
Braunschweig


Delphi


Florence

MUSEUMS

Energy Efficiency and Sustainability in Retrofitted and New Museum Buildings

Handbook


Marzabotto


Lisbon


Ljubljana


Kristinehamn


West Bromwich

Herzog-Anton-Ulrich Museum, Braunschweig, Germany

Archaeological Museum of Delphi, Greece

Bardini Museum of Florence, Italy

National Etruscan Museum ‘Pompeo Aria’, Marzabotto, Italy

National Archaeological Museum, Lisbon, Portugal

Slovene Ethnographic Museum, Ljubljana, Slovenia

Kristinehamn Museum of Contemporary Art, Sweden

THEpUBLIC Arts Centre, West Bromwich, United Kingdom

ENERGIE, ENVIRONNEMENT
ET DÉVELOPPEMENT DURABLE

European Commission Directorate-General Energy and Transport
www.sustainable-european-museums.net

Museums- Energy Efficiency and Sustainability in Retrofitted and New Museum Buildings Handbook

Project Co-ordinator

Meletitiki A. N.Tombazis and Associates Architects Ltd
Monemvasias Street 27
GR-15125 Polydroso, Athens, Greece
Tel: +30.210-680 0690
Fax: +30.210-680 1005
Email: meletitiki@hol.gr

Building Design Teams

Herzog-Anton-Ulrich Museum,
Braunschweig, Germany

Building owners:
Staatshochbauamt Braunschweig I

Architects:
Staatshochbauamt Braunschweig I

Energy consultants:
Institut für Gebäude- und Solartechnik,
TU Braunschweig

Archaeological Museum of Delphi,
Delphi, Greece

Building owners:
Hellenic Ministry of Culture

Architects:
Meletitiki-A.N.Tombazis and Associates Architects Ltd

Energy consultants:
Department of Applied Physics,
National Kapodistrian University of Athens

Bardini Museum of Florence
Florence, Italy

Building owners:
Municipality of Florence

Architects:
Arch Lombardi

Energy consultants:
ABITA Centre, University of Florence

National Etruscan Museum 'Pompeo Aria',
Marzabotto, Italy

Building owners:
Soprintendenza per I Beni Archeologici dell' Emilia Romagna

Architects and Energy consultants:
Ricerca & Progetto – Galassi, Mingozzi & Associates, Bologna

National Archaeological Museum,
Lisbon, Portugal

Building owners:
Museu Nacional de Arqueologia

Architects:
Carlos Guimaraes & Luis Carneiro

Energy consultants:
IDMEC, University of Porto

Slovene Ethnographic Museum,
Ljubljana, Slovenia

Building owners:
Slovene Ethnographic Museum

Architects:
INTEX Biro, d.o.o.

Energy consultants:
Faculty of Civil and Geodetic Engineering,
University of Ljubljana

Kristinehamn Museum of Contemporary Art,
Kristinehamn, Sweden

Building owners:
City of Kristinehamn

Architects:
Christer Nordström Arkitektkontor AB

Energy consultants:
WSP Environmental

THEpUBLIC Arts Centre,
West Bromwich, United Kingdom

Building owners:
THEpUBLIC LTD

Architects:
Alsop Architects

Energy consultants:
Battle McCarthy Consulting Engineers and Landscape Architects

Daylighting and Acoustics consultant:
Mike Wilson,
LEARN, University of North London

The Museums handbook is based on the results obtained during the implementation of the ENERGIE demonstration project “Museums - Energy Efficiency and Sustainability in Retrofitted and New Museum Buildings” (NNE5-1999-20). This project was based on a former research JOULE III Project entitled “Retrofitting of Museums for Antiquities in the Mediterranean Countries” (JOR3-CT95-0013) and of a SAVE II Project entitled “Guidelines for the Design and Retrofitting of Energy Efficient Museums for Antiquities in the Mediterranean Countries” (XVII/4.1031/Z/97-086).

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Coordination: Alexandros N. Tombazis

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PREFACE

This handbook is the outcome of a demonstration project dealing with energy efficiency in museum buildings. The idea for this project originated from two preceding ones, a research project carried out within the framework of the Joule III programme of the European Commission and a further SAVE II project. Both projects dealt with energy efficiency in a specific building type - archaeological museums - and in a specific climatic region - the European member states around the Mediterranean. The former was a research project, the latter developed design guidelines for the energy efficient design of museum buildings in the Mediterranean region. Having reached this point, the time had come to implement the results of the research, and to test in real-life conditions its outcome so as to have the necessary feedback for future use. The opportunity for this implementation was provided within the framework of the European Commission's ENERGIE programme.

