GENERAL PROJECT DESCRIPTION

CASE STUDIES

CASE STUDY 1
Waaghaus, Bolzano, Italy

CASE STUDY 2
Palazzo D’Accursio, Bologna, Italy

CASE STUDY 3
Palazzina della Viola, Bologna, Italy

CASE STUDY 4
The Material Court of the Fortress, Copenhagen, Denmark

CASE STUDY 5
Hötting Secondary School, Innsbruck, Austria

CASE STUDY 6
Warehouse City and Others, Germany

CASE STUDY 7
Industrial Engineering School, Béjar, Spain

CASE STUDY 8
Strickbau, Weissbad / Appenzell, Switzerland

GENERAL EVALUATION
OF CASE STUDIES AND CONCLUSIONS
GENERAL PROJECT DESCRIPTION

Alexandra Troi, EURAC research

In extreme synthesis, the project can be summarised in five sentences:

1. The FP7 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.

2. 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.

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 CO₂ 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...
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.

**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.
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).

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.
Conclusions

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.
CASE STUDIES

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).

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Class. | Description | Case studies
--- | --- | ---
Csa | Mediterranean climate (dry hot summer, mild winter) | Bejar, 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
Dbf | 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
<table>
<thead>
<tr>
<th>Name</th>
<th>Waaghaus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Bolzano / Bozen, Italy (46°50' 0&quot;, 11°35' 5&quot;)</td>
</tr>
<tr>
<td>Date of construction</td>
<td>Thirteenth century</td>
</tr>
<tr>
<td>Architectural style(s)</td>
<td>Romanesque arcade building ('Laubenhaus')</td>
</tr>
</tbody>
</table>
| 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 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
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.

**Pre-intervention analysis**

**Historic evolution of the building**

Fig. 1.2: The fresco by Albert Stolz on the arch over the alley shows the ‘Fronwaage’.

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-thermo-graphy, 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.
Physical properties of materials and construction details

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.

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).

<table>
<thead>
<tr>
<th>Component</th>
<th>Exterior wall (north side)</th>
<th>Parapet under window (north side)</th>
<th>Ceiling over porticos (inserted floor ceiling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material/construction</td>
<td>Lime plaster, natural stone /lime mortar</td>
<td>Lime plaster, natural stone /lime mortar</td>
<td>Lime plaster and mortar, wooden slats, wooden beams, filling of earth, sand and pebbles</td>
</tr>
<tr>
<td>Thickness [m]</td>
<td>0.62</td>
<td>0.26</td>
<td>0.60</td>
</tr>
<tr>
<td>Measurement time [h]</td>
<td>96</td>
<td>96</td>
<td>120</td>
</tr>
<tr>
<td>Conductance [W/m²K]</td>
<td>1.36, (1.37)¹</td>
<td>2.86</td>
<td>0.48</td>
</tr>
</tbody>
</table>

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

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.

Distribution of daylight on the first floor

Outside
Vertical illuminance = 500 lx
Horizontal illuminance = 660 lx

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 %)
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.
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.
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.

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).

Tab. 1.5: Replacement of box-type windows from the 1950s/60s by a Smartwin historic (triple glazing plus additional historic glazing)

<table>
<thead>
<tr>
<th></th>
<th>$U_\text{g}$</th>
<th>$U_\text{f}$</th>
<th>$\Psi$ installation (without parapet)</th>
<th>$g$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing box-type</td>
<td>2.8 W/m²K</td>
<td>2.5 W/m²K</td>
<td>0.24 W/mK</td>
<td>0.77</td>
</tr>
<tr>
<td>Smartwin historic</td>
<td>0.57 W/m²K</td>
<td>0.97 W/m²K</td>
<td>0.16 W/mK</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Insulation of other envelope parts

