Sustainable refurbishment of museums

Protecting artworks, conserving monuments, achieving energy efficiency
Straight to the point

There are more than 7,000 museums in Germany. Especially in the 19th century, magnificent buildings were built for exhibition purposes, most of which still exist today. However, many museum buildings are now in need of refurbishment and their systems technology is outdated. At the same time, the financial position of cities and municipalities has become so acute that public amenities, such as swimming pools and libraries, are being forced to close. There is therefore a move towards transforming museums into independently operated enterprises that have to bear at least part of the maintenance, upkeep and utility costs for their buildings themselves.

The extensive building services technology, which is mostly required for conservation reasons, can incur considerable energy costs that have a significant impact on the overall expenditure. Museum operators therefore have an interest in consuming as little energy as possible in order to achieve an adequate indoor environment. However, it is not enough to rely on contracting external providers with the task of optimising the system operations on a success basis. Only a comprehensive, energy-oriented refurbishment can lead to a sustained reduction in the energy consumption. If other structural measures are pending, for example in order to comply with fire protection requirements, this provides an excellent opportunity to simultaneously improve the energy efficiency.

Planning the sustainable refurbishment of a museum building requires a holistic approach and a high level of knowledge among the operators and designers. Since 2008, a research team has therefore been working on this aspect as part of a joint research project. The team is involved in numerous planning and construction projects. The projects are pursuing three aims: preserving the building fabric as historic monuments, meeting conservation requirements with low technological effort and improving the overall energy efficiency.

However, the refurbishment work should not focus solely on the indoor environmental requirements and their energy balance. Sensible pest prevention is just as elementary as concepts for easy-to-clean floor surfaces, fire protection and safety, security and devising emergency plans. Successful refurbishments therefore offer an opportunity to bring the energy-saving strategies to a wider audience.

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Museums prepare for the future

Many museums in Germany and Europe were built at a time when the energy consumption of the buildings was not yet an issue. They are only able to provide visitors and exhibits with an adequate environment with extensive building services technology and corresponding energy expenditure. However, these days museums are being forced to work cost-efficiently and they are therefore looking for future-oriented strategies.

Museums house mankind’s cultural heritage and reflect social developments. Maintaining the different exhibits is an important task and an investment in the future. At the same time, the museum buildings themselves are often of high architectural, historic and urban heritage value. They are operated for much longer periods of times than other buildings of the same age. Accordingly, their energy consumption also has a greater impact over their duration of use.

The first buildings conceived as museums were erected during the mid-19th century. Aristocratic residences converted into exhibition spaces sometimes date back even further. The thermal conditioning of these buildings was carried out with a minimum of technical effort. This changed during the 1960s and 1970s. A profligate use of energy as a virtually unlimited raw material was a characteristic feature of buildings of that time. When the first oil crisis in the mid-1970s led to increased awareness and a greater focus on energy efficiency, including in buildings, museums as prestige symbols continued to be unaffected by economic constraints. This attitude in museum architecture is still evident to a certain extent today.

The vast majority of all museum buildings have insufficient thermal protection. By deploying extensive building services technology and utilising considerable energy, operators attempt to reconcile the indoor environment and lighting with the needs of the exhibits and visitors. In the monitored museums, the research team recorded final energy characteristic values between 100 and 250 kWh/m² p.a. for the heating and between 20 and 100 kWh/m² p.a. for the building electricity. Due to their control technology, heating and ventilation systems that seem oversized by today’s standards are often incapable of adapting to an increasingly variable use of space. Poorly planned daylight utilisation and extensive use of artificial lighting create high cooling requirements. Such building deficiencies not only incur high energy costs but also take their toll on artworks and users through the radiation asymmetries, temperature gradients and UV-light components.

The financial restraints facing many municipalities coupled with rising energy prices are also forcing museums to operate more cost-efficiently. Measures for providing thermal protection and energy-optimised operation are therefore becoming essential. Nearly-net zero energy new-build schemes such as the Ritter Museum in Waldbrunn or buildings to the Passive House standard such as the Kunstmuseum Ravensburg demonstrate suitable approaches.

What defines a museum?

The International Council of Museums (ICOM) defines a museum as a “non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment”. The four pillars of traditional museum work are therefore collecting, researching, communicating and conserving cultural assets. Often only about 20 to 30 per cent of museums’ collections are on display in the public galleries; the rest is stored in archives or storage depots.
Refurbishment as a holistic task

Problems with the building services technology or fire protection are often the catalyst for structural measures. However, sustainable, energy-oriented refurbishment cannot be limited to these aspects. The difficulty lies in simultaneously meeting conservation requirements while providing visitors with a comfortable indoor environment and optimal lighting and while at the same time reconciling everything with listed building requirements.

A comprehensive survey provides the basis for all planning. This enables the users, designers and specialists involved to examine, discuss and subsequently determine the refurbishment requirements and their objectives. The early integration of all relevant aspects and the continuous involvement of specialist designers provide the key to success here (Fig. 3).

Compiling detailed information

Studies of the building fabric document the construction age, historical value, construction materials, energy efficiency of the building envelope and any building damage incurred over the years. Measurements of the indoor environment show which temperatures and moisture problems occur. This enables load peaks caused by poor lighting or inadequate ventilation to be identified, such as when there are widely varying visitor numbers or major events, and thus avoided in future. Thermographs and air tightness measurements help to assess the structural conditions and leaks in the building envelope. A light dosimeter can be used to measure the lighting conditions and the effect of light on sensitive materials. Invoices from the energy supplier or the corresponding meters provide information on the current consumption for heating, cooling and electricity. With conceptual changes, for example regarding the indoor air flow, measurements before and after the refurbishment can verify any improvements. The recorded characteristic values enable museums to be mathematically depicted in accordance with the calculation requirements specified by DIN V 18599. That provides initial indications for the energy efficiency and potential for improvement.