However, this project differed from the previous ones in two aspects: Its spectrum became much broader in the sense that it included a wider range of museums (not only archaeological) in an extended geographical region covering the whole European continent. Eight suitable building projects were selected. Seven of these museums were to be retrofitted and one was to be a new building.

The purpose of this handbook is to communicate to interested parties the experience and the knowledge gained during the implementation of this project. In this sense it neither attempts to provide exhaustive information on the subject of museums and energy efficiency nor does it document extensive research covering all aspects of the subject. It is merely a record of the outcome of the MUSEUMS project and of the activities which took part during its five year duration. The eight projects involved cover a wide range of museum types and as such have a high replication potential, but on the other hand they do focus mainly on art (visual arts and handicraft) and do not include, for example, other museum types such as historical museums, natural history museums, etc. In this respect the handbook has a particular focus.

One great advantage of being part of such a European project aimed at the achievement specific of targets is in its multi-nationality. While each of the eight projects had its own design and consultant teams, each project team had the opportunity to benefit from the expertise of the other participants. A group of experts was formed from among the project partners, who could consult with their colleagues in matters of specific interest. I do feel that as such, the project has had a great added value. The responsibility for the final outcome in each project remains, of course, with its designers, consultants and, last but not least, building owners.

This handbook addresses not just the scientific community, but aims to reach a wider audience: Museum building owners, architects, designers, consultants, students - anyone involved in the building process for a new museum. It has an informative and non-commercial nature for which reason it can also be accessed through the web (http://www.sustainable-european-museums.net). It is not intended to be read necessarily from page 1 to the end, but is developed in more or less independent sections, each of which deals with a specific subject (e.g. architecture, environmental design, lighting, acoustics, etc.). Annexed to this is a chapter containing information on each of the eight museums, and a section analysing the performance monitoring and the results achieved.

As this five-year project approaches its end, I wish to thank my colleagues and partners in the project, Åke Blomsterberg, Manfred-Norbert Fisch, Ales Krainer, Eduardo Maldonado, Angelo Mingozzi, Christer Nordstrom, Marco Sala, Mat Santamouris, Mike Wilson and Marc Zanchetta - with special thanks for the experience of working together and for your valuable contribution to the project. Thanks also to Vivienne Brophy for her work in disseminating information on the project and especially for the editing of this book. Thanks to all the MUSEUMS project building owners who entrusted their building to us and believed in the concept of an energy-efficient and environmental friendly museum. Thanks to my colleagues in my office who enabled the execution of this project. Last but not least I would like to extend my thanks to the Technical Officers of DG TREN, Mr Stefano Conte, Mr Antonio Paparella and Mrs Gabriele Willbold-Lohr who consulted us throughout the duration of the project. Their contribution and guidance has been valuable.

December 2004

Alexandros N. Tombazis, architect
MUSEUMS project coordinator

CHAPTER 1 - OBJECTIVES OF THE PROJECT

1.1 Introduction

This handbook is prepared within the framework of a demonstration project entitled “MUSEUMS-Energy Efficiency and Sustainability in Retrofitted and New Museum Buildings” carried out for the European Commission’s 5th Framework Programme, ‘ENERGIE’. The project’s purpose is to:

- construct eight energy-efficient demonstration projects in different European member states,
- provide guidelines on energy-efficient refurbishment and design of museum buildings,
- analyse and emphasise the differences and similarities in the eight cases involved,
- disseminate to different interested the know how achieved.

This project, ‘Museums’ is based on results obtained during the implementation of the JOULE III project “Retrofitting of Museums for Antiquities in the Mediterranean Countries” and the SAVE II project “Guidelines for the Design and Retrofitting of Energy Efficient Museums for Antiquities in the Mediterranean Countries”.

These projects studied various of museums to highlight their problems and retrofitting potential. Moreover, generic conclusions and retrofitting guidelines were developed in the project.

The Museums project demonstrates the retrofitting, extension or conversion of seven existing buildings and the construction of one new building and proves in practice that energy efficiency measures applied to museums can provide excellent comfort conditions for both artifacts and users (visitors and staff).

The eight museums within the project include some representative case studies, of worldwide significance as well as some smaller projects.

The following museums were selected:

1 Kristinehamn Museum of Contemporary Art, Sweden

2 Archaeological Museum of Delphi, Greece

3 National Etruscan Museum of ‘Pompeo Aria’, Marzabotto, Italy

4 Bardini Museum of Florence, Italy

5 Herzog-Anton-Ulrich Museum, Braunschweig, Germany

6 National Archaeological Museum, Lisbon, Portugal

7 National Archaeological Museum, Ljubljana, Slovenia

8 THEpUBLIC Arts Centre, West Bromwich, United Kingdom

Map indicating the eight Case Studies

All cases selected have a unique character and a high status among museum buildings of their country. They also have aspects that could be regarded typical, so the design strategies dealing with these can set an example for similar interventions.

