed in the boiler room and the electrical boxes to measure energy in order to analyse the energy performance of the building before and after implementation of efficiency strategies.

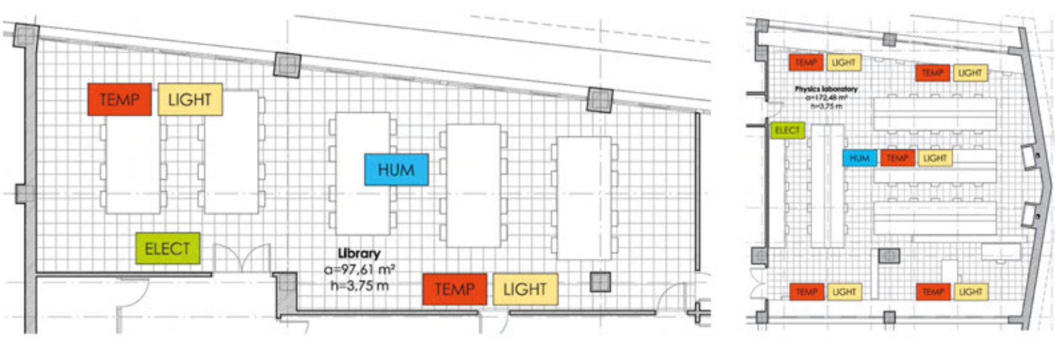


Fig. 7.6: Monitoring systems in the physics laboratory and in the library

Result and proposal of interventions

The retrofitting strategies implement new efficiency solutions to solve the energy problems detected in the building. The combination of diagnosis tests, simulations, and the monitoring system facilitates detection of the main solutions which will improve both energy performance and comfort levels. The proposal of interventions is described below.

	PASSIVE SOLUTIONS	ACTIVE SOLUTIONS	CONTROL
Energy efficiency	→ Internal / external insulation → Airtightness	→ Thermal distribution improvement → Ventilation with heat recovery	→ Lighting system
Comfort	-	-	→ Lighting system → HVAC system
RES Integration	-	→ Solar PV → Biomass boilers	-

Description of interventions

Interventions were centred on user comfort. The main strategies deployed for the comfort improvement were related to distribution of the lighting systems to increase the use of daylight, and the optimisation of the cooling system.

Lighting system

As previously mentioned, the luminaires are distributed perpendicular to the windows in several rooms of the building. This distribution does not make effective use of the daylight while maintaining the adequate luminance levels. A redistribution was accomplished (see Fig. 7.7), keeping in mind the previous concept and the occupancy pattern. This new distribution is accompanied by an automated system which uses a controller for turning the lights on and off, depending on the luminance level detected by the lighting sensors and the occupancy detected by the presence sensors. This new distribution, using only half the luminaires, assures energy savings while maintaining the comfort level.

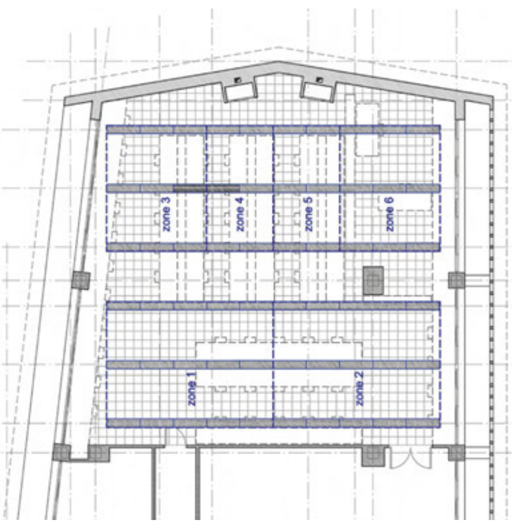
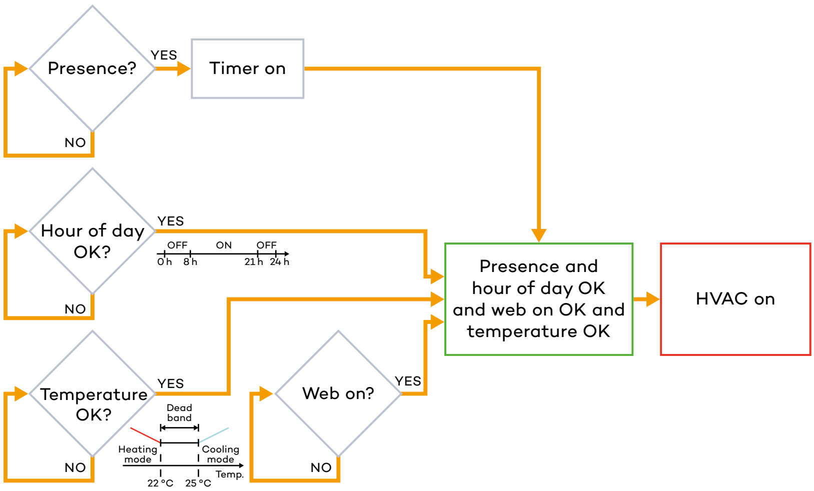


Fig. 7.7: Redistribution of the luminaires in the physics laboratory

HVAC strategy

The HVAC strategy involves the fan-coil units in the library where low comfort was detected in the diagnosis. An automated system for turning the fan-coils on and off based on the temperature of the room and the occupancy pattern, as well as a timetable, was therefore established. For controlling the systems, the algorithm is basically the one shown in Figure 7.8, where presence, time, and temperature (this is configurable) are all taken into account. It is considered that a sufficient comfort level is achieved between 22°C and 25°C.

Fig. 7.8: Control algorithm for the HVAC systems



As a result, for example the average temperature in May has been reduced from 23.95°C to 22.22°C, the latter being considered adequate for comfort. The standard deviation has also been decreased from 2.22 K to 1.92 K, which means the temperature is more stable with fewer variations. As expected, however, the electrical consumption has not been reduced, maintaining the measurements. In the same month, the fan coil in the centre consumed 2.3 kWh before and 2.1 kWh after the changes. The south fan-coil increased its consumption from 6.9 kWh to 8.9 kWh, and the north fan-coil reduced from 6.6 kWh to 4.6 kWh. On average, the total consumption of the fan-coils is maintained.

Historic value conservation

The evaluation of the impact of proposed interventions on the historic value of a building is probably the most complex and subjective in the whole process. Some methodologies, such as the Danish Survey of the Architectural Values in the Environment (SAVE) method, have been working towards objective determination of the historic value of a building, and that could be combined with the evaluation of energy savings and comfort improvement strategies.

In this case study, the historic value of the building lies more in its cultural features than in its aesthetics or design, so strategies to add internal insulation or reduce the level of infiltrations have a low impact on its historic value. Nevertheless, other strategies, such as the integration of energy generation systems from renewable sources (for example photovoltaic) have a higher impact and should be studied in more detail, however; the real measures carried out do not impact on heritage value and conservation aspects. No additional installations are needed, the control strategies could be programmed remotely, and therefore the aesthetic value is preserved. On the other hand, comfort conditions are improved with reference to the requirements of the current building, but the results could be extrapolated to another building with different indoor conditions, such as museums with frescoes.

Focus: lighting refurbishment

One of the interventions carried out in the case study is the previously mentioned redistribution of the lighting system and an automatic control algorithm which covers occupancy patterns of the laboratory and the lighting levels for optimal comfort. The control algorithm shown in Figure 7.9 detects the presence according to the pattern calculated by the combination of several sensors in the test room. It measures the light level in the room, which is compared to the comfort level. If the conditions need the lights to be switched on (i.e. presence and not enough light), the appropriate circuit is turned on, and a timer is activated to prevent keeping the lights on when there is no presence or there is enough luminosity. Last but not least, the switches are prioritised to the control algorithm in case university staff require higher lighting levels.