Involving the historic buildings and monuments authorities

Many museums are listed as historic monuments. The guiding principle in building conservation is to retain as much of the original fabric of buildings as possible as relics of bygone times. To ensure a sensitive approach to historically significant buildings, all measures must be coordinated with and authorised by the historic buildings and monuments authorities – from painting facades and replacing windows to modifying the buildings or their surroundings. The sooner the competent authority is involved, the easier it is to find historically appropriate solutions for any changes concerning func-
Checking the air tightness

The German Energy Saving Ordinance (EnEV 2014) does not stipulate requirements for the air tightness of existing buildings. However, if the building envelope is not impermeable, the heating and air conditioning systems have to compensate for the resulting ventilation heat losses. In unfavourable cases leaks can cause increased fluctuations in the temperature and relative humidity, which from a conservation point of view must be avoided at all costs. Prior to carrying out refurbishment measures, air tightness measurements (blower door tests) according to DIN 13829 conducted in conjunction with the localisation of leaks help to assess the energy efficiency of the building envelope and to identify weak points. With energy-oriented refurbishments, the same air tightness should be sought as required for new buildings.

Compared with the requirements of the German Energy Saving Ordinance (EnEV) for new buildings, the buildings investigated in the research project show that they are relatively airtight (Fig. 4). However, this high impermeability is not a consequence of the building components or materials, but is mainly due to the fact that users have retrospectively screwed together casement windows or sealed joints. Where this is not possible (metal windows/skylight situations), higher values were correspondingly measured. However, these can still be described as good in relation to the building age and the current EnEV ordinance.

<table>
<thead>
<tr>
<th>Building</th>
<th>Measurement scope</th>
<th>Averaged $n_{50}$-value [h⁻¹]</th>
<th>EnEV specified $n_{50}$-value [h⁻¹] for new buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Städtisches Museum</td>
<td>2 rooms</td>
<td>1.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Braunschweig</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kaiser Wilhelm Museum,</td>
<td>2 rooms</td>
<td>2.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Krefeld</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kunsthalle Mannheim,</td>
<td>3 rooms</td>
<td>2.9</td>
<td>1.5</td>
</tr>
<tr>
<td>before refurbishment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(building with ventilation system)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herzogliches Museum,</td>
<td>Entire building*</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Gotha</td>
<td></td>
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* Measurements of large volumes distort the results because large leaks are underestimated in relation to the volume.

“Refurbishment offers an unusual opportunity for museums, since investments in cultural building sites are not within the immediate remit of the respective funding bodies. That’s why it’s important to involve all stakeholders and to ensure high quality, sustainability and cost efficiency. A comprehensive and in-depth analysis of both the museum’s own remit and the building itself is of essential importance for achieving sustainability. The materials and solutions used should be systems that are recognised and long-established in technology and construction, with the thrust being on innovation – but with no experiments but rather the evaluation of experience. The building materials used should also be assessed in terms of their ageing behaviour – including both the associated patina of building materials during ageing and the longevity of the building systems or technologies. In case of doubt, mechanical solutions without high maintenance should take precedence over electrical solutions, and electrical solutions should take precedence over electronic ones. That increases the reliability and sustainability. All the components and techniques used should be assessed in terms of their ease of maintenance and energy consumption.”

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Prof. Dr Stefan Simon
Director of the Rathgen Research Laboratory for the National Museums in Berlin and the appointed inaugural director of the Institute for the Preservation of Cultural Heritage, Yale University, New Haven, CT

“I can answer that very concisely: sustainable implies measure that equally respects and takes into account all three pillars of sustainability: the ecological, economic and social pillars. This is an optimisation game, since improvements in one area generally come at the expense of less favourable conditions elsewhere. The social pillar includes the conservation aspect. If, however, the ecological side, for example the CO₂ balance, and/or the economic feasibility and financial viability are not taken into account, then the refurbishment is not sustainable.”

Michael John
Head of Technical Services for the Dresden State Art Collections

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tional, design and energy-related aspects. As part of the research project, concepts have been developed for various buildings and building components.

**Defining the requirements**

The challenge in museum design lies in reconciling the conflicting requirements for protecting exhibits while also ensuring visitor and employee comfort. In terms of their materials, the exhibits require a constant and defined indoor environment that is independent of the outdoor temperature, often preferably in the cooler range. Visitors, on the other hand, want to view the exhibits at a comfortable room temperature and without draughts.

At the same time, however, they bring with them waste heat, moisture and possibly pollutants. It is also very difficult to illuminate the exhibits well without the light causing damage to them.

With refurbishment, of overriding importance in regard to the technical issues is the goal of consuming less energy. Here it is important to keep the economic aspects in proportion and, in addition to the technical possibilities, to also assess the achievable savings. Many historical buildings that are not air-conditioned have managed to preserve exhibits over extended periods of time without complications. Therefore as part of the renovation it should be carefully checked whether it is at all necessary to equip the building with additional building services technology.

### Sustainability certification and lifecycle

Numerous evaluation systems are available for the construction sector in order to quantify and assess the social, economic and environmental impacts of the construction measures. Among the best known are the American LEED system (Leadership in Energy & Environmental Design), the British BREEAM system (British Research Establishment Environmental Assessment Method) and Germany’s DGNB (German Sustainable Building Council) and BNB systems (Sustainable Construction Assessment System for Federal Buildings). Although a system dedicated to the evaluation of museum buildings is not yet available, there are nevertheless several certified museums worldwide, of which 162 have LEED certification. In Germany, the Kunstmuseum Ravensburg is the first DGNB-certified museum. It was awarded a “Pre-certificate in Silver” in the DGNB’s “New assembly buildings” category.

In order to assess the specific needs of museum buildings appropriately, supplementary assessment profiles need to be developed. In particular this applies to preventive conservation, but also to the lifecycle of museum buildings. Properties are used, on average, for up to 100 years. Museums usually significantly exceed this service life due to their core remit of providing a home to valuable collections. Their extended usage times mean that the operational phase of museums buildings, consisting of use and renewal, is much more significant.