1.2 Why Museums?

A museum is defined according to the International Council of Museums as: “a non-profit making permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits for purposes of study, education and enjoyment material evidence of people and their environment”.

Museums represent our heritage and are buildings of great importance. Retrofitting, conversion and extension of existing buildings into museums is an obvious solution to the increased functional requirements of museums as well as a solution for the maintenance of historic buildings.

Musée d'Orsay, Paris, France. Retrofitting design by G. Aulenti (Photo: A. N. Tombazis)

Moreover, retrofitting actions offer an answer to the problems of the aging museum building stock of most European countries, including deteriorating building fabric, obsolete mechanical networks, the lack of adequate space for the ever increasing needs, disruptive acoustics, the lack of easy adaptability to the new Museum model of a multi-use and multi-culture facility, and the need to improve the indoor environment and the visitor comfort.

Museums are visited by millions of people and often become landmarks and symbols of area development. In this respect they can be an important tool to educate the public. Indeed, if museum design addresses energy-efficiency and sustainability issues, The building can become a teaching aid for energy consciousness and ecological awareness in general, and thus have great demonstration potential.

Guggenheim Museum, Bilbao, Spain
Architect: F. Gehry (Photo: N. Vratsanos)

1.3 Objectives of the Project

The main objectives of the project were to:

- Apply and test new and innovative technologies to promote integrated environmental control strategies in harmony with architectural design.
- Demonstrate that energy-efficient, sustainable museum buildings can meet fully the architectural, functional, visual and thermal comfort, control and safety requirements.
- Provide better conditions in terms of thermal comfort, air quality, daylighting and acoustics.
- Facilities reorganisation of space layouts where applicable.
- Optimise daylight performance and integration with artificial lighting.
- Minimise the environmental impact of the buildings and their installations, by the optimisation of the HVAC equipment.
- Use healthy, environmentally friendly and renewable materials.
- Provide exemplary cases for conversion of other build types into museums.
- Achieve total energy savings of over 35% in retrofitting and 40% in new projects, and reduce CO_2 emissions by over 50%.
- Set a new standard for energy consumption in museums.
- Contribute to the preservation of our European cultural heritage and to the acceptance of innovative and renewable energy technologies and materials in public buildings.

2.1 ARCHITECTURAL DESIGN

2.1.1 The Museum: A Unique Building Type

Museums represent a very special case of architectural typology within society. Their role is to preserve and demonstrate our heritage. Museums have special requirements nowadays which have developed from the desire to attract as many visitors as possible, whereas in the past they were visited mainly by researchers, schools and only occasionally by the public.

Nowadays, we associate social well-being not only with comfort and social security but also with access to amenities represented by art, travel, science and history. In this context, increased and easy access to cultural events is considered highly desirable.

Moreover, a contemporary museum must, instead of simply accommodating its visitors, maintain their interest without creating a sense of fatigue.

The role of museums nowadays has been broadened, and, rather than being mere exhibition halls, museums tend to be multi-use cultural centres, combining the preservation of artifacts, temporary exhibitions, research, education and recreation. This evolution in their role is taking shape not only in new purpose-built museums, but also in those being extended, remodelled, renovated and refurbished, these issues are addressed in this project. Apart from being a source of cultural transformation, museums have also become an important tool for promotion of social cohesion, enhancement of urban areas and local economic growth, as, for example, design of the Guggenheim Museum in Bilbao, Spain, has demonstrated).

In this respect, the architectural museums is important aspects of education for the public. If these architectural lessons are combined with a bioclimatic approach to design, then a museum building can be an excellent teaching resource for energy consciousness and ecological awareness in general.

2.1.2 Brief Historical Evolution

“The bison drawings in the Lascaux caves and the vulture paintings in the Neolithic dwellings of Catal Huyuk are two examples of the basic human need to collect and present images and objects, and to protect them inside a pre-existing or constructed precinct” (from Steele, James, Museum Builders, Academy Editions, London 1994, page 7).

In the same way statues of Gods were held in Greek and Egyptian temples, but were accessible only to temple “personnel”. Eventually in the Greek “polis” (city), small buildings called “Pinakotheke” in which paintings were placed on planks, were established and were accessible to all citizens.

One of the kings of the Greek Dynasty of Ptolemaioi in Egypt founded a building in Alexandria called “Mouseion” in the 3rd Century BC , in which statues of philosophers were placed within botanical and zoological parks.