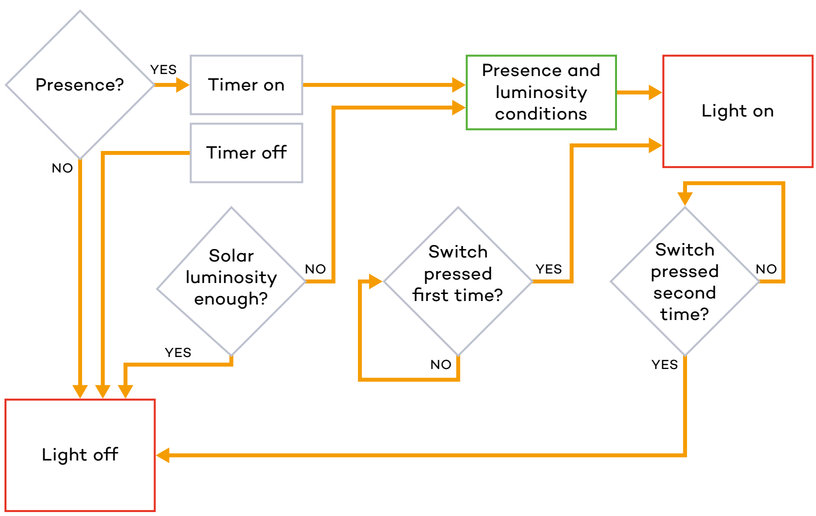


Fig. 7.9: Physics laboratory control algorithm that was developed

	ELECTRICITY CONSUMPTION BEFORE	ELECTRICITY CONSUMPTION AFTER
April	2.60 kWh	0.90 kWh
May	3.30 kWh	1.70 kWh
June	0.60 kWh	0.70 kWh
July	1.60 kWh	0.40 kWh
August	0.00 kWh	0.10 kWh
September	0.50 kWh	0.40 kWh
October	1.40 kWh	1.00 kWh
November	2.20 kWh	1.30 kWh
December	1.50 kWh	1.00 kWh
January	1.30 kWh	1.10 kWh
Total	15.00 kWh	8.60 kWh

Tab. 7.2: Electricity consumption in the physics laboratory

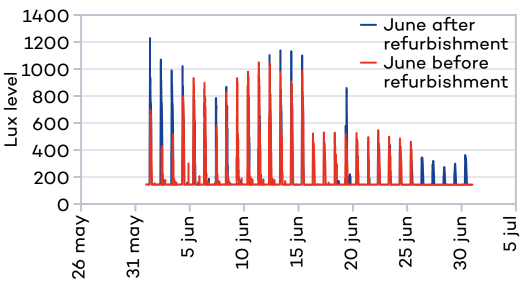


Fig. 7.10: Physics laboratory lighting level in June

The novelty of the control algorithm can be summarised in the Freely Programmable Modules (FPM) for development, an emerging technology that allows integration of more advanced algorithms and improvements in the time response. In historic buildings, there are some restrictions when more hardware installations are needed; therefore, this development should be integrated into the current hardware. The FPM framework provides a piece of software such as a 'virtual hardware' which could be deployed into the current building management system. It also allows the calculation of more efficient and advanced occupancy patterns with the combination of several sensors to better detect the presence status of large rooms. Once the algorithm was implemented, the new control strategy was deployed and the same parameters as before the refurbishment were measured. Table 7.2 illustrates the electricity consumption of the physics laboratory (almost all the energy is consumed by the lighting system). As can be observed, the electricity consumption has decreased by 43%, while the comfort level has been maintained. Figure 7.10 demonstrates that in May, for example, the light level is almost restricted in the comfort band (between 500 and 1000 lux in these rooms) during the same time span. In the same month, Table 7.2 shows a significant reduction of the electricity consumption with the same conditions regarding comfort levels, occupancy and timetables.

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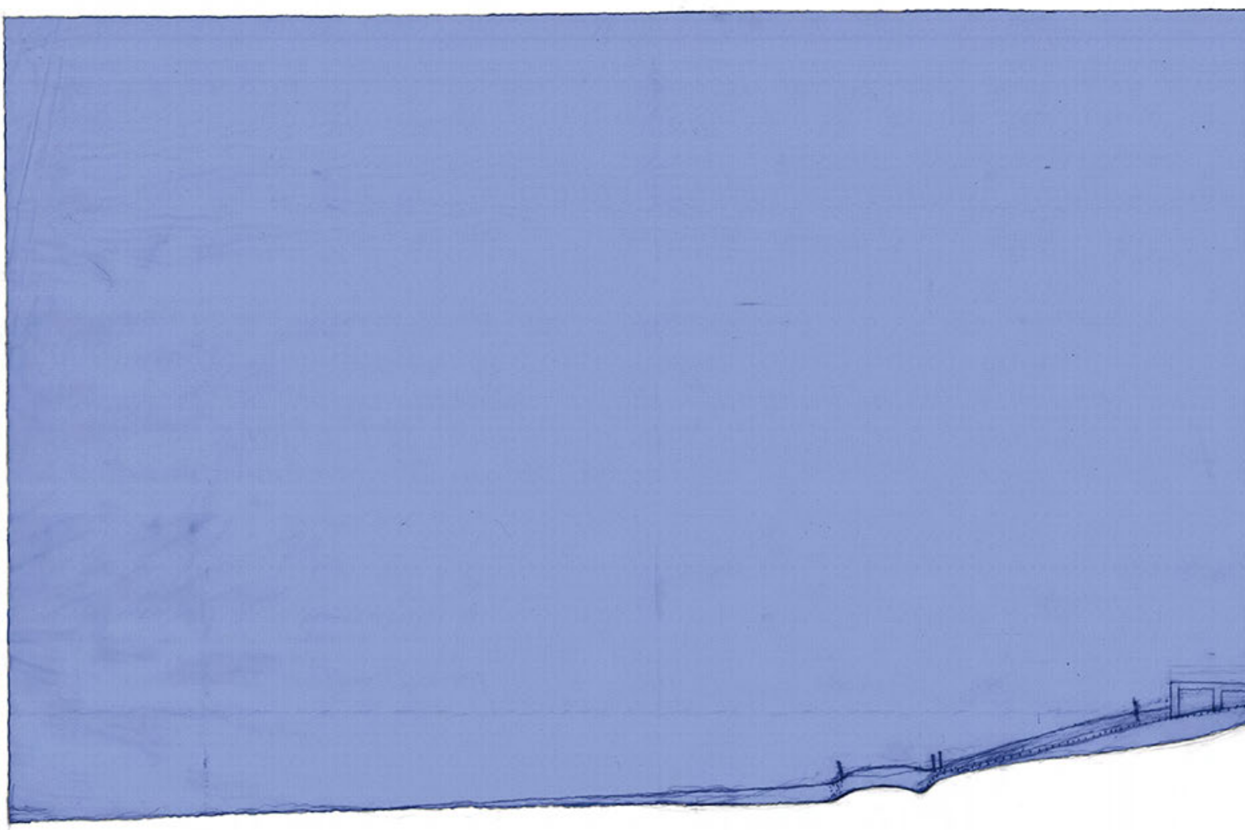
3ENCULT, D6.2 CS7, 2014 3ENCULT deliverable 6.2, Hernandez, J.; Antolí, J.; García, M.A.; Sanz, R.; Corredera, A., *Documentation of CS7 Engineering School of Béjar, Salamanca (Spain)*, 2014

García, 2012 García, D.; Corredera, A.; de Torre, C., *CS7 – Description of the Monitoring System, Report*