In order to forecast climatic conditions and the resulting energy requirements, dynamic simulation programmes are better suited than the computational method stipulated by the German Energy Saving Ordinance (EnEV). With their help, the specialists involved can simulate refurbishment alternatives without major expense and, to a certain degree, assess them in advance. Users, owners, conservationists and specialist designers can compare and discuss the different options in terms of the conservation parameters and the energy consumption, and develop a refurbishment concept optimised for the particular case. However, the special features of museums, such as the geometric diversity, unknown wall structures, specialised plant system solutions or even difficult-to-determine material values also pose challenges for the simulation. Nevertheless, with appropriate effort insights can be obtained that would not be possible with traditional planning or analysis methods.

Strictly speaking, there is interaction between all the phenomena that are calculated with such simulations. However, it is often sufficient to ignore or replace some of them with reasonable assumptions. Alternatively, it is already possible to link together various programmes that map these dependencies.

### Possible simulations when refurbishing

<table>
<thead>
<tr>
<th>What is simulated</th>
<th>Why?</th>
</tr>
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<tbody>
<tr>
<td>Light simulation</td>
<td>Lighting conditions</td>
</tr>
<tr>
<td>Thermal building simulation</td>
<td>Thermal or hygric processes in the building</td>
</tr>
<tr>
<td>Structural Simulation</td>
<td>Moisture in the building fabric</td>
</tr>
<tr>
<td>Flow simulation</td>
<td>Flow field and convective heat transfer</td>
</tr>
</tbody>
</table>

Fig. 7 Simulation model of a room with a large picture on the outer wall. The computation enables all essential thermal and aerodynamic phenomena relating to the building physics to be taken into consideration. The flow processes can be mapped using the fine mesh. Source: TU Dresden / Ralf Gritzki
The “Sustainable refurbishment of museum buildings” research initiative

As part of its Energy-Optimised Building (EnOB) key research area, the German Federal Ministry for Economic Affairs and Energy has funded a joint project on the sustainable refurbishment of museum buildings. Under the coordination of the Institute for Building Services and Energy Design (IGS) at the Technical University of Braunschweig, five renowned German universities and several associated institutes have joined forces to investigate various museum buildings, develop refurbishment concepts and advise owners for an initial period of four years. In individual museums selected as demonstration projects, the scientists have tested both innovative refurbishment concepts as well as the deployment of new, energy efficient construction materials and technologies. They have also monitored the projects throughout the entire refurbishment period with simulations and measurements.

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Fig. 8 Energy consumptions of selected museums and the mean values for existing buildings according to the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. Source: Volker Huckemann / TU Braunschweig

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Fig. 9 These museums were involved as project partners.
Conservation requirements

While visitor comfort is required six days a week for eight to ten hours, the conservation requirements – especially regarding the indoor environment and lighting – need to be met permanently. They are central concerns both when designing and refurbishing museums.

Whether museums can be operated safely, sustainably and successfully is determined by the preventive parameters on site, i.e., the building should preserve and protect the collections exhibited and stored within it. The preservation of the cultural assets usually requires a constant indoor environment that is defined within relatively narrow limits. Light and vibrations caused by shaking or noise emissions also impact on the exhibits.

Systematically preventing damage

In recent decades, a new field has established itself within restoration known as preventive conservation. This considers not just the artworks themselves but also their environmental conditions and the context of the collection as a whole. In order to analyse and evaluate risks, holistic strategies to reduce the damage processes and decay mechanisms are developed and established with all stakeholders in the planning team. The main aspects are:

- Air-conditioning issues (temperature, relative humidity, pollutant content, etc.)
- Dealing with daylight and artificial lighting (radiation)
- Pest prevention / Integrated pest management
- Inventory and collections management
- Safety and fire protection requirements
- Museum logistics such as deliveries, internal transport routes, hanging, loans, etc.
- Disaster and emergency management
- Legislation / Establishment of standards

These directly influence the architecture, energy concept and use of the buildings. Preventive conservation is therefore a central aspect in the dialogue between the users and designers of museum buildings. These days, almost all conservators and museum authorities have recognised that such a holistic approach not only protects the original fabric but also significantly saves costs in the long term. Systematic methodologies and technologies are currently being researched in many areas in order to develop strategies for long-term management and to anchor them in daily museum practice.

Questioning the necessary indoor environment

Organisations that concern themselves with the indoor environment for exhibition displays, such as ICOM, IC-
CROM and ASHRAE, define benchmarks for optimal conditions. Since the early 1960s, almost all museums and collections have endeavoured to comply with these values by often deploying very elaborate technical solutions. In times when there were relatively unlimited supplies of energy and resources, the fully air-conditioned museum was considered the optimum condition to aspire to. However, rising energy prices, which have a direct impact on the operating and maintenance costs for museums, and a simultaneous reduction in the financial resources have led to greater criticism of the high-tech solutions. The currently internationally demanded indoor environment values of 50 or 55 ± 5% relative humidity and a temperature of 20 °C, which are largely requested as part of commodities, cause immense energy costs, especially for large museums. Since the beginning of the 1990s, a somewhat more differentiated approach has therefore developed in regards to the target values for temperature and relative humidity, which were originally not meant to be binding and were merely aimed at providing a guide. Indoor environments according to the needs of preventive conservation are based on excellent solar and thermal protection as well as controlling the air exchange and relative humidity.

Every material reacts differently

The questioning of the strict guideline values has meant that scientists are once again focussing on how the indoor environment affects artworks. Different materials (metal, stone, canvas, oil, wood, leather, paper, ivory, etc.) respond differently to temperature and humidity fluctuations. Target value ranges therefore need to be defined for specific materials. Here, however, new problems emerge: firstly, the individual artworks themselves are frequently made of complexly structured composite materials; secondly, museum collections and ensembles mostly consist of a wide range of artworks with diverse materials in widely varying states of preservation. Each target value specified for the indoor environment for mixed collections is therefore a compromise between the requirements of the individual works of art and material groups, and cannot always be the optimal solution for the individual artwork. Exhibiting the artworks in individual display cabinets offers an alternative here.