In the beginning of the 18th Century, artifacts tended to belong to private collections accessible only to a small number of people. Only since the Enlightenment did museums emerge as public places, and become educational cornerstones of democratic societies, such as the British Museum in London or the Metropolitan Museum in New York City.

Sir Sloane’s house, London, U.K.
Source: The Architectural Review

Eventually the character of museums changed from a reliquary of curiosities to an environment specifically created for exhibition, and began to

The nine Muses

fulfil their etymological function as a "Temple of the Muses" the goddesses of fine arts according to Ancient Greek mythology.

The museums designed in the last 30 years are characterised by a series of specific functions. However, as all architectural typologies are subject to a process of change and modernisation, museums also evolved over time to become more complex.

Museums changed from spaces of permanent exhibition, storage and conservation changed to public places with a much broader role, including:

- Permanent and temporary exhibition.
- Work and study.
- Storage and conservation.
- Recreation (restaurants, cafes).
- Commercial (shops, publication centres).
- Research and education centres.
- Multi-use activities.

Centre Pompidou, Paris, France, as a multi-purpose centre. Architects: R. Piano and R. Rogers (Photo: N. Vratsanos)

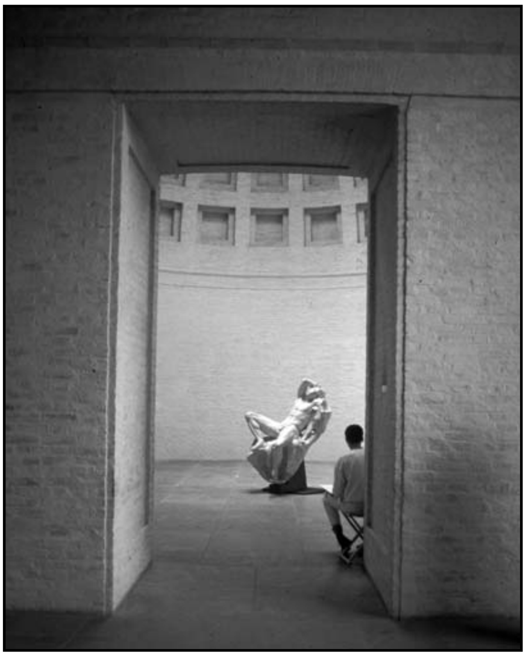
These changing needs have led to further extensions, remodelling, renovation and refurbishments and this has also been the case with the MUSEUM project buildings.

Museum of Modern Art, New York City, U.S.A., with successive layers of extensions (Photo: N. Vratsanos)

2.1.3 Museum Buildings and the Environment

In the past, museum buildings depended on their environment, to a great extent for heating, lighting and cooling as the mechanical means available were rudimentary and could not fulfil the required demands. Thus, the architectural form of buildings was influenced greatly by their energy needs: Openable windows provided ventilation; skylights, glazed roofs and clerestories were incorporated to leave unobstructed wall space for exhibition; narrow spaces helped the even distribution of light; thick masonry walls provided thermal inertia, which ingenuity was employed to take best advantage of the environment.

Furthermore, the majority of the artifacts exhibited were produced and related to the natural environment. The exhibits ranged from everyday artifacts to sculptures, architectural elements and relics. Works of art, as with those of the Impressionist movement, inseparably linked to the natural surroundings of their creation, especially sun and light. Many of these exhibits worked best in condition of variable light and daylight gave them the necessary variety.

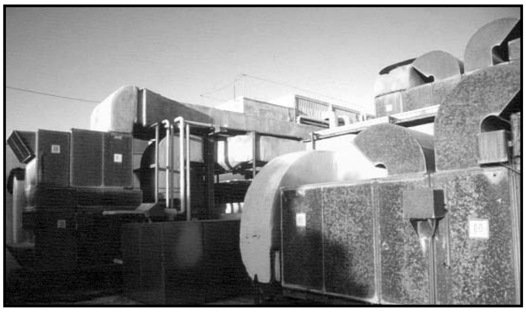


The use of daylight and material in the Glyptothek in Munich, Germany. Architect: Leo von Klenze (Photo: N. Vratsanos)

While this empirical approach to designing with nature was often highly developed, recent advances in science have enabled a greater understanding of the building physics involved.

With the advent of sophisticated lighting and air-conditioning techniques in the post Second World War era, curators and museum authorities began to ask for “black box” solutions, with neutral artificial indoor environments. Often convenient from the control point of view, such systems can deny the advantages of an ever-changing environment that can better enhance qualities of the exhibits.