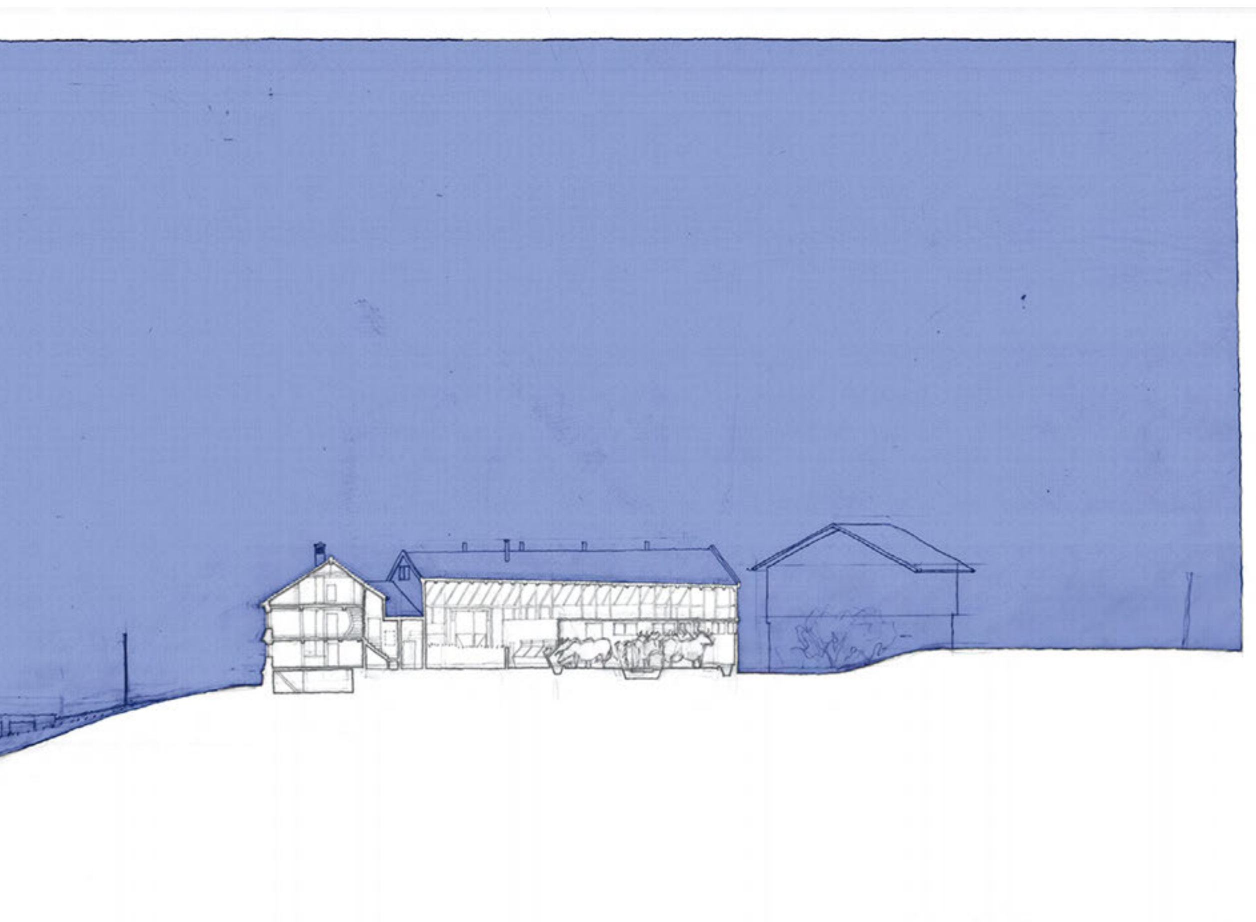
Name	Appenzell / Weissbad
Location	Weissbad, Switzerland, (47°30' 1.672 – 9° 44' 09.64)
Date of construction	1630
Architectural style(s)	Strickbau (log building)
Construction type / materials	Timber
Original building use	Farmhouse / residential building
Current building use	disused / residential
Main interventions	internal insulation added
Heating demand / consumption before intervention [kWh/m²a]	not known
Heating demand / consumption after intervention [kWh/m²a]	100 kWh/(m²a)



CASE STUDY 8

STRICKBAU, WEISSBAD / APPENZELL, SWITZERLAND

Harald Garrecht, Simone Reeb, University of Stuttgart



Building history and general description

The Appenzell farmhouse, built of solid logs, is one of the most original types of construction in Switzerland; this method was used up to the late nineteenth century. With a share of more than 50%, it still forms the basis of most houses in Appenzell today. The construction is a kind of solid log construction with corner connections that are typical of the region. Today, these houses are mostly clad with panelling or shingles. The facades are characterised by rows of windows and colourful decoration. At present, this type of building in the Appenzell region is significantly threatened by increasing demolition. The building conservation department in Ausserrhoden (one half of Appenzell) estimates that there is an annual loss of 20–30 houses in the semi-canton alone. Older houses from before 1800 seem to be especially affected by this.

The building examined in the course of the present research project is estimated to have been built in 1630. The part of the house that is most in need of repair is the shingle cladding. Figure 8.3 shows the east and west facades of the house. The wooden top floors bear partially on a cellar with quarry-stone walls. Visual inspection indicates that the load-bearing structure of the basement is intact.

Fig. 8.1: Eastern facade (left) and the geographic location (right)

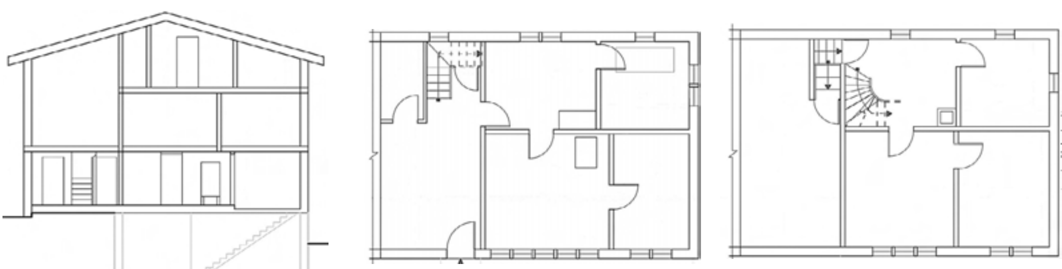


Fig. 8.2: Cross section (left) and floor plans (middle and right)

Fig. 8.3: East (above) and west facade (bottom)

The wall surfaces inside do not show any damage and the floors are relatively level. The downstairs rooms are primarily panelled (see Fig. 8.4, left) and the walls upstairs are painted (see Fig. 8.4, right). The roof of the house is supported by a simple purlin roof truss. This also shows no significant damage. A small room was built into the attic at a later date.

On the uphill eaves side of the house there is a stable building, which is also a later addition. In contrast to the stable, the house will be demolished after the end of the research project. The house was inhabited up to 2011. If it is to continue in use, the sanitary installations and heating must be renewed. As with many of these buildings, the ceilings and doorways are uncomfortably low.

Fig. 8.4: Living room on ground floor (left), bedroom on first floor (right)

Pre- and post-intervention analysis

Comprehensive testing was conducted during the planning process and after the implementation of energy-saving restoration measures. Table 8.1 provides an overview of the theoretical and experimental tests performed.

Tab. 8.1: Theoretical and experimental tests before and after energy-efficient retrofitting

	METHOD	SOFTWARE TOOL/ TESTING EQUIPMENT
Component behaviour	U-value / thermal bridges	THERM Version 6.3.44.0
	Simulation of the coupled hygrothermal construction elements behaviour	DELPHIN Version 5.6.5
	Measurement of the airtightness	Blower-door (DIN EN 13829)
Heat energy requirement	Calculation of the energy efficiency	PHPP
Monitoring	Climate and component monitoring	
	Energy monitoring	Monitoring system using 1-wire network

All components of the envelope's heat-dissipating surfaces were analysed with regard to thermal behaviour and to thermal bridges. The U-values shown in Table 8.2 have been calculated for individual constructions in the original condition and after the energy-efficient retrofit.