Indoor environment in the investigated museums

Measurements of the indoor environment were carried out in several of the museums investigated in the research project. These give an idea of the range of actual indoor environmental conditions in museums. The values measured for relative humidity and temperature often differ considerably from the specified requirements and high aspirations.

Fig. 13 clearly shows the difference in relative humidity between museums with both extensive air-conditioning technology and elaborate facility management (A and B) and museums with only partial air-conditioning (E and F). In the absence of humidification, values less than 30 and even 20% relative humidity were reached in individual museums in winter. That is well below the recommendations for indoor environments in museums.

There are also significant differences with the indoor temperature. With a view to ensuring visitor comfort, a temperature range between 20 and 24 °C is generally aimed at with a seasonal adjustment of the temperatures. A glance at the reality shows, however, that this range is often exceeded, either because of missing or faulty summer thermal protection (Museum G), or because lower temperatures are also permitted in some museums. That can certainly make sense in terms of the conservation, as the chemical and biological decay processes are then much slower.

![Fig. 12 Climatically induced paint peeling on a restored altar. Source: Fraunhofer IBP / Kristina Holl](image-url)
Preventing short-term indoor environmental fluctuations

A relatively new approach for air-conditioning museum spaces and storage depots is to no longer maintain a constant indoor environment throughout the year. With indoor environments that change along with the seasons, seasonal variations are acceptable to some degree. If short-term fluctuations are still strictly avoided, this does not harm the objects. Even earlier solutions with a minimal use of building services technology created fairly stable indoor environments that enabled the preservation of artworks to the present day.

Radiation damages artworks

In addition to the indoor environment, the radiation exposure is also important for the conservation. Visual tasks can be enhanced if more light is available (DIN 5035). This stands in direct contradiction, however, to the aim of protecting exhibits.

In practice, limit values in the broadest sense for exposing exhibits to light have been available for many years now. These values, which are given in lux, generally represent, however, a limitation of the incident radiation and are thus an indication of the degree of exposure. In reality the lux unit is a photometric parameter for evaluating the spectrum of light visible to the human eye (380 nm to 750 nm). From the conservation point of view, however, it is particularly the exposure to short-wave UV radiation (<380 nm) that needs to be limited. Because, for example, the UV spectrum ranges from 280 nm (UV-B) to 380 nm (UV-A), it is the radiation intensities in this wavelength range that should be crucial for assessing the UV protection. This wavelength range, however, is not even covered by the lux value. The discussion is further complicated by the classification of the UV range in other countries. For example in the United States the neighbouring short-wavelength range from 380 – 400 nm is also defined as being part of the UV range, and it is certainly feasible that potential for damage also exists in the densely grouped, short-wavelength area beyond German standardisation. At the same time, damage caused to exhibits through further wavelengths (such as the visible range) is still the subject of research.

Lighting: strength and duration are decisive

In the current discussion on light protection, the focus is no longer on the maximum illuminance in lux but on the duration of the exposure. With an identical light composition, 1 hour at 200 lux has the same damage potential as 20 hours at 10 lux. This has been well known for years in specific areas such as photography exhibitions, which is why the exhibits only remain for a short time on display. The processes can be easily transferred at different scales of magnitude to other types of objects.

These physical principles apply to artificial and natural light to the same extent. They therefore provide the basis when designing artificial lighting concepts as well as when designing window and skylight arrangements.


In practice

Kunsthalle Mannheim – Thermal protection instead of air-conditioning technology

From 2009 to 2013, the main building for the Kunsthalle Mannheim underwent extensive refurbishment. One goal was to preserve and restore the art nouveau building as faithfully as possible. The careful structural measures managed to reduce the building’s energy consumption to such an extent that the building services technology was able to be reduced to a minimum. The refurbishment has reduced the primary energy requirement by about 60 per cent.

The thermal insulation of the building envelope was improved where it was possible to do so in line with building conservation requirements. Considerable potential was provided by the roof, floor plates and glazing. Since external insulation of the natural stone facade was not desired, the designers conceived a special internal thermal insulation: tubes for adjusting the temperature of the wall surfaces are integrated in calcium silicate panels. The heating and cooling of the spaces, which was previously carried out using supply air, will now be largely achieved using surface heating and cooling systems in the walls, floors and ceiling. This means that the air exchange for the new air intake and exhaust system only has to take into consideration the hygienic and conservation requirements, and can therefore be significantly reduced. In order to preserve the historical windows, a second window level was inserted on the inside with thermally insulating glazing. Glare, UV and burglary protection are integrated within the glass structure of these new windows.

Single-glazed skylights above a transparent intermediate ceiling originally brought light in the exhibition spaces on the first floor. However, this lighting had been blocked by timber panelling following failed attempts to control the indoor environment. By inserting specular louvre glazing with a U-value of 1.3 W/m²K, this enabled the glazed ceilings providing daylight to be reactivated. These now allow diffused light into the exhibition spaces on the first floor while blending out a large part of the incident solar energy, thus reconciling the conflicting demands for providing natural daylighting while protecting against light for conservation reasons.

The Sistine Chapel in a new light

The maintenance of churches has to reconcile the conflicting interests posed by conservation aspects, visitor requirements and energy efficiency. A famous example is the Sistine Chapel in Rome. 500 years ago Michelangelo embellished it with his world famous frescoes. For centuries, the paintings could only be seen in daylight or candlelight. Candles and torches are meanwhile taboo because of the build up of soot. Artificial lighting with halogen lamps was installed in the 1980s – but only from the outside. In order to minimise damage from UV radiation, translucent plastic panels were installed to reduce the light penetrating through the twelve windows. The frescoes themselves were therefore mostly in semi-darkness.

LED lights now simulate the original natural lighting and fully render the entire range of colours of the frescoes. Because the spectrum of the LED diodes contains hardly any ultraviolet and infrared radiation components, the new lights are installed directly in the chapel. The light therefore comes from the same direction as the daylight did previously. The new installation allows much greater illuminance while nevertheless developing little heat. In addition, the installation is expected to consume 60 per cent less power during normal operation than the previously installed versions.