The resulting buildings were often highly dependent on electromechanical installations and in many older museum buildings the natural potential was often abused, e.g. openings were blocked in favour of air-conditioning and artificial lighting.



A/C units fitted a posteriori on the rooftops of the Archaeological Museum of Heracleion, Greece, blocking the rooflights (Photo: A. N. Tombazis)

Nevertheless, modern light filtering techniques have enabled natural lighting to be more controllable and adjustable, so the argument that the black box solution is inevitable, to obtain stable light conditions, is less compelling.

New works of art including video art, happenings, installations etc., created an additional, significant need for change in museum design to accommodate these new events. However, variety and change are within the nature of these forms of art, so the variable conditions of the natural approach can be applied here to good effect.

2.1.4 Design Parameters - The Container and the Contained

Fundamental to the architectural concept for a museum building are the parameters that must be considered at a very early design stage. Such as the role of the museum, and its relationship with exhibits and people, the ever changing nature of museums and their role in society.

2.1.4.1 Relationship to artifacts

The relation to the background wall with the exhibit in the Exposition d’Art by Le Corbusier. Source: Bill, Max, Le Corbusier & P. Jeanneret 1934-1938, Les Editions d’Architecture, Zurich, 1947

Despite the great architectural value of many museum buildings, many museum interiors were reduced to ‘minimalist’ spaces in the post war era to provide a ‘neutral’ background, but often lost the sense of space and the ability to create an agreeable environment. Although this treatment often facilitated the very large pieces of modern sculpture and painting which were produced at that time, it often did not enhance other artifacts.

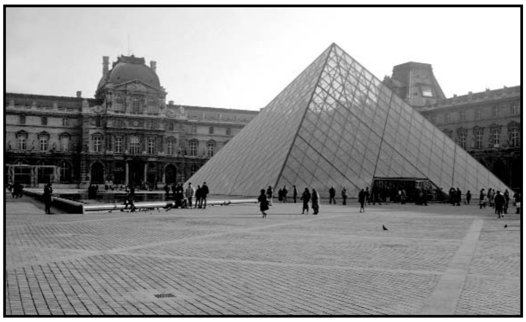
The exploration of a closer relationship between ‘container’ and artifacts by Carlo Scarpa and others led to much more sensitive design decisions that called for a specific design solution for each group of exhibits within articulated, flexible spaces, including the treatment of light which must be variable to fulfil the requirements of individual artifacts, rather that providing uniform background.

2.1.4.2 The introduction of movement

Modern museums tend to place greater emphasis on the movement of visitors. However, it was only after the building of the Guggenheim Museum in New York City, by Frank Lloyd Wright, that such movement was really celebrated and became a main parameter of museum design that was integrated with spatial design. Visitor move-ment results in additional requirements regarding:

- the handling of light (the importance of natural light as its playful variations complement and are necessary for the variety of human movement),
- acoustics
- visual references (views to the outside, relief from museum fatigue, visual access to exhibits, the need to see and be seen.

2.1.4.3 The importance of the container



The civic space created by the Grand Louvre Museum in Paris, France (Photo: A. N. Tombazis)

The grand museum edifices of the 19th Century, no matter how grandiose or imposing, were closely related to their content, which they protected in a distant and dignified manner. But as museums have universally become a part of the popular culture, they have tended to become self-selling icons, irrespective of their content. The strong identity of the building is ultimately superimposed on the artifacts and so the design solutions, including space configuration and lighting, can cease to relate to the artifacts with negative consequences. Thus it is very important for museum design to maintain the subtle balance between the image of the building and the importance of the exhibits.

2.1.4.4 The complexity of function

The modern museum, configured to accommodate an increasing variety of activities, functions and artifacts differs considererably from the classical, monofunctional museum typology. The need for research centres, shops, restaurants, multipurpose halls, social facilities, communication hubs, are all added to the design brief to create a versatile, multi-purpose, educational, commercial and scientific centre. The museum cannot stay confined within its walls and activities extend to connected with the street life, the landscape, and the often historical site. This amalgam of everyday street life, art, science, history and commerce brings a life to the museum that was often denied to formerly. The museum, instead of being merely a ‘container’ becomes a “processor” of information, of social relationships, of culture.

These developments and the need for greater autonomy of collateral functions, has begun to create “buildings within a building” that increase not only the complexity of the design process, but introduce different sometimes contradicting requirements in terms of lighting, ventilation and acoustics.

2.1.4.5 Emergence of the virtual museum space

The ease with which one can nowadays, obtain information regarding the artifacts and visit virtually a museum and its previously inaccessible archives, without physically entering the building, increasingly deprives the museum building of its role as a showcase. It diminishes the sense of privacy between the individual viewer and the isolated exhibit. The once sacred place of scientific and artistic contemplation becomes a place for socialising, gathering, and interacting. Thus, the designer must take into account that, in addition to its role as a processor of values, the museum itself has become a raw material to be processed.