<table>
<thead>
<tr>
<th></th>
<th>ROOF</th>
<th>BASEPLATE TO GROUND</th>
<th>BASEMENT CEILING</th>
<th>SLABS TOWARDS ARCADES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction as-is state</td>
<td>Partly 8 cm rock wool</td>
<td>Concrete slab</td>
<td>Vaulted natural stone ceiling, lime mortar joints</td>
<td>Wooden beams; sand, earth and pebble filling; underside ceiling lime plastered; floor wooden substructure and boards</td>
</tr>
<tr>
<td>U-value as-is state</td>
<td>2.6 W/m²K / 1.4 W/m²K</td>
<td>2.7 W/m²K</td>
<td>1.0 W/m²K</td>
<td>0.44 W/m²K</td>
</tr>
<tr>
<td>Intervention</td>
<td>25 cm of insulation ($\lambda$ 0.042), 11 cm between rafters, 14 cm from below</td>
<td>12 cm perlite ($\lambda$ 0.05) in pavement structure</td>
<td>12 cm perlite ($\lambda$ 0.05) in pavement structure</td>
<td>Substitution of existing filling material between beams with 18 cm insulation ($\lambda$ 0.042), additionally a 3 cm continuous layer on the wooden beams</td>
</tr>
<tr>
<td>U-value refurbished</td>
<td>0.17 W/m²K</td>
<td>0.36 W/m²K</td>
<td>0.30 W/m²K</td>
<td>0.17 W/m²K</td>
</tr>
</tbody>
</table>

1 Check thermal bridges caused by interior walls

Tab. 1.6: Energy efficient enhancement of opaque parts of the envelope
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.

![Heating demand CS1 with different refurbishment solutions](image)

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.

**Ventilation**
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 development 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 façade 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

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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).
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).

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).
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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<thead>
<tr>
<th><strong>Name</strong></th>
<th>Palazzo d'Accursio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Bologna, Italy</td>
</tr>
<tr>
<td><strong>Date of construction</strong></td>
<td>Thirteenth century</td>
</tr>
<tr>
<td><strong>Architectural style(s)</strong></td>
<td>Not one homogeneous architectural style, austere architectural language for the fourteenth century section, decorated and embellished features for the fifteenth century section</td>
</tr>
</tbody>
</table>
| **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, consumption before intervention [kWh/m²a]** | Average value (2010–2013): 106 kWh/m²a |
CASE STUDY 2

PALAZZO D’ACCURSIO, BOLOGNA, ITALY

Manuela Faustini Fustini, Federica Legnani, Francesco Tutino, Comune di Bologna / Valerio Nannini, Sandra Deisvaldi, Nicola Silingardi, Mena Viscardi, ICIE / Enrico Esposito, Artemis Srl / Camilla Colla, Elena Gabrielli, Marco Giuliani, DICAM, University of Bologna
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.
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.
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
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.
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%).

<table>
<thead>
<tr>
<th>Heat flows [kWh/(m²a)]</th>
<th>Losses</th>
<th>Gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non useful heat gains</td>
<td>79</td>
<td>21</td>
</tr>
<tr>
<td>Exterior wall – Ambient</td>
<td>80.4</td>
<td>20</td>
</tr>
<tr>
<td>Floor slab/ Basement ceiling</td>
<td>9</td>
<td>90</td>
</tr>
<tr>
<td>Unheated area</td>
<td>45.5</td>
<td>256</td>
</tr>
<tr>
<td>Windows</td>
<td>45.5</td>
<td>10.8</td>
</tr>
<tr>
<td>Ventilation</td>
<td>3.63</td>
<td>1.06</td>
</tr>
<tr>
<td>Solar gains</td>
<td>21</td>
<td>6.1</td>
</tr>
<tr>
<td>Internal heat gains</td>
<td>21</td>
<td>6.1</td>
</tr>
<tr>
<td>Heating demand</td>
<td>21</td>
<td>6.1</td>
</tr>
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</table>

Fig. 2.8: Pre-intervention energy balance

Fig. 2.9: Post-intervention energy balance

<table>
<thead>
<tr>
<th>Energy balance heating (annual method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated floor area 1015.0 m²</td>
</tr>
<tr>
<td>Requirements</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Space heating</th>
<th>Heating demand</th>
<th>273 kWh/(m²a)</th>
<th>15 kWh/(m²a)</th>
<th>no</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating load</td>
<td>124 W/m²</td>
<td>10 W/m²</td>
<td>no</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Space cooling</th>
<th>Overall spec. space cooling demand</th>
<th>2 kWh/(m²a)</th>
<th>—</th>
<th>—</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling load</td>
<td>19 W/m²</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Frequency of overheating (&gt; 25 °C)</td>
<td>17 %</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Primary energy</th>
<th>Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances</th>
<th>54.3 kWh/(m²a)</th>
<th>120 kWh/(m²a)</th>
<th>no</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHW, space heating and auxiliary electricity</td>
<td>4.39 kWh/(m²a)</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Specific primary energy reduction through solar electricity</td>
<td>kWh/(m²a)</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Airtightness</th>
<th>Pressurization test result n₅₀</th>
<th>5.9 1/h</th>
<th>0.6 1/h</th>
<th>no</th>
</tr>
</thead>
</table>

* empty field: data missing; ∗:* no requirement
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.
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.