Tab. 8.2: U-values measured for the main components of the log building

	U-VALUE [W/(m²K)]	
	Non-renovated condition	**Renovated condition**
Exterior wall	0.755	0.268
Interior wall	0.855	0.28
Basement ceiling / Ground floor	1.190	0.299
Ground floor ceiling / First floor	1.429	0.325
Doors	2.277	2.277
Single-pane windows	5.620	5.620
Box-type windows	3.350	
Box-type windows with Plexiglas pane added on the inside		2.460

All relevant geometric thermal bridges were also examined. Because the distances between most of the existing thermal bridges were less than the required 100 cm, they were considered isolated to simplify. This method facilitates the assessment of the influence of thermal bridges on the heating requirement with respect to the energy retrofitting.

An exact evaluation of thermal bridge losses was made by means of the length-related thermal bridge loss coefficient Ψ according to DIN 4108-6. The heat flows and surface temperatures were determined according to DIN EN ISO 10211 in connection with DIN 4108-2 and DIN EN ISO 6946. The necessary thermal basic value and surface temperatures required for the calculation of Ψ were computed using THERM, a finite element method software. The use of this software facilitates the calculation of the U-factor, better known as the U-value. By multiplying the U-factor by the component length, the thermal guide value L2D can be determined. In a simplified form, the length-related thermal bridge loss coefficient Ψ is calculated by subtracting the product from the U-value and the length of the undisturbed component from the thermal guide value L2D. Altogether, seventeen thermal bridges were examined two-dimensionally this way.

In order to analyse the coupled heat and moisture behaviour of the construction in combination with interior insulation, numeric calculations were performed with the DELPHIN software tool,

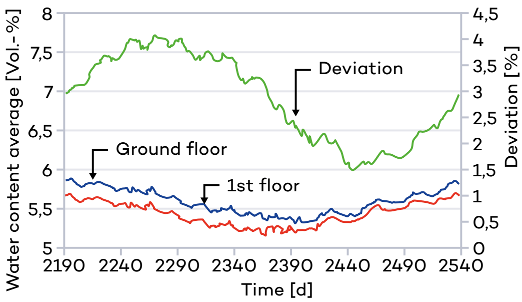


Fig. 8.5: Comparison of the annual course of the average moisture content in the logs (year 7) on the ground and first floors

developed by the Technical University of Dresden. For the consideration of weather conditions, a test reference year was generated for the location of Appenzell, using the METEONORM program. With an annual rainfall of 1336 l/m², this weather data set corresponds to the highest driving rain exposure group (III) according to WTA data sheet 6-1-01. For the indoor climates according to WTA data sheet 6-2-01, a sine curve was plotted on the basis of monthly averages, assuming a normal moisture load. The north-east corner of the building was examined using this type of simulation calculation. The construction elements analysed in this way differ only insofar as there is wood panelling in the rooms of the ground floor. The result, that is the average water content during the year, is illustrated in Figure 8.5. It was basically determined in [Schweickert, 2012] that the volumetric water content differs from floor to floor. The average water content on the ground floor is up to 4% higher.

Apart from the effects on comfort (draughts), the airtight execution of building envelopes plays a special role in thermal insulation. Leakage not only causes undesired energy loss, but can also induce moisture damage due to convective water vapour transport. The airtightness of the building examined was measured with the differential pressure method in accordance with DIN EN 13829, using the blower-door test. Infrared thermography was used to detect possible leaks. The rooms that were fitted with insulation and an airtightness layer were examined again in the further course of the project. In the non-renovated condition, leaks were located in the window and component gaps, as well as through the walls. The renovation work succeeded in reducing the air exchange rate by between 52% and 74%. Only in the living room (room 0.2), a lesser improvement was reached, of around 17%. This is due to the fact that no airtightness layer could be installed on the eastern wall.

Description and evaluation of interventions

The aim of the tests conducted was to examine and demonstrate the possibilities of energy-efficient retrofitting as an example for similar buildings. Besides increased energy efficiency, the renovation work was aimed at improving user comfort while complying with the conservation requirements for historic monuments. The examinations were started in the summer of 2011, after the tenants had moved out. Because the building will be demolished after the two-year examination period, a wood fibre interior insulation could be installed as a feasibility study. An interior insulation concept was therefore developed in consultation with the cantonal building conservation department and the ETH Zurich, a project partner, and tested experimentally. To this end, a comprehensive monitoring system was set up with which the temperature and moisture conditions in selected construction areas could be recorded and evaluated.

Four rooms located along the east facade (Rooms 0.2, 0.3, 1.2, 1.3) on the ground and the first floors were included in the examination. Due to the lack of heating and to opened windows, the walls to the adjacent rooms were treated as thermal-loss surfaces (see Fig. 8.2). This also applied to the unheated attic and the basement. In order to be able to simulate real conditions during residential use, the four subsequently insulated rooms were equipped with electric radiators and air humidifiers. This way it became possible to force critical room climate conditions during periods of cold weather. These cause a more-or-less developed moisture problem and possibly damage in the form of biogenic infestation within the construction. To forestall such damage, a comprehensive monitoring system was installed. This made it possible to analyse and evaluate the structural and physical behaviour of the interior-insulated construction in all rooms in relation to the ambient climates.

On the inside of all of the exterior walls, as well as the walls adjoining unheated rooms, timber frames (thickness = 60 mm) were attached at a distance of 40 mm to the wall. Wood-fibre insulating boards with a thickness of 100 mm were installed in the space between the members of the frames (see Fig. 8.6). Subsequent to the installation of insulation, a vapour retarder was installed. Here, all membrane joints were glued airtight and overlapping. In order to install the vapour retarder effectively, i.e. without back flow, any holes in the floorboards and ceiling boards were closed tightly with wooden dowels (see Fig. 8.6 centre).

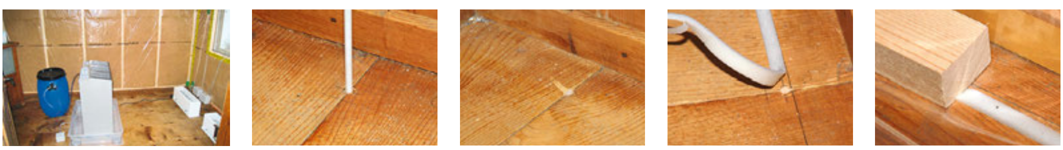


Fig. 8.6: Installation of the internal insulation

In order to compensate for surface irregularities and avoid skips, expanding adhesive tape was laid between floors or ceilings and the timber frames (see Fig. 8.6 right). This was bonded to the floor respectively the ceiling; above this the foil was fixed and a timber beam placed on this. The entire framework was constructed so that it could be braced in a stable way.

In the attic, as well as below the ceiling on the ground floor, the insulation was installed in the form of exterior insulation. In order to create an airtightness layer, the vapour retarder membrane was installed across the entire wooden frame and the insulation.

The windows of the building are single-pane, with wooden frames. These frames overlap each other and can be slid to the left and right. Every window has an additional outer layer. This consists likewise of single-pane glazing in wooden frames and these can be fastened from the outside. In order to simulate the conversion of these windows into box-type windows, a frame structure was built in the rooms in front of the existing windows and then acrylic glass panes were inserted into it.

Focus: Analysis of monitoring data

For the monitoring, a bus system was used that is not commonly used in housing technology. The 1-wire bus consists of a bus master on which the communication and control software is installed. The measurement and actuator assemblies are connected to this bus master. A PC located in the living room was used as the bus master. This way, it was possible not only to record and archive the measured values, but also to control the heating registers and the humidifiers. Altogether, more than 200 sensors for recording the temperature and relative humidity were installed across the entire object. A particularly dense sensor network was installed around critical construction elements. This made it possible to assess both the near-field strain as well as the surface temperatures on these components with regard to the potential hazard. Figure 8.7 shows two exemplary measuring points in room 1.3 (first floor).

These can be used, for example, for evaluating the hygrothermal condition of the structure in the area of thermal bridges. Figure 8.8 shows the room climate in room 1.3 and the weather conditions over the course of the year. It becomes clear here that the desired room temperature of 24°C was reached during the heating period. However, the relative humidity during the winter months could not be consistently maintained above 40%. The collected data is sufficient, however, to evaluate the influence of increased room moisture on the retrofitted structure during the cold weather periods.