2.1.4.6 The museum as a public space

These changes in emphasis only strengthen the character of the museum as a public place, which as such deserves the special attention given to the design of public spaces, i.e. to incorporate in the museums the principals of public space design including light, variety of spaces, variable relationship between closed and open space, relationship to site context, versatile spaces to be adapted to the users' needs and moods etc.

2.1.5 Design Parameters - External Factors

In the design process of a museum building there are certain external factors that can influence the design in addition to the main design decisions. These factors have a crucial role and a direct impact on the overall energy profile of the building.

2.1.5.1 Functions / uses

- The variety of the exhibits: a "monochromatic" collection, which promotes a uniform environment or a "polychromatic" one, calling for a variable and more complex environment.
- The frequency with which exhibition layouts are changed either for temporary exhibitions, or because of the specific nature of the museum: The extent of change requires corresponding alterations in lighting and thermal conditions.
- The need to incorporate public amenities and multi-purpose activities: Stores, bars, restaurants, libraries, assembly and presentation halls etc., are functions that lead to an entirely different concept of the required indoor environmental conditions (lighting / ventilation / relationship to external spaces etc.).

2.1.5.2 The site

The site, whether rural, urban or suburban, plays a crucial role in the design and in the energy behaviour of the building. It can lead to introvert or extrovert built forms, to open shapes with the ambient space creeping in, or to closed forms detached from the environment sometimes incorporating an open space.

The urban context of the Museum of Contemporary Art in Los Angeles, U.S.A. Architect: A. Isozaki (Photo: A. N. Tombazis)

Innovative adaption to the surrounding environment, whether it is natural or man-made can enhance indoor comfort and visual contact with the changing nature of the outdoor spaces.

Visual contact with the exterior in the Folk Art Museum in Hamar, Bispegard, Norway. Architect: Sverre Fehn Source: Fjeld, Per Olaf, The Thought of Construction, Rizzoli, New York City, 1983

The museum building may have a profound relationship with its site if it is thematically connected to it, as is common in European archeological museums adjacent to archaeological sites.

2.1.5.3 Museology

The science of museology should be part of an holistic, integrated museum design process involving with architecture, structure, mechanical and electrical engineering, acoustics, energy etc. Alas,in many cases it is performed independently, or as a retrofitting action to an already completed shell often with poor results.

Such an holistic design approach can result in architecture that is much more energy and environmentally conscious while providing greater flexibility and adaptability for current and future exhibits, activities and functions than is possible with a design approach that turns its back on the environment.

2.1.5.4 Retrofitting an existing building

Retrofitted existing buildings form a significant portion of the museum building stock in Europe, for reasons both cost (compared to building a new edifice) and cultural heritage (new uses for historic buildings of other types). This can pose constraints that compromise the possible design scope, especially if the building is a designated landmark where in some cases the façade - one of the most important and effective areas for bioclimatic design interventions - must remain intact.

Despite these constraints, the use of an existing shell may have its benefits. Often massive load bearing structures these buildings can provide substantial thermal inertia which is useful in moderating temperature savings and can thus reduce cooling and heating loads. In addition, they often depend greatlyon natural light and ventilation, so the apertures are already there and operating and can be of great benefit in the new design.

Apart from the technical issues of retrofitting existing buildings, one should note the added historic value of these edifices, which can enhance the image of the museum.

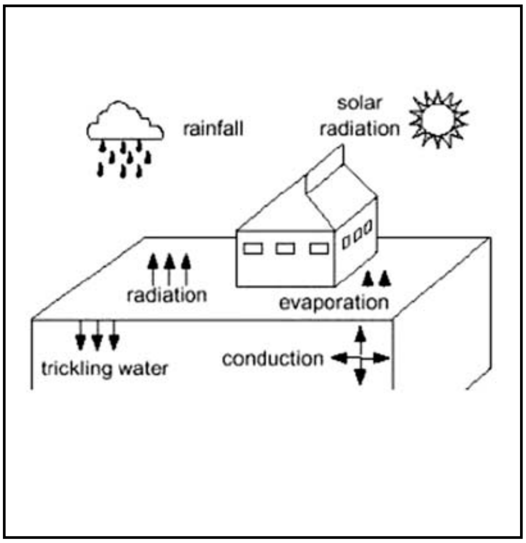
Furthermore, as existing buildings are converted to many other uses, any energy conscious retrofitting design for use as a museum can be an exemplar for retrofitting actions in buildings destined for other uses.