---

**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.
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 microclimate 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.
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

References

Hubert, 1993 Hubert, Hans W., Der Palazzo Comunale von Bologna, 1993.


Codes and regulations


<table>
<thead>
<tr>
<th><strong>Name</strong></th>
<th>Palazzina della Viola</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Via Filippo Re 2, 40126 Bologna, Italy (Lat N 44° 29’ – Long E 11° 20’)</td>
</tr>
<tr>
<td><strong>Date of construction</strong></td>
<td>1497 by Giovanni II Bentivoglio</td>
</tr>
<tr>
<td><strong>Architectural style(s)</strong></td>
<td>Renaissance</td>
</tr>
<tr>
<td><strong>Construction type / materials</strong></td>
<td>Lightweight-masonry building with ceilings made of timber beams or more recent concrete and brick elements, steel beams</td>
</tr>
<tr>
<td><strong>Original building use</strong></td>
<td>Hunting lodge and leisure activities</td>
</tr>
<tr>
<td><strong>Current building use</strong></td>
<td>Since March 2012, International Relations Dept, University of Bologna</td>
</tr>
<tr>
<td><strong>Main alterations</strong></td>
<td>VRF system, DOAS with heat recovery, restoration of windows and floor, solar film on glazed surface of galleries</td>
</tr>
<tr>
<td><strong>Heating demand / consumption before intervention [kWh/m²a]</strong></td>
<td>Calculation using PHPP protocol: 278 [kWh/m²a]</td>
</tr>
<tr>
<td><strong>Heating demand / consumption after intervention [kWh/m²a]</strong></td>
<td>Calculation using PHPP protocol: 264 [kWh/m²a]</td>
</tr>
<tr>
<td><strong>Other noteworthy characteristics</strong></td>
<td>Presence of frescoes and painted wooden ceilings attributed to Amigo Aspertini, Prospero Fontana, and others (15th–16th century)</td>
</tr>
</tbody>
</table>
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

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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.

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**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).

---

<table>
<thead>
<tr>
<th>Area</th>
<th>$n_{\text{RH}}$ [1/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1F3</td>
<td>25.40</td>
</tr>
<tr>
<td>1F2 + 1F9</td>
<td>10.06</td>
</tr>
<tr>
<td>1F9</td>
<td>9.01</td>
</tr>
<tr>
<td>1F4, 5 + 6</td>
<td>14.65</td>
</tr>
</tbody>
</table>

---

**Fig. 3.3:** Investigation of ceiling build-up by GPR (left), 2D radargram showing the elements of the ceiling (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).
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).
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’.
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/(m²a). Calculations performed do not refer to space cooling because PHPP only shows the frequency of
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).

**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]
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.
References


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<tr>
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<td>Location</td>
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<td>Current building use</td>
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<td>Main interventions</td>
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<td>Heating demand / consumption before intervention [kWh/m²a]</td>
<td>151 (calculated value)</td>
</tr>
<tr>
<td>Heating demand / consumption after intervention [kWh/m²a]</td>
<td>130 (measured value)</td>
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</table>
CASE STUDY 4

THE MATERIAL COURT OF THE FORTRESS, COPENHAGEN,
DENMARK

Christoffer Pilgaard, Torben Dahl, Ola Wedebrunn, The Royal Danish Academy of Fine Arts
The Material Court of the Fortress is an ambitious restoration project, aiming at reducing the building’s energy consumption and CO₂ 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 CO₂ emissions. The private foundation Realdania Byg has owned the building since 2007 (see Fig. 4.1).

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).
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,
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 CO₂ 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, CO₂ 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.
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.

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).

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.

Floor insulation
Since the wooden floor had to be replaced on the ground floor, it was convenient to insulate the new flooring.
Post-intervention analysis

The interventions selected in the multidisciplinary process improved heat loss, with a CO₂ 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 CO₂ savings are expected to be 4.29%. Copenhagen Energy supplies district heating in the form of steam, where one ton of CO₂ corresponds to 6.8 MWh. Dong Energy supplies electricity, where one ton of CO₂ corresponds to 1.9 MWh. That is how the energy consumption is converted to CO₂. 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).
Third workgroup meeting: directional selection

The different interventions had an impact on the building’s energy consumption and CO₂ 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 CO₂ 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.