The retrofitting was carried out during the building’s ongoing use. At the same time, the existing air conditioning system is also being modernised, which can no longer cope with the demands made by up to 20,000 visitors a day.

Further information:
www.led4art.eu

En passant

Fig. 16 Refurbishment of the Kunsthalle Mannheim: the wall heating leaves out the central parts of the walls used as hanging space for the pictures. Source: Kunsthalle Mannheim / Cem Yüce tas 2014

Fig. 17 Since November 2014, 7,000 LEDs have illuminated the Sistine Chapel with a colour temperature between 3000 and 4000 kelvins. Source: Governatorato dello Stato della Città del Vaticano – Direzione dei Musei

Fig. 18 The elaborate restoration between 1980 and 1994 already showed that Michelangelo’s frescoes were not painted in dull sepia tones as originally assumed. Source: Sistine Chapel Daniel beforandafter from Michelangelo – Webgallery of art, Bartz and König, “Michelangelo”. Licensed under public domain via Wikimedia Commons.
Improving thermal insulation

Good thermal insulation in museums not only reduces energy losses but also creates a high thermal inertia and thus a more constant indoor environment. The energy efficiency of the building envelope therefore determines how much technical effort is needed to operate the building within the usage requirements.

The building fabric of museums generally corresponds to their age. Museum buildings were also evidently not built with an improved quality. U-values greater than 1 W/m²K were quite common for external building components, which at that time were considered sufficient for maintaining (minimum) hygienic conditions.

Thermal insulation stabilises the indoor environment

Today, U-values less than 0.24 W/m² are required for the same external components used in energy efficient renovations. Transferred to the surface temperature, this can lead to a temperature difference of several degrees. Improved thermal protection therefore opens up immense scope for arranging objects. High insulation values for the facades and hygrically active materials on the inside accord with the minimal fluctuations in the indoor temperature and humidity required for conservation reasons and also help to prevent mould formation.

However, it is generally not feasible to improve all external building components up to a new-build standard due to listed building, component connection and, last but not least, financial aspects. The measures must also be assessed in relation to the achievable savings.

In terms of meeting listed building requirements, the greatest potential for improving the thermal insulation is provided by doors, windows, pitched roofs / glazed ceilings and top floor ceilings. In principle, building components should first of all be insulated that have no major impact on the appearance of the building, such as the foundation slab or roof. Depending on the existing building fabric, in addition to providing thermal insulation between rafters, conventional thermal insulation on or under the rafters may also be possible. It is only when these possibilities have been exhausted that insulation should be considered on the mostly architecturally defining external facades.

Care needs to be taken with connection points with basement insulation

In addition to the usual technical facilities, the basements of the museum buildings examined within the research project also often house high-quality uses such as archives or depots. Conceptually, the hygric conditions and the maintenance of constant humidity levels
play a more important role here than the room temperatures. In this respect, the location of the insulated envelope structure should be carefully determined in consultation with the users. When insulating the floor, connection points relating to, for example, the staircase dimensions and lintel heights must be considered that might limit any thermal insulation in these areas. One advantage is that in historical buildings the foundation slabs often lie between the rising walls. When an area is being rebuilt, this provides an opportunity to provide comprehensive insulation. At other points, highly insulating materials enable slim superstructures.

Coordinating external wall insulation with historic buildings and monuments authorities

An individual thermal insulation concept needs to be developed for the walls and exterior facades in consultation with the historic buildings and monuments authorities. Preserving the original interior and exterior surfaces as well as the proportions of the architecture mostly takes precedence with historically significant buildings. This can be compensated for by carrying out measures on other parts of the building such as the foundation and floor slabs, or by utilising technically optimised equipment or renewable energy sources. However, aspects concerned with achieving stable surface temperatures and the preventive conservation of exhibits need to be considered as well when dispensing with thermal insulation.

Challenge posed by glazed ceilings

Many museums built in the mid-19th century have internal spaces that are only naturally lit through glazed ceilings. These ceilings were also originally used for ventilating the rooms and the building. Unsealed areas or vents were provided as an integral part of the design. From an energy perspective, these now represent leaks through which heat is lost in an uncontrolled manner. In addition, single glazing is used for the glazed ceilings and the roof. The heat transfer is correspondingly very high and the inside surface temperatures are low. The drainage of condensation in the roof space above the glazed ceilings therefore creates considerable problems from a structural point of view and condensation damage can often be observed. Because historic roof structures have often already exhausted their limits in terms of meeting current structural load-bearing requirements, it is frequently not possible to increase their surface weight.

There are basically two ways for renovating such glazed ceilings: one is to design the heat-insulated envelope in the plane of the pitched roof. In the museums investigated, this option was consistently chosen due to fire protection and smoke extraction requirements, whereby the steel structures also had to be completely upgraded or even renewed in a better quality. If alternative solutions can be found for the fire protection requirements, the level of the dust roof and thus the upper storey ceiling can be alternatively used to complete the thermal envelope. This has the advantage that the entire roof area is thermally decoupled and there are less stringent requirements for the pitched roof components.

Windows: a multi-functional construction component

All transparent surfaces require particular attention when refurbishing museums. Among others, they need to meet the following requirements:

- Entail minimal intervention in the original building fabric
- Provide optimum thermal protection
- Be airtight
- Provide generally high acoustic insulation
- Be burglar proof
- Operable by the personnel only
- Reduce incident radiation
- Control incident light
- Ensure high colour rendering
- Entail low maintenance/follow-up costs

This applies both for normal window situations as well as the glazed exhibition spaces frequently encountered in museums. In practice, this complex requirements profile actually leads to complications in the planning and execution process in all museums. It is therefore recommended that this aspect is addressed as soon as possible by involving experts such as lighting designers and structural engineers along with the expert users themselves, and by budgeting accordingly.
Air and light

19th century museum buildings primarily used natural ventilation and daylight. The air-conditioning technology and artificial light that are standard with new museum buildings were frequently added later. If it is intended to meet conservation requirements in an energy efficient manner, particular attention needs to be paid to the building services technology.