2.2 ENVIRONMENTAL DESIGN

2.2.1 Why Environmental Design is Important

The thermal behaviour of a museum building may be affected by various parameters. These include the main design variables, which can be controlled at the design stage. Other climatological parameters are the environmental variables which are not subject to human control. Insufficient attention to these aspects at the design stage, can lead to an uncomfortable indoor environment. During summer, especially in climates with hot weather, buildings are exposed to high intensities of solar radiation and high temperatures. This may result in overheating conditions that exceed the threshold of indoor thermal comfort. A similar solution can occur during the winter in cold climates. Under such conditions, the protection of the museum buildings and artifacts from direct environmental influence can be of great importance.

It has been estimated that in hot or cold regions, the energy needs for cooling or heating of large museum buildings, can be very high. Proper environmental design should therefore be considered thoroughly to control the interior comfort conditions and to reduce the need for heating or air-conditioning units which can cause environmental, indoor air-quality problems and additional running costs.



Building environment

The study and application of environmental design is a multilayered and multidisciplinary process. Heating and cooling processes should not be considered as isolated phenomena, but rather in close relationship to the shape and type of building, the occupancy patterns, and the sources of heat gains or losses under different climatic conditions.

2.2.1.1 Energy and environmental benefits

- Reduction of air-conditioning use, which in recent years has caused a shift in electricity consumption and increased peak electrical demand in the summer season.
- Reduced heating loads and need for electrical energy generation contributing to slower depletion of fossil fuels, less atmospheric pollution and a milder climatological changes.
- Decrease in CO_2 levels caused by the use of fossil fuels currently used for heating,and electricity thus reducing the global generation “greenhouse effect”.
- Reduction of heat rejected to the environment during the production process, minimising the phenomenon of the ‘urban heat island’.
- Slowing-down of Ozone layer depletion caused by CFCs and HFCs used in the refrigerant of air-conditioning units (due to the potential for leakage during manufacture and maintenance).

2.2.1.2 Indoor air quality benefits

- Reduced symptoms of illness reported in people working in air-conditioned buildings (known as ‘sick building syndrome’).
- Improved indoor comfort conditions. Reduction in PPD index (% of People Dissatisfied).

2.2.1.3 Economic benefits

- Installation of smaller Heating and A/C units reducing the construction cost of a building.
- Reduced trade deficit of a country due to the cost of importing heating or A/C equipment.
- Decrease in economic or political dependence of countries with limited natural resources.

2.2.2 State of the Art Environmental Design

The considerations of architectural, energy and environmental design will often run parallel and relate closely to one another. Thus facilitating a holistic integration of strategies, features and design.

A useful framework for considering environmental design with emphasis on energy use for heating or cooling can be under as follows:

2.2.2.1 Microclimate

The use of cool materials and of green spaces can contribute greatly to a reduction in ambient temperatures and thus minimise the cooling load of museum buildings. Design techniques to direct air to where needed can enhance the potential for natural and night ventilation. The use of cool sinks such as the ground or water can also contribute to the improvement of the local microclimate.

Appropriate species and placement of vegetation on the site can have positive effects both during winter and summer. Deciduous trees to the south can offer natural protection from solar radiation and evaporative cooling in the summer, while allowing solar access for the internal spaces in winter. Furthermore they absorb large amounts of solar radiation helping to keep the air and ground beneath cool, while evapo-transpiration can further reduce temperatures.

Vegetation creates a barrier to wind and therefore reduces air pressure differences on the building surfaces. By reducing wind speeds around buildings, vegetation can modify the convective interaction between the building envelope and the outside air.

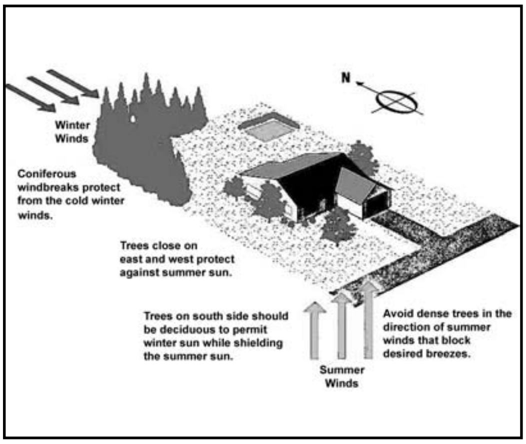
Vegetation can also help to mitigate the greenhouse effect, filter pollutants, mask noise, prevent erosion and create a sense of tranquillity.