References
Bramsen; Bo Bramsen; Bo, Københavns før og nu – Gammelholm og Frederiksholm, Fogtdal, Copenhagen, 1987–1993.
Strunge; Jensen Strunge; Jensen, Eksempel projekt - Energirenovering i fredede bygninger, Realdeania Byg, Copenhagen, 2009.
| **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.
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.
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 CO₂ 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]).

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 n₅₀-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 n₅₀≈ 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
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.
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 CO₂ concentration in the corridor rises, the air flow rate of the central fan in the heat recovery unit rises in order to keep the CO₂ 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.

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].
References


<table>
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<tr>
<th>NAME</th>
<th>WAREHOUSE CITY BUILDING</th>
<th>WILHELMINIAN VILLA</th>
<th>BAROQUE BUILDING</th>
<th>RENAISSANCE BUILDING</th>
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<td>Heating demand after intervention [kWh/m²a]</td>
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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.

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.
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.

![Monitoring](image)

**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...
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**

The moisture content of the wooden beam in the west facade 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
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.
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.

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.
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).

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.
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.

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.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>DESCRIPTION</th>
<th>U-VALUE [W/(m²K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>window</td>
<td>wooden composite window</td>
<td>2.5</td>
</tr>
<tr>
<td>outer wall</td>
<td>mixed brick masonry – plaster exterior</td>
<td>1.0–2.5</td>
</tr>
<tr>
<td>roof</td>
<td>false ceiling – unheated attic</td>
<td>1.0–1.2</td>
</tr>
<tr>
<td>ceiling above ground floor 1</td>
<td>vault</td>
<td>0.7</td>
</tr>
<tr>
<td>ceiling above ground floor 2</td>
<td>false ceiling</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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.

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 sufficient to buffer the indoor temperature.

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).
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.

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, photovoltaic 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.

Figure 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 $U < 0.1 \text{ W/m}^2\text{K}$. 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).

![Monitoring system](image)

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.
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, 25 l/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.

Summary and 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.

References


WTA Fachwerkinstandsetzung nach WTA, Vol. 1, 8–1 to 8–9, Freiburg: Adeficatio-Verlag, 2001.


<table>
<thead>
<tr>
<th>Name</th>
<th>Industrial Engineering School of Béjar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Béjar, Salamanca, Spain (40° 23' 6.756&quot;, -5° 45' 39.48&quot;)</td>
</tr>
<tr>
<td>Date of construction</td>
<td>1968</td>
</tr>
<tr>
<td>Architectural style(s)</td>
<td>Constructivism</td>
</tr>
<tr>
<td>Construction type / materials</td>
<td>Reinforced concrete, brick and zinc panel</td>
</tr>
<tr>
<td>Original building use</td>
<td>Academic: University</td>
</tr>
<tr>
<td>Current building use</td>
<td>Academic: University</td>
</tr>
<tr>
<td>Main interventions</td>
<td>Lighting and HVAC: Control algorithms</td>
</tr>
<tr>
<td>Heating demand / consumption before intervention [kWh/m²a]</td>
<td>Electricity demand: 23 kWh/m²a (only lighting) Heating demand: 70 kWh/m²a</td>
</tr>
<tr>
<td>Heating demand / consumption after intervention [kWh/m²a]</td>
<td>Electricity demand: 18 kWh/m²a (only lighting) Heating demand: 70 kWh/m²a</td>
</tr>
<tr>
<td>Other noteworthy characteristics</td>
<td>Lattice</td>
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</tbody>
</table>
CASE STUDY 7

INDUSTRIAL ENGINEERING SCHOOL, BÉJAR, SPAIN

José L. Hernández, Miguel A. García, Roberto Sanz, Álvaro Corredera, CARTIF
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](image1)

![Fig. 7.2: Plans of the building](image2)
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 $U = 1.50 \text{ W/m}^2\cdot\text{K}$. The roof is made of zinc plate with a transmittance of $1.75 \text{ W/m}^2\cdot\text{K}$. The window frames are metallic and have large horizontal strips with thermal bridge optimisation and double glazing $4/20/4$ with a transmittance of $3.45 \text{ W/m}^2\cdot\text{K}$ and a $g$-value of 0.76. The overall transmittance of the building is $2.10 \text{ W/m}^2\cdot\text{K}$. 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 $581 \text{ kW}$ with efficiency of 88.5%, while the support boiler’s actual output is $418.6 \text{ kW}$ 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, CO₂ 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.
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.