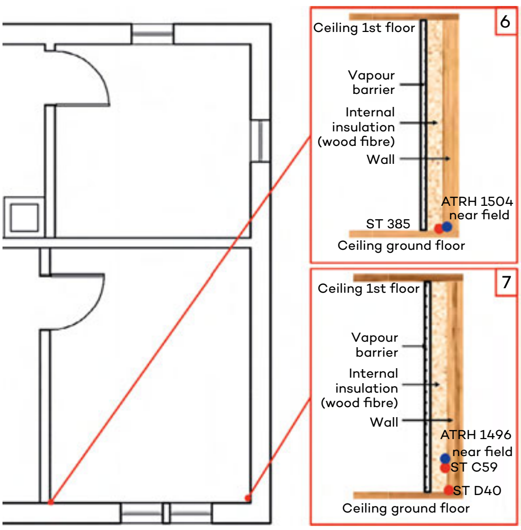
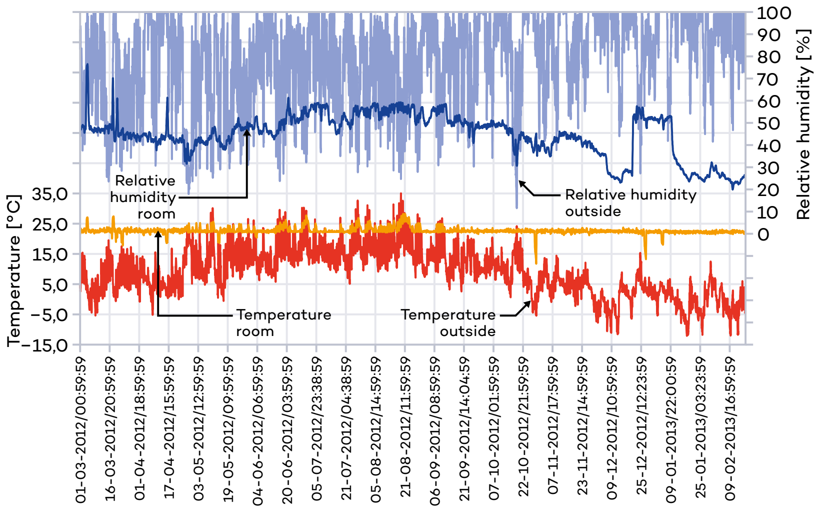


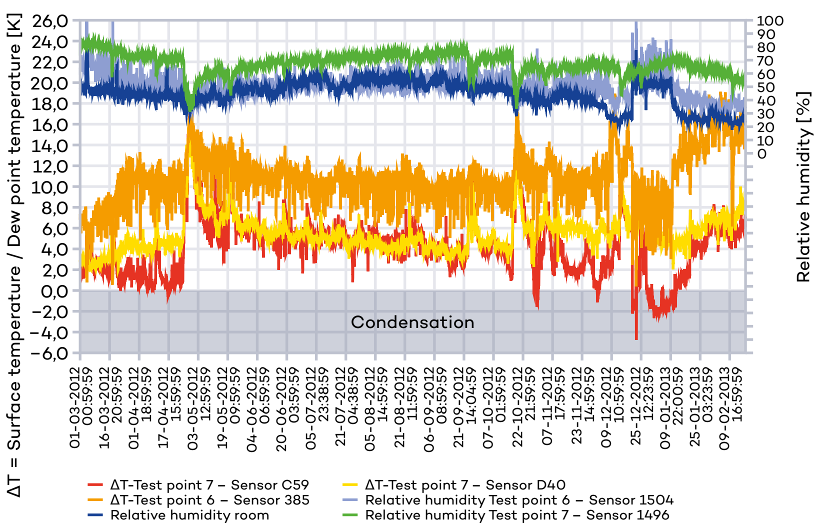
Fig. 8.7: Exemplary test points 6 + 7 for structure monitoring (ATRH = near-field climate; ST = surface temperature)

Fig. 8.8: Room climate v. outdoor climate



In Figure 8.9, the relative humidity of the air inside the room and in the near-field of the examined measuring points is depicted, together with the difference between surface temperature and dew point temperature. If the difference ΔT ≤ 0, condensation water forms in the structural layer. During the examination period, it was observed that no condensation formed at any time in the area of the incorporating wall (see Fig. 8.9, orange trace). In the vicinity of the outer corner of the building however, condensation formed behind the insulation layer during cold winter periods. However, room moisture of more than 50% RH was necessary for this (see Fig. 8.9, brown trace).

Fig. 8.9: Evaluation of condensation risk potential in the construction element (see sensor position in Fig. 8.7)

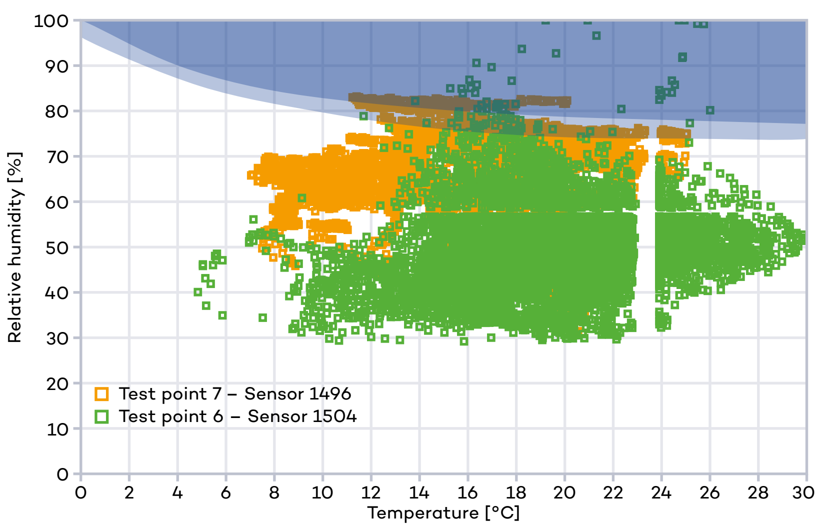


Almost all wood-destroying fungi need for their development moisture contents in the range of the fiber saturation.

This is on average about 30% and arises only in the presence of a long-term moisture exposure. Moisture loads can result from constant condensation or a relative humidity of 100% close to the wood surface. The potential danger to the wooden structure from dry rot infestation is therefore an important criterion to be evaluated. The condensation observed in the area of the outer corner could create the conditions necessary for dry rot infestation. In the authors' opinion, however, we may assume that the condensate was present only for a relatively short time. Owing to the prior treatment of the wood, its moisture content did not reach the levels necessary for dry rot growth. We may furthermore assume that in such cases the condensed water will mainly be absorbed by the fibrous boards of the interior insulation. These will then release the stored moisture as soon as the conditions are suitable for them to dry out.

Another criterion for evaluating the danger to the structure is the appearance or spread of mildew. The various mildew species need significantly different conditions for growth. This is why the evaluation of microclimates in the zone behind the insulation layer is based on the isopleths model for substrate groups I and II according to WTA data sheet 6-3-05. Figure 8.10 shows, to assess the risk potential, the measured microclimates of a seasonal cycle at test points 6 and 7. Here we can observe that climates favourable to mildew activity rarely develop close to the incorporating wall (see Fig. 8.10, green marks). The mildew risk at the outer corner of the building must be estimated as slightly higher, however.