Tree shade reduces cooling energy use inside a building in three ways:

- preventing direct solar radiation through windows,
- reducing the amount of heat reaching the interior through the envelope,
- keeping the soil around the buildings cool (the “heat sink” effect).

It is possible to increase the speed of the air flow towards the inside of the building or above it, by constructing a fence or a hedge around the building, or to divide the wind current, and drive part of it through the building while another part goes above it. The combination of the different windbreaks (low or high walls or trees) and their distance from the building can give various different results improving cross ventilation and creating a calm sheltered zone behind.

Besides vegetation and techniques to help define the route and intensity of the wind, other landscape techniques include the use of ponds, streams and cascades for evaporative cooling. These techniques may be implemented in warm and dry climates to considerable effect.



A body of water around a building will exhibit different thermal behaviour to most land surfaces. This is a consequence of:

- Differences in how solar radiation is transmitted or absorbed.
- Convection and mixing that allows the water to store heat, more effectively deep within its mass.
- Heat loses due to evaporation.

The presence of a large water mass causes an air temperature drop that extends downwind depending on wind velocity and mass of water. Ponds and fountains can be effective air conditioning systems in open spaces because of their ability to keep water temperatures lower than air temperature, and due to their lower reflectance.

2.2.2.2 Materials for the buildings exterior

Materials used in the external façades of buildings as well as in courtyards and pavements either absorb or reflect incident solar radiation. Use of high albedo materials can reduce the amount of solar radiation absorbed by the building envelope and structures thus keeping their surfaces cooler. Appropriate materials can result in lower surface temperature and thus reduce the induced air conditioning load. Materials for ‘cool roofs’ or walls should present a high albedo to solar radiation, (close to 70%), while conventional roofing or finishing materials may typically have a mean albedo of around 20%. Important energy savings can be expected when solar reflective materials are used in the exterior surfaces of buildings.

Many building envelope design and retrofit scenarios involve traditional envelope measures, such as added insulation (on the exterior or interior), improvement or replacement of windows (with improved U-values etc.), and greater air-tightness to reduce infiltration.

However, these scenarios which aim to reduce heating energy use may also include measures such as heat recovery from variable ventilation air, ventilation rates (lower rates at night and/or in winter), adjustment of temperature set points (both reduced heating set points and increased cooling set points), and greater use of daylight to replace artificial lighting.

Modification of roof colours

The objective here is to reduce the energy demand by means of a reduction in the solar radiation that is absorbed. This is particularly applicable in cooling dominated climates where reducing the heat absorbed by dark coloured roofs can reduce the cooling demand significantly. The reduction of solar heat gains by using light colours is more significant for roofs with lower mass and higher U-values. Improvements can be achieved by using low solar absorption materials such as:

- Reflective finish materials.
- Adding white gravel or pebbles that may also have an insulating effect.
- Light coloured tiles.

When gravel is used, it is necessary to take into account the weight on the structure and to check that the operation of the rainwater drainage system is not impaired.

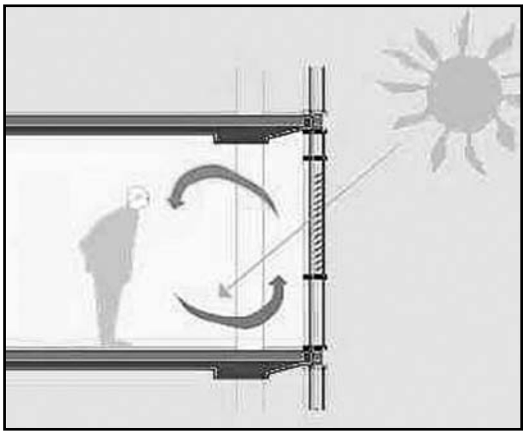
The movement of the sun in relation to the building and the reduced sunshine hours in winter can have a major effect on the heating loads.

Evaluation of improvements derived from the use of light colours should take account of the degeneration of the materials due to dirt and age.

2.2.2.3 Passive heating

Prevention of heat losses

Insulation of the external opaque elements of the façades and roof is one of the simplest and most efficient measures to be considered. Retrofit measures carried out on the building façade to save energy almost always occur in conjunction with façade renovations for other reasons. It is theoretically possible to insulate a wall so well that the heat loss will be practically negligible.



Addition of insulation to the building roof will decrease heat transmission through the usually large roof area and will reduce high temperature problems on the top floor of the building during the summer period. It can also, reduce the condensation risks when outdoor temperatures are low. Various insulation materials can be used such as polyurethane foam or minerals fibres.

As with walls, guidance concerning appropriate insulation level can be obtained from the local building regulations. Technological improvements, mainly in the field of transparent insulation, offer another alternative especially useful for northern climates.