<table>
<thead>
<tr>
<th>HEATING ENERGY BALANCE</th>
<th>PHPP (kWh/m²a)</th>
<th>TRNSYS (kWh/m²a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation losses</td>
<td>17.90</td>
<td>25.70</td>
</tr>
<tr>
<td>Transmittance losses</td>
<td>94.70</td>
<td>154.89</td>
</tr>
<tr>
<td>Windows</td>
<td>34.60</td>
<td></td>
</tr>
<tr>
<td>Floor/slab basement</td>
<td>13.20</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>11.90</td>
<td></td>
</tr>
<tr>
<td>Ext. wall (ground)</td>
<td>2.30</td>
<td></td>
</tr>
<tr>
<td>Ext. wall (ambient)</td>
<td>32.70</td>
<td></td>
</tr>
<tr>
<td>Solar gains</td>
<td>11.60</td>
<td>62.72</td>
</tr>
<tr>
<td>Internal heat gains</td>
<td>13.00</td>
<td>22.23</td>
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<tr>
<td>Convection</td>
<td></td>
<td>12.26</td>
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<tr>
<td>Radiation</td>
<td></td>
<td>9.97</td>
</tr>
<tr>
<td>Annual heating demand</td>
<td>88.00</td>
<td>95.64</td>
</tr>
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</table>
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.

**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 ($n_{50} \approx 8.91/h$), 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](image-url)
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.

<table>
<thead>
<tr>
<th></th>
<th>PASSIVE SOLUTIONS</th>
<th>ACTIVE SOLUTIONS</th>
<th>CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency</td>
<td>→ internal/external insulation → Airtightness</td>
<td>→ Thermal distribution improvement → Ventilation with heat recovery</td>
<td>→ Lighting system</td>
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<tr>
<td>Comfort</td>
<td>-</td>
<td>-</td>
<td>→ Lighting system → HVAC system</td>
</tr>
<tr>
<td>RES Integration</td>
<td>-</td>
<td>→ Solar PV → Biomass boilers</td>
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</table>

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.

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.

![Diagram of the lighting control algorithm](image-url)
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.

<table>
<thead>
<tr>
<th></th>
<th>Electricity Consumption Before</th>
<th>Electricity Consumption After</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>2.60 kWh</td>
<td>0.90 kWh</td>
</tr>
<tr>
<td>May</td>
<td>3.30 kWh</td>
<td>1.70 kWh</td>
</tr>
<tr>
<td>June</td>
<td>0.60 kWh</td>
<td>0.70 kWh</td>
</tr>
<tr>
<td>July</td>
<td>1.60 kWh</td>
<td>0.40 kWh</td>
</tr>
<tr>
<td>August</td>
<td>0.00 kWh</td>
<td>0.10 kWh</td>
</tr>
<tr>
<td>September</td>
<td>0.50 kWh</td>
<td>0.40 kWh</td>
</tr>
<tr>
<td>October</td>
<td>1.40 kWh</td>
<td>1.00 kWh</td>
</tr>
<tr>
<td>November</td>
<td>2.20 kWh</td>
<td>1.30 kWh</td>
</tr>
<tr>
<td>December</td>
<td>1.50 kWh</td>
<td>1.00 kWh</td>
</tr>
<tr>
<td>January</td>
<td>1.30 kWh</td>
<td>1.10 kWh</td>
</tr>
<tr>
<td>Total</td>
<td>15.00 kWh</td>
<td>8.60 kWh</td>
</tr>
</tbody>
</table>

Tab. 7.2: Electricity consumption in the physics laboratory

Fig. 7.10: Physics laboratory lighting level in June

References


3ENCULT, D6.2 CS7, 2014 3ENCULT deliverable 6.2, Hernandez, J.; Antoli, J.; García, M.A.; Sanz, R.; Corredera, A., Documentation of CS7 Engineering School of Béjar, Salamanca (Spain), 2014