Fig. 8.10: Evaluation of risk potential for mould; test points 6 + 7 (Substrate group I = light blue area; Substrate group II = dark blue area)



The measured data shows that critical climates in the zone behind the insulating layer only form if the indoor air has been humidified actively. At an average relative indoor air humidity of 30%, however, no condensation was observed in the critical areas. Here a relative air humidity of <70% developed (see Fig. 8.9). In Figure 8.9, the relation between the relative room humidity and the relative air humidity behind the insulation becomes clear. An increase in the relative room humidity of more than 50% in December 2012 had a direct impact on the near-field climate of the insulation layer. This suggests that water vapour molecules can enter the insulation layer. This is why the authors deem it necessary to take all of the measures recommended for building maintenance before conducting energy-efficient retrofitting. This includes, among other things, the realignment of floor boards to achieve better airtightness beforehand. Although the measured data and the visual checks during the removal of the interior insulation did not indicate that structural damage had occurred during the test period, such damage cannot be ruled out completely, since the residual risk depends on the intensity of use and the weather conditions with regard to the aforementioned damage mechanisms. This is why additional measures for the protection of the structure should be taken when installing the interior insulation:

Mechanical ventilation system, so that excessive room moisture cannot form in cold weather.

Install heating cables in the endangered areas. With these, it is possible to increase the surface temperature by only a few Kelvin if needed, sufficiently for condensation not to form.

The examined building was heated by a single stove in the early stages of use. For this reason, there is no information about the heating energy consumption before energy retrofitting. Figure 8.11 shows a comparison of the calculated and the real heating consumption after the retrofit. The real heating consumption for the test period was 97 kWh/m^{2}a; the value calculated with the PHPP tool was 130 kWh/m^{2}a. Since the actual and the calculated heating consumption after the retrofitting deviate, we must assume that the actual heating demand for the non-renovated building is also slightly less than the 284 kWh/m^{2}a calculated. For this reason, the authors assume that the heating demand before retrofitting was approximately 200 kWh/m^{2}a. Thus the heating demand was in fact reduced by more than 50% by the energy-saving measures implemented. Within the scope of the research project, electric heater batteries were used for heat generation. However, these negatively affect the primary energy demand. If the existing wood stove were to be used, this would, for example, reduce the primary energy demand. As the stove does not have significant impact on the

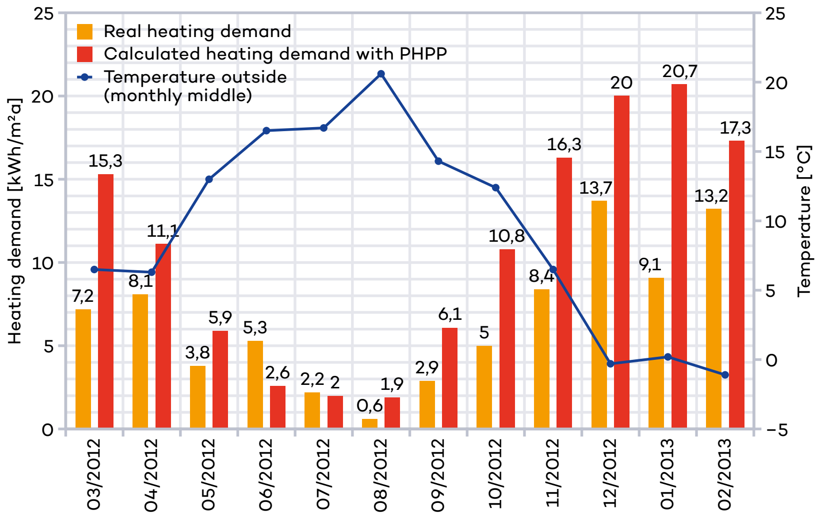


Fig. 8.11: Heating demand after retrofit (the orange bar was calculated using PHPP and the yellow bar was measured)

temperatures on the first floor, however, additional heating systems could be installed that are more suited to reducing the primary energy demand.

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GENERAL EVALUATION OF CASE STUDIES AND CONCLUSIONS

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From theory to practice: lessons learnt from case studies

The 3ENCULT project approached the question of how to come up with energy efficient solutions for cultural heritage in two overall ways; the top-down and the bottom-up approach. Both approaches have advantages and disadvantages. The first, more general approach covered a wide range of universal solutions, concepts, and possibilities, while the individual case studies were necessary to demonstrate and validate the generalised concepts for a specific building and environment. The two approaches may be summarised as follows:

The *top-down approach* looks for solutions based on the evaluation of impact analyses as well as the comprehensive diagnosis of built heritage for sustainable intervention. This approach may start either from a wide perspective of integration in urban sustainability concepts and strategic environmental assessments, also considering building energy issues, or from a smaller perspective involving historical and structural investigations, and diagnosis of a building assessed with an inventory system (see Section 3.2.). The structural diagnosis is closely linked to the investigation of building physical problems which ideally could be solved collaterally with the enhancement of energy efficiency.

The *bottom-up approach* for the development of energy efficient solutions is to analyse specific case studies (CS) and their special needs. Tailor-made solutions for the individual requirements of historic buildings can be developed, realised, and monitored on a real scale. The optimal solutions are analysed and their transferability and applicability to other climates or different contexts of historic, architectural and conservational values are investigated in an interdisciplinary way.

This chapter gives a general evaluation of the case studies and conclusions from both the conservation and the energy efficiency points of view. It is based on the task 'Preservation issue surveillance' from 3ENCULT [3ENCULT, 2014] which assured the conservation compatibility of the developed products and methods.

Internal surfaces (walls and ceilings)

The possibility for interventions such as internal insulation depends on the quality and historic value of the interior surfaces. For example, in CS1 wall paintings and frescoes were found. Historic wall surface layers or stucco ceilings, however, must also be taken into account, such as paint layers, the appearance of the historic plaster, or the uneven surfaces and edges that allow us to perceive the history of the building. This is evaluated in the conservator's assessment. All these factors make the biography of the house readable. From a conservator's point of view the inner surfaces of a building are like the skin of a human being. They have to be preserved for their historic value or typical workmanship. The usual approach of renovations of the interior wall surface is to determine a layer of historic value, expose it, and preserve this layer with limewash paint. In general it has to be decided room by room how the surfaces should be covered. For ancillary rooms the technical and aesthetical value of the surfaces also has to be evaluated individually.

Historic surfaces that are covered with thermal insulation are not visible and 'perceivable' anymore. This can be a problem from the conservation point of view. There are spray-on insulation systems (such as cellulose fibre) or insulation plaster systems which follow the original surface contour; however smaller unevenness is not reproduced. Moreover, any changing of the symmetry of stucco ceilings and any change in the delicate original proportions of the rooms should be avoided.

Summary of recommendations from the conservators' point of view:

→ any risk of harm for the original structure must be avoided;
→ internal insulation should be removable and should not leave any trace on the existing walls (the principle of reversibility);
→ existing flooring should be conserved.

External surfaces / facades

Similar to the internal surfaces, external surfaces and facades have to be assessed by the conservator. Components such as frescoes, historic plaster, the type of masonry (material and mortar joints), and decorative frames around the window show the construction history of the building.

The original proportions of the facade should remain evident. For this reason no interventions such as external insulation were possible in most cases (see CS1-CS8); hence depending on the inner surfaces, internal insulation had to be considered. In some cases, solutions for applying external insulation (which increases the wall thickness) while keeping the original proportions can be found. For example, if the window is shifted towards the outside, the window's visible dimension can be kept the same, while the new position of the window is within the insulation layer. This also helps reduce the thermal bridges at the window installation.

For large buildings the thickness of the external insulation is mostly negligible in terms of proportion of the facade; however symmetry has to be taken into account.

From a building physics point of view, external insulation would be the first choice, because the original wall is kept dry and temperature fluctuation is reduced. Consequently, the original structure is preserved well against humidity, frost, and temperature stress. In CS5 external insulation would also solve the problem of corrosion of the steel reinforcement of the ceilings.

Similar to internal insulation, reversibility is important, hence materials such as cellulose fibre are preferred.

Roof

The approach to assessment of roofs by conservators depends on the individual construction type (mostly wooden rafters) and the roof covering. Historic tiles have to be preserved due to their historic value and/or because of the homogeneous appearance of the roof-scape in historic city centres, especially if they can be seen from surrounding elevations.