The ventilation in museums needs to fulfil several tasks, including providing fresh air for visitors and employees, discharging emissions (e.g. carbon dioxide, water vapour, vapours from the furniture) while simultaneously preventing dust infiltration and regulating the humidity. The stability of the indoor environment determines whether natural ventilation is sufficient for the museum or whether an air-conditioning system is required to achieve the desired indoor environment.

Air quality requirements

As a so-called pilot substance, the CO₂ concentration is commonly used as an indicator for assessing the contamination of the indoor environment caused by people. The limit value of 0.1 % by volume or 1,000 ppm CO₂, defined by Max Josef Pettenkofer (1818–1901) is still used as a criterion for the air quality today. It is directly referenced in DIN 1946-2 (1994) and DIN EN 13779 (2007) with a value of approximately 800 – 1,400 ppm. This value can be assumed as initially acceptable for large-scale exhibition spaces with small visitor numbers. However, special attention needs to be given to areas with temporary exhibitions, large throngs of visitors and spaces in museums used for educational purposes, which as teaching spaces should be categorised as classrooms.

Necessary air changes

Investigations show that there is generally potential for improvements and savings in the existing buildings both in terms of the CO₂ regulation and the room ventilation. In order to keep the indoor environment stable, the smallest possible outside air exchange rate is desirable. From an energy efficiency point of view, the minimum flow rate should be calculated according to the pollutant loads and can be determined using a concentration calculation. Which air exchange rate is at least necessary for the ongoing museum operations depends on the number of visitors (with a required fresh air flow rate per person per hour of between 20 and 30 m³). From a hygiene point of view, it is usually sufficient to have a maximum of 0.5 air changes per hour in the exhibition spaces. If a fresh air supply is not required during closing times when there are no visitors, the supply air can be conditioned in recirculation mode (air change rates < 0.1 per hour). This requires much less energy. With good indoor environment stability, low pollutant content and additional static heating, mechanical ventilation can be eliminated entirely. With high indoor environment requirements, the humidification and dehumidification of the rooms determines the required air flow rate.

Separating heating and cooling functions from the ventilation

Air-conditioning ventilation systems that exclusively heat and humidify rooms using just the air may require up to 4.5 times the number of air changes. This results in large duct cross-sections and high costs. Heat and moisture recovery or air re-circulation in the air-conditioning system can reduce the necessary fresh air rate required. As far as possible, these days designers try to avoid conditioning exhibition spaces by exclusively using ventilation or...
air-conditioning systems and instead supplement the building services technology with wall or surface heating and cooling systems that cover the base load for the heating and cooling requirements.

Decentralised air-to-air systems are ideal for retrofitting museum buildings. Frequently, it is possible to add fresh air to the circulating air. This enables the air exchange rate to be reduced to the minimum required for health and air quality purposes.

**Fans support natural ventilation**

Whether a museum can also deploy natural ventilation depends on the number of visitors. Dispensing with a ventilation system saves not only on the costs for the technology and ducts but also on the operating costs (electricity required for fans, maintenance, etc.). However, natural ventilation depends on wind pressure and thermal buoyancy as driving forces. It requires openings in the right places with sufficient cross-sections to ensure the required air exchange. Since these are generally not available in the building envelopes of museums due to fire and burglar protection reasons, the natural ventilation can be supported in individual cases by fans.

**Flexible control of air-conditioning systems**

Buildings with less stable indoor environments or with high internal load changes require partial or full air-conditioning systems. These days renewable energy or local and district heating and cooling networks are also coming into consideration as energy sources. When operating air-conditioning systems, it is generally the case that the more the target values for the supply air differ from the annual mean values for the outside air, the

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**Museums without air-conditioning**

Buildings without air-conditioning systems, for example castles or palaces, are naturally ventilated through windows and gaps. Such massive buildings that are only heated can achieve fairly stable indoor temperatures. Hygrically open wall, ceiling and floor surfaces (e.g. wallpaper, unsealed wood surfaces, cement plaster) provide a buffer against humidity peaks. A combination of thermally inert, dense buildings and hygrically functional wall surfaces therefore provides a good basis for the minimum use of systems technology. However, with larger visitor numbers and a greater need to achieve a constant indoor environment, restrictions are then necessary such as limiting the number of people or opening times, as pollutants or moisture loads cannot be discharged in a targeted manner.

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**Own rules for depots**

Usually only a small part of the collections are put on public display. The majority of artworks are stored in the museums’ own depots. In principle these can ensure a stable indoor environment without any great technological expenditure, as depot buildings or spaces are purely functional facilities that do not have to meet representative needs or be publicly accessible. The small number of people present means that the air exchange can focus on removing pollutants (e.g. wood preservatives from furniture).
greater the energy requirement and the associated operating costs. An important approach for air-conditioning museum spaces is therefore a shift away from providing a year-round constant climate towards providing an indoor environment that changes with the seasons. If required, air-conditioning components can be turned off during closing times and the indoor air stability of the rooms can be utilised. This requires regulation that is linked via a building control system with the desired and actual values of the rooms and the heating system. If full air-conditioning is coupled with stationary heating (radiators with thermostatic valves or surface heating), fine tuning of the two systems is necessary to ensure that they complement rather than work against each other.

Putting exhibitions in the right light

Lighting is a key aspect in museums, since it directly relates to the main task of the buildings as places for viewing exhibits. Similar to the indoor environment, the visual requirements conflict with the requirements of preventive conservation, which are aimed at limiting the exposure of exhibits to radiation. Especially in recent decades, there has therefore been an increased emphasis on using artificial light.

Utilising daylight

These days, modern glazing and filter structures generally make it possible to bring daylight into museums again and thereby reduce the usage or intensity of artificial light. However, the extent to which natural light can be used in museums depends greatly on the nature of the exhibits and the exhibition concept. Low g-values for the glazing and filters that limit the incident sunlight and radiation to the visible spectrum also help to keep the indoor environment within defined limits. Combining this with complete darkness outside the opening times increases this potential and reduces the exhibits’ exposure to radiation.