<table>
<thead>
<tr>
<th><strong>Name</strong></th>
<th>Appenzell/Weissbad</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Weissbad, Switzerland, (47°30' 1.672 – 9° 44' 09.64)</td>
</tr>
<tr>
<td><strong>Date of construction</strong></td>
<td>1630</td>
</tr>
<tr>
<td><strong>Architectural style(s)</strong></td>
<td>Strickbau (log building)</td>
</tr>
<tr>
<td><strong>Construction type / materials</strong></td>
<td>Timber</td>
</tr>
<tr>
<td><strong>Original building use</strong></td>
<td>Farmhouse/residential building</td>
</tr>
<tr>
<td><strong>Current building use</strong></td>
<td>disused/residential</td>
</tr>
<tr>
<td><strong>Main interventions</strong></td>
<td>internal insulation added</td>
</tr>
<tr>
<td><strong>Heating demand / consumption before intervention [kWh/m²a]</strong></td>
<td>not known</td>
</tr>
<tr>
<td><strong>Heating demand / consumption after intervention [kWh/m²a]</strong></td>
<td>100 kWh/(m²a)</td>
</tr>
</tbody>
</table>
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)
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.

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.

<table>
<thead>
<tr>
<th>METHOD</th>
<th>SOFTWARE TOOL/ TESTING EQUIPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component behaviour</td>
<td></td>
</tr>
<tr>
<td>U-value / thermal bridges</td>
<td>THERM Version 6.3.44.0</td>
</tr>
<tr>
<td>Simulation of the coupled hygrothermal</td>
<td>DELPHIN Version 5.6.5</td>
</tr>
<tr>
<td>construction elements behaviour</td>
<td></td>
</tr>
<tr>
<td>Measurement of the airtightness</td>
<td>Blower-door (DIN EN 13829)</td>
</tr>
<tr>
<td>Heat energy requirement</td>
<td></td>
</tr>
<tr>
<td>Calculation of the energy efficiency</td>
<td>PHPP</td>
</tr>
<tr>
<td>Monitoring</td>
<td></td>
</tr>
<tr>
<td>Climate and component monitoring</td>
<td></td>
</tr>
<tr>
<td>Energy monitoring</td>
<td>Monitoring system using 1-wire network</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th></th>
<th>Non-renovated condition</th>
<th>Renovated condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior wall</td>
<td>0.755</td>
<td>0.268</td>
</tr>
<tr>
<td>Interior wall</td>
<td>0.855</td>
<td>0.28</td>
</tr>
<tr>
<td>Basement ceiling/Ground floor</td>
<td>1.190</td>
<td>0.299</td>
</tr>
<tr>
<td>Ground floor ceiling/First floor</td>
<td>1.429</td>
<td>0.325</td>
</tr>
<tr>
<td>Doors</td>
<td>2.277</td>
<td>2.277</td>
</tr>
<tr>
<td>Single-pane windows</td>
<td>5.620</td>
<td>5.620</td>
</tr>
<tr>
<td>Box-type windows</td>
<td>3.350</td>
<td></td>
</tr>
<tr>
<td>Box-type windows with Plexiglas pane added on the inside</td>
<td></td>
<td>2.460</td>
</tr>
</tbody>
</table>

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 $\Psi$ 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 $\Psi$ 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 $L_{2D}$ can be determined. In a simplified form, the length-related thermal bridge loss coefficient $\Psi$ is calculated by subtracting the product from the U-value and the length of the undisturbed component from the thermal guide value $L_{2D}$. 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,
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).

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.
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 \( \Delta T \leq 0 \), 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).
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/m²a; the value calculated with the PHPP tool was 130 kWh/m²a. 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/m²a calculated. For this reason, the authors assume that the heating demand before retrofitting was approximately 200 kWh/m²a. 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
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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**WTA 6-2-01** WTA Merkblatt 6-2-01/D: Simulation wärme- und feuchtetechnischer Prozesse, WTA Publications, Munich.

**WTA 1-2-05** WTA Merkblatt 1-2-05/D: Der echte Hausschwamm - Erkennung, Lebensbedingungen, vorbeugende Massnahmen, bekämpfende chemische Massnahmen, Leistungsverzeichnis, WTA Publications, Munich.

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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
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 C5. 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...
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.
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).
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.

References

BDA Austria, 2011 BDA, Richtlinie Energieeffizienz am Baudenkmal, Bundesdenkmalamt, Austria 2011.