If insulating a historic roof is considered, the eaves should not be changed by, for example, raising the roof covering to put insulation above the rafters. The profile and proportions of the roof edge should be preserved.

In some cases the insulation between and below the rafters is possible. However, a vapour barrier (and airtight layer) is necessary to avoid any damage by convection and diffusion of humid indoor air.

The other possibility is to apply an insulation layer at the top floor ceiling as in case of CS5. The disadvantage of this solution is that the attic becomes an unheated space with different usability.

Installation of tubes and cables

For any installation work to be done, the principle of reversibility holds. The recommendation of the conservators is to use existing building openings, inspection chambers, and chimneys as much as possible. The latter can be used also for ventilation ducts; however it should be noted that historic chimneys are often not perfectly straight. As an alternative to conventional air handling, the principle of active overflow ventilation (as demonstrated in CS5) can be applied, which helps avoid ductworks.

For horizontal distribution of installation cables and tubes, existing gaps in the floors and ceilings should be used as far as possible, and baseboards for cable distribution can be used where appropriate. It has to be analysed and decided individually if it is possible to cut out slots and apertures for vertical distribution of cables and tubes depending on the existence of, for example, mural paintings.

If possible, the vertical distribution of cables and tubes should be avoided. Inserting floor sockets or exposed laying of cables (e.g. in a trunking) is recommended instead.

It has to be decided individually if existing holes or apertures in the exterior walls can be closed or not, depending on their position and original function, such as ventilation.

If there is no need to use existing holes in the building structure, or if they have no relevant function, they can be closed. Closing holes must be well documented during the process of construction.

Windows, shading and daylight redirection

Before any window renovation measure is considered, the existing window structure in terms of window openings and their history has to be investigated in detail (original structure, and possible changes and extensions).

Original windows are an important part of conservation values. Old windows should be restored rather than replaced, and only if they are in a very bad condition is a new window acceptable.

Firstly, the dimension of the original window apertures as well as function, division, and proportion of the historic windows should be analysed from original material or documents (if available). However, in some cases, such as CS1 (main structure from the early Middle Ages) there is neither an original window nor any existing documentation. In this case a decision on design and function must be made by the conservator. In the case of the Waaghaus (Public Weigh House), a typical Bolzano box-type window was the model in terms of function, division, and proportion. Detailed specifications and recommendations on profiling, colour, glass type, and material, as well as the type of the hinges and metal mount were given for the development of a prototype which was both conservation compatible and energy efficient (see Figs. 9.1 and 9.2).

Fig. 9.1: CS1, drawings of the second window prototype for the Waaghaus as box-type window

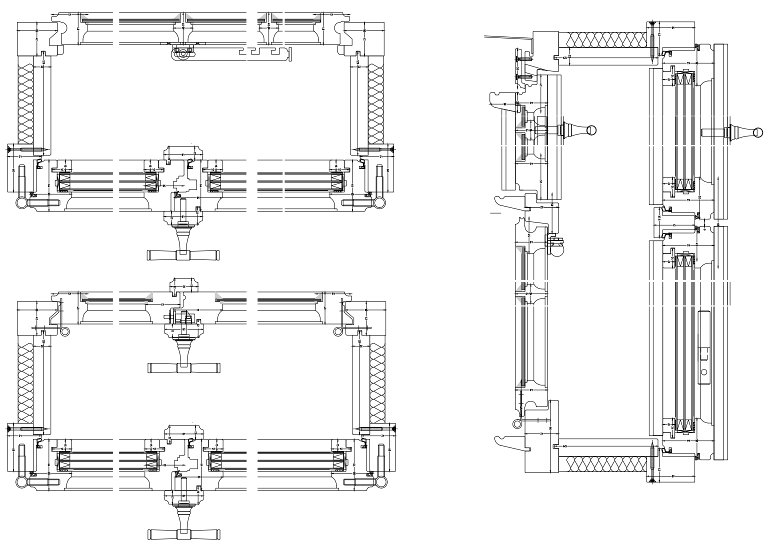


Fig. 9.2: CS1, drawings of the second window prototype for the Waaghaus as coupled window

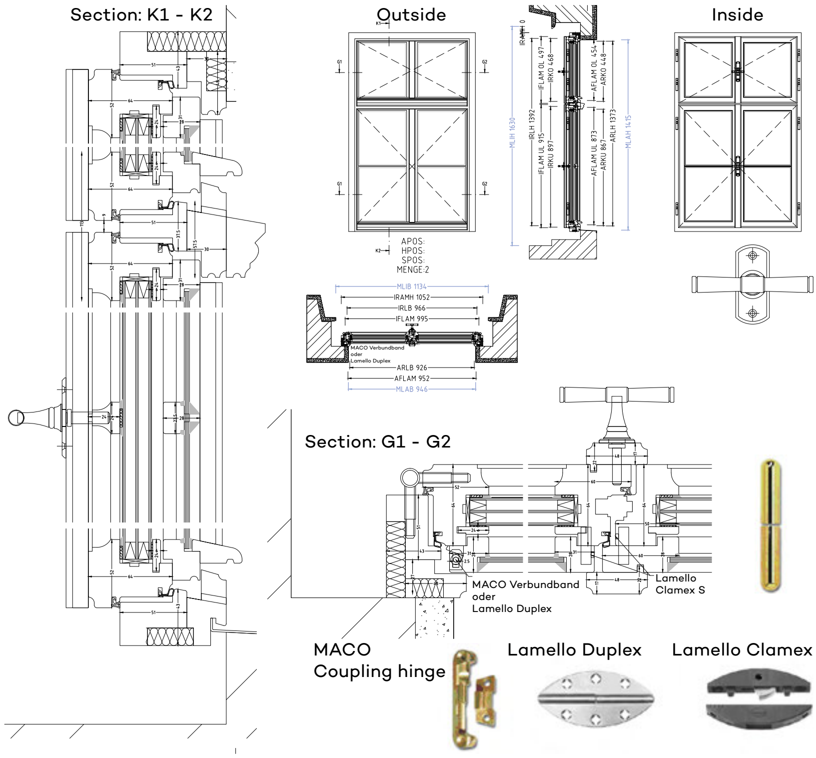
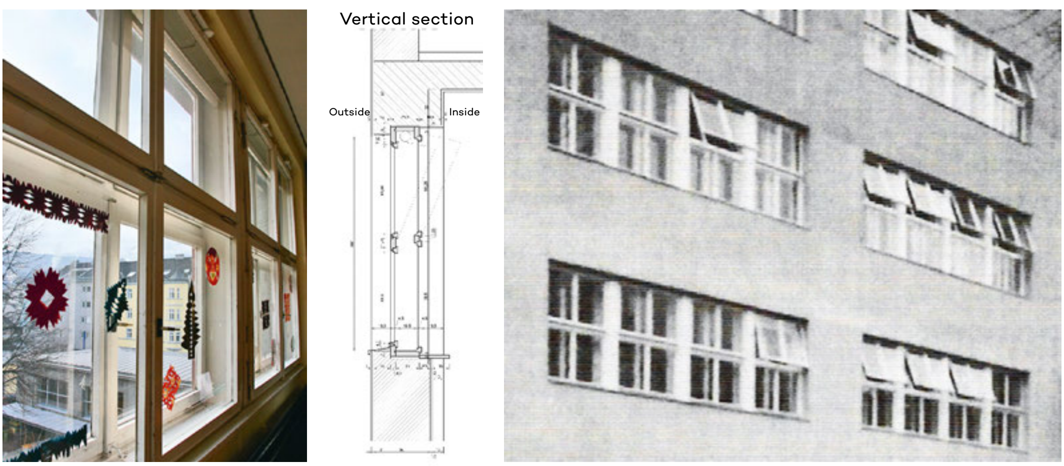


Fig. 9.3: CS5, Box-type window before intervention: l-r, both panes opening to the inside (view from inside); vertical cross section; original photograph from the outside, upper pane opening to the outside

In other cases, such as CS5 (main structure early Modernism, 1929/30), detailed drawings and photographs from archives may help to reconstruct the original proportion and function. For the intervention, it was decided to reconstruct the opening of the upper pane to the outside as it was in the original windows in 1930 (see Fig. 9.3).