Less light and less radiation mean that less cooling is required, which can ensure greater operational security in terms of both the investment and operating costs as well as the indoor environment. However, if the exhibits are subject to considerable indoor environmental requirements, the use of extensive glazed surfaces should be questioned or at least validated scientifically in advance.

Finding suitable luminaires

Pure artificial lighting solutions are easier to plan and control, and in many cases enable a more focused presentation of the exhibits than when daylight is used. The main criterion when selecting luminaires for museums is ensuring protection against light damage; the second is ensuring visual comfort.

In order to minimise the loads on the exhibits, it helps to reduce the radiation spectrum to the proportion of visible light and to filter out the invisible portion as far as possible.

Whereas incandescent light bulbs or low-voltage halogen spotlights emit most of their radiation in the infrared...
In practice

Kaiser Wilhelm Museum, Krefeld – An optimum indoor environment in a historic monument

The intention is that the Kaiser Wilhelm Museum, which exhibits modern 20th century art ranging from Andy Warhol to Joseph Beuys, who was born in Krefeld, shall meet the highest indoor environmental requirements following its general refurbishment. In view of the climate requirements laid down in international commodities, the research team first of all developed a holistic energy concept for the building, which was built at the close of the 19th century. In order to intervene as little as possible in the building fabric, the plan envisages the use of facade-integrated ventilation units under the windows. The removal of existing radiators in favour of very low-profile floor activation meant that interventions were anyway required in the old heating niches and that the necessary ducts could be installed easily. Both systems now jointly meet the required heating and cooling capacities. The exhaust air is fed centrally via a closed-circuit interconnected system in order to enable heat recovery.

The air supply is concealed in the windows of the historic facade. The architect (Winfried Brenne, Berlin) already designed a similar concept for the Deutsches Historisches Museum in Berlin and was therefore able to build on his experience – which is an exception in public procurement projects. In combination with the natural stone facade and the original, refurbished timber windows, this detail allows a listed building-compatible solution that is fully integrated into the historical facade.

Advantages:
- Relatively low electricity requirement per lumen
- Avoidable cooling loads
- Low UV proportion in selected types
- Wide range of applications (dimmable, consistency in light colour, etc.)
- Supposedly long life

Disadvantages:
- Large number of LEDs required to achieve defined illuminances
- Heat emitted on semiconductor crystal, control system, transformers, etc.
- Colour rendering
- Relatively higher investment costs
- No long-term experience

range and therefore only cause relatively little degradation, conventional fluorescent lamps have an appreciable proportion of blue – like many older LED variants.

If a new lighting installation is being planned, it is advisable during the sampling stage to obtain manufacturer specifications for the actual spectral distribution or to have it measured in a suitable institution. Based on this information or by using corresponding filter structures it is possible to find various modern luminaires that only expose the exhibits to low load levels.

LEDs (light emitting diodes) are appearing in museums

LED technology is developing at a rapid pace. It is already being widely used in exhibition concepts and display cases. The light colour can now be adjusted easily. The Rahtgen Laboratory belonging to the Stiftung Preußischer Kulturbesitz, Berlin, is currently developing a comprehensive database on the spectral distribution of different LEDs in cooperation with the Germanisches Nationalmuseum, Nuremberg. Internationally, more information is available at www.ssl.energy.gov/caliper.html. However mostly American products are presented here.

Advantages:
- Relatively low electricity requirement per lumen
- Avoidable cooling loads
- Low UV proportion in selected types
- Wide range of applications (dimmable, consistency in light colour, etc.)
- Supposedly long life

Disadvantages:
- Large number of LEDs required to achieve defined illuminances
- Heat emitted on semiconductor crystal, control system, transformers, etc.
- Colour rendering
- Relatively higher investment costs
- No long-term experience

Fig. 27 By combining different coloured LEDs, special lamps enable precise matching of the colour temperature on the exhibits.
Source: OSRAM

Fig. 28 Indoor environmental concept for the Kaiser Wilhelm Museum
Source: TU Braunschweig / Volker Huckemann

Fig. 29 Listed building-compatible air supply under the window drip with decentralised, facade-integrated air-conditioning technology (left: Deutsches Historisches Museum Berlin, right: Kaiser Wilhelm Museum, Krefeld, window niche during construction with air supply openings) Source: Volker Huckemann

Fig. 26 Surface activation heating / cooling (exhibition area)
Decentralised facade air-conditioning devices
Radiator
F Window ventilation (workshops, offices)
Mechanical Ventilation (kitchen, cafe)
Central exhaust with heat recovery
Air-conditioned (archive)
Quality assurance and monitoring

With complex construction projects such as the refurbishment of museums, quality assurance plays a crucial role. This concerns not only the construction but also the systems operation. Accompanying commissioning sets the course for maintaining the planning specifications and ensuring permanently low energy consumption. Subsequent monitoring enables fine-tuning of the control parameters.

Implementing refurbishment plans requires constant control. Agreements are often too easily forgotten and priorities shift in terms of their importance. Here it helps to keep re-checking the planning specifications and to document them during the construction process. Whereas it is relatively easy to check insulation thicknesses and installed materials, the systems technology and the glazing are more difficult to verify. This often requires measurements from independent laboratories.

Documenting and controlling

When implementing construction measures, project deadlines and financial constraints easily lead to decisions that impair the quality of the overall building. The effects of individual changes induced during the construction process are not always immediately evident. This makes it even more important to document these changes and to attempt to assess their importance through simulations.

Similar to appraisals, checklists covering different aspects of the concept/design help with the control. Here the following aspects are particularly relevant, which for their part also contain numerous sub-aspects:

- Insulation of the building envelope
- Window design taking into regard preventive conservation aspects
- Lighting situation and management
- Supply concept at the room and building level

The tests require fully trained specialists or a team of cooperating professionals. The tasks of these specialists extend beyond monitoring the building or quality control during the construction phase.