South facing windows without overhang or east/west-facing windows may produce a risk of overheating if no sun shade is installed. Generally the original system should be restored. New shutters or awnings are generally not acceptable as they will greatly change the character of the facade which is an important part of the historic value. The same holds for most new kinds of external shading. Internal shading is not a solution because it has almost no effect and protects against glare only. A compromise is a 'glazing-integrated shading' placed between the glass panes as close to the outside as possible for optimal effect. A box-type window gives the opportunity to integrate shading and daylight redirection as demonstrated in CS5. Such an intervention can be considered if it does not noticeably affect the building's heritage value. From a technical point of view, it is a challenge to find a product with the height of the stack of blind slats that is also small enough to be hidden behind the frame.

Ventilation

As described in the section about ventilation, most historic buildings were originally ventilated through windows taking advantage of cross and stack ventilation. During winter, the ventilation in historic buildings worked similarly to the way extract air systems work today. The negative pressure inside the building was created by the stove via the chimney in the same way as by a fan. The outdoor air entered through leakages in the building envelope. In summer, window stack ventilation during the night helped keep the building cool during the day.

The following questions have to be answered before considering any interventions in the ventilation:

→ What was the original use of the building (humidity sources, odour emission, etc)?
→ Is there any damage from moisture (mould growth, wood rot, wood worms, etc)?
→ What was the original method of ventilation (opening windows, leakages in the building envelope, internal flow paths such as ventilation shafts, etc)?
→ What is the intention for future use of the building (humidity sources, odour emission, etc)?
→ Airtightness level of the building envelope after the interventions?
→ Which type of heating system will be applied in future?

Problems with mould growth may arise if the building envelope is made more airtight and the stove heating system is replaced by a central heating system. Humidity from indoor sources is not vented out effectively if the users do not open the windows regularly.

Mechanical ventilation may help solve humidity problems even with changed conditions of use, and can fulfil modern comfort demands. CS4 for example is used as an office building today. The responsible engineer decided that window ventilation was sufficient in single office rooms. In larger office spaces, however, there must be a mechanical ventilation. The cultural heritage authority accepted exhaust air through the chimney, even though a standard fresh air intake valve in the windows was refused. From the architectural point of view suspended ceilings were rejected in rooms with a stucco ceiling.

If it is possible to install heat recovery ventilation, comfort as well as energy efficiency is significantly improved. The section about ventilation describes several new ideas and developments particularly relevant to integration in historic buildings; however there is no generic solution or one ventilation method that has optimal compatibility with conservation. If any ducts are necessary, the tips in section 'Installation of tubes and cables' should be considered, but the best way is to avoid ducts as far as possible (for example by cascade ventilation or active overflow; refer to CS5 and the section 'Ventilation').

Heating and cooling

Lessons learnt about the decisions on appropriate heating and cooling systems for historic buildings are similar and sometimes correlated to the ventilation system. They usually strongly depend on the future use of the building and the demands of temperature and comfort.

Moreover, the size and type of the system applied depends on the new heating and cooling loads after the interventions have been performed. All reductions of heat losses by enhancement of the insulation of the building envelope, improvement of its airtightness, and installation of any heat recovery system will minimise the heating load, and consequently reduce the size of the required heating and distribution system. If the heat emitting surface

Fig. 9.4: CS5, Original radiator with new pipes inside the thermal envelope

remains the same, as in the case of the historic radiators in the class rooms of CS5 which are part of the original architectural design, the flow temperature can be reduced significantly.

The treatment of the heat distribution system in the case of a central heating system depends very much on the location of the insulation layer with respect to the heating pipework. Originally most tubes were placed within the wall. This is not a problem if external insulation is applied. If an internal insulation layer is to be installed, the location of the tubes has to be changed because of frost risks. New internal insulated ducts have to be mounted or integrated into the insulation layer if possible. The latter solution is expensive with thermal bridging problems and inappropriate penetration of the airtight layer (internal plaster).

In CS4, fan coils under the windows are used both for heating and cooling via air recirculation. This decision was the result of an interdisciplinary discussion of the case study team consisting of an engineer, an architect, and a conservation authority. Perceivable and irreversible mechanical devices in a historic building are basically unacceptable; however all other solutions would have had a higher negative impact on ceilings and walls. The ceilings are an essential part of the architecture, especially if the windows reach up to the ceiling and therefore no suspended ceiling can be created.

In CS1, the possible use of the thermal inertia of the cellar for cooling in summer was investigated. Any direct ventilation of the cellar with warm and humid air should be avoided due to the risk of condensation and mould growth. Air recirculation via a counter flow heat exchanger may be able to be used since the separation plates in the heat exchanger will prevent direct transmission of the air mass, but not of the heat. This way, the temperature of the cellar will rise (lower condensation risk) and the summer comfort in the rest of the building can be enhanced.

Artificial light and electricity

Energy-saving light sources open up a wide range of opportunities in addition to the savings potential of electronic ballasts and control. New LED technology, close to a market breakthrough, also gives the possibility of light temperature control. A prototype of this technology, with daylight-adaptive light temperature control, was tested in one classroom of CS5. The cultural heritage authority agreed with the substitution as the existing fluorescent tubes were not original (Figure 9.5 shows the original incandescent light bulbs).

Besides improved energy efficiency and light quality (colour temperature), the LED technology gives new impetus to further improvements leading to a high-quality artificial light in museums and historic buildings for illumination of paintings and artefacts

Fig. 9.5: Original incandescent light bulb (left); fluorescent tube - old technology (right) and LED technology (bottom)

(for example, the LED wall washer developed by 3ENCULT for CS2). The energy diagnosis for CS2 highlighted that a very high amount of electric energy, corresponding to 25% of the entire energy consumption of the museum area, is consumed by light sources. Solutions able to significantly reduce the electricity consumption of artificial lighting have been studied, i.e. working with power regulation depending on the number of visitors present in the room.

Acoustics

The acoustics in historic buildings are part of their individual characteristics. They are strongly influenced by the equivalent sound absorption areas of all materials and surfaces in the space. The higher the total equivalent sound absorption area of the room, the lower its reverberation time. As the reverberation time strongly influences speech intelligibility, it should be reduced according to the use of the room (e.g. auditorium, class room). In the case of historic buildings, covering surfaces with sound absorbers is usually not acceptable (e.g. for architectural reasons, stucco, or paintings) or not suitable (blocking the thermal inertia of ceilings or walls resulting in reduced summer comfort). In this case, vertically suspended absorbers (baffles) are useful, if the design fits into the room and its architecture. 3ENCULT developed special absorbers for the prototype class rooms in CS5, which also work well in combination with the daylight redirection (see Fig. 9.6).

Fig. 9.6: Acoustic elements (made by ORGANOID) in combination with daylight redirection

Summary

Renovating protected buildings is typically much more difficult than standard renovations due to the preservation issues and the complexity of the planning process. This fact makes the work of the design team more demanding, but at the same time creates challenges and triggers the creation of novel and innovative solutions. Such approaches can develop model solutions for similarly restricted objects and even be used in conventional construction without heritage protection.

The case studies of 3ENCULT are located all over Europe. The outcomes are not solely bound to the selected buildings, but are applicable to numerous other sites. Although heritage legislation in Europe acts in accordance with generally accepted charters and guidelines, the organisation and evaluation differs from country to country. Nevertheless the recommendations proposed by the Austrian guideline *Energieeffizienz am Baudenkmal* [BDA Austria, 2011] is generally accepted (see Section 4.2.). Keeping these basic recommendations in mind, new solutions, concepts, and ideas arise, suitable for both the conservation of our built heritage and for environment protection by energy efficiency and use of renewables.

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