Accompanying commissioning increases efficiency

The comprehensive systems technology used for such buildings and a bewildering variety of control variables make accompanying commissioning necessary. It is only through observing the newly installed technology and monitoring the indoor environmental conditions and system responses that it is at all possible to identify malfunctions. Although such errors in unaccompanied commissioning may be compensated for if the building services technology has a sufficient output, they nevertheless negatively impact on the consumption and cost-effectiveness.

Accompanying commissioning can assess which indoor environment conditions are actually established in the rooms while taking into account possible running-in processes and the normal operation of the air-conditioning system. Here the following parameters are assessed:

- Temperature consistency within permissible limits
- Maintaining maximum change speeds for the temperature
- Maintaining tight humidity bandwidths for the surrounding ambient air
- Maintaining minimum UV irradiation of the paintings to minimise photochemical processes
- Maintaining agreed illuminances
Prior measurement phase without systems in operation

The building services technology should be commissioned in gradual stages. Changes to the wall structure relative to its original state, for example as a result of installing cladding or interior wall insulation, can change its hygroscopic and thermal properties. This is why following the refurbishment it first of all makes sense to conduct a measurement phase for the temperature and humidity without the systems in operation, whereby the rooms should be operated without significant additional loads. In addition to the indoor environment, the external environment (temperature, humidity, radiation) is also relevant. There are no generally applicable running-in strategies for commissioning the systems (e.g. only heating or cooling), since buildings can be completed at any time during the year. Rather, it must be observed whether and at what speed the existing, freely fluctuating indoor environment – which exists when the systems are not in operation – gradually shifts towards the specified target values.

Independent measurement technology supports adjustments

The data can be collected either by means of measurement technology in the rooms or using the sensors belonging to the building management system (BMS). However, the quality of the installed sensors is rarely sufficient for scientific purposes. The numerical recording format used for the BMS data must generally be processed for evaluation purposes. With buildings with air-conditioning systems, it generally makes sense during the commissioning to record the system data at 5-minute intervals to enable possible malfunctions (component failure, vibrations, hydraulic faults, etc.) to be identified and corrected in good time. The system data includes the target and actual values for the supply, exhaust and outside air, as well as for all control variables (valve lift, speed of fans and rotors). The measurement positions, recording intervals and preciseness can be best of all controlled and individually adjusted to the requirements using separate measurement technology. Independent data acquisition also enables comparisons to be made with the BMS parameters, from which conclusions can in turn be drawn about the accuracy, positioning of the sensors or adjustment factors for the control variables.

Long-term monitoring required

Accompanying commissioning with monitoring requires at least one year. Only such a time frame makes it possible to observe and optimise the system behaviour in a wide load range. Monitoring, on the other hand, can also verify how system malfunctions affect the environmental conditions and the extent to which the room properties can diminish the effect of the malfunctioning.

The aim of the monitoring must be to control the systems operation, confirm the design data or provide a basis for optimisations and thereby reduce the energy consumption. The evaluation of the recorded data includes both as well as comparisons with energy efficiency parameters. Changes in both the systems technology as well as in the regulation and control systems should not only be documented but also validated by monitoring. A feature of the transfer of the commissioning into the final systems operation is the addition of scheduling functions and optimisations. The scheduling functions should take into account possible shutdowns or changes in the target values such as reductions in the proportion of outside air or increases in fluctuation ranges.

Measuring close to the exhibits

For aesthetic reasons, the BMS temperature and humidity sensors that determine the systems control are usually positioned in the corner of the rooms or near the door. However, the reference value should be the indoor environment in the vicinity of the pictures or objects, since measurements in the vicinity of the exhibits often vary significantly from values measured in “inconspicuous” places. With highly valuable exhibits, measurement-based monitoring of the ambient conditions in the vicinity of the exhibits is therefore of considerable importance. This enables conclusions to be drawn about necessary target value adjustments and shifts in respect to the systems control. The measurement results can also be of great interest for conservators.
Outlook

An essential feature of sustainable, forward-looking museum buildings is intelligent internal organisation that arranges the uses so that the exhibits are ideally protected against external influences. Highly insulated building envelopes not only reduce energy losses but also create a high thermal inertia and thus a more constant indoor environment. This requires special solutions, particularly with museum buildings that are listed as historic monuments.

The function of windows as interfaces to the outside world must be qualified in the museum context: high thermal protection is just as fundamental as controlled radiation transmission in the visible and invisible spectrum. At the same time, there are high demands regarding the light transmission and colour rendering. When choosing between natural and artificial lighting it is important to find the right balance between the natural perception and presentation of the exhibits and their optimal protection.

The discussions about the indoor environment will continue: Is there a universal indoor environment throughout the building or are the display cabinets air-conditioned? In this case how flexibly can the collection be presented in terms of its content? As long as short-term fluctuations and high change rates are avoided, the seasonal shifting of the building’s indoor environment should be allowed instead of trying to ensure a constant climate throughout the year by regulation. This reduces the energy consumption and at the same time protects the exhibits from damage caused, for example, by the sudden failure of air-conditioning systems. However, this requires a shift in thinking by international lenders.

For large museums, it will still only be possible to achieve these conditions in future using air-conditioning – especially with exhibitions with high visitor numbers. In order to increase the energy efficiency, this makes it all the more crucial to ensure that there is precise balancing of the systems technology, combined with long-term monitoring and continuous optimisation efforts.

Project organisation

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Links and literature (in German)

- Analysis of complex existing buildings in terms of their energy utilisation. BINE-Projektinfo brochure 16/2013
- Making well-informed decisions when refurbishing windows. BINE-Projektinfo brochure 15/2013
- Lightweight envelopes for old buildings. BINE-Projektinfo brochure 08/2012
- Insulation through vacuums. BINE-Themeninfo brochure I/2011
- Material data for energy-oriented refurbishment of old buildings. BINE-Projektinfo brochure 07/2007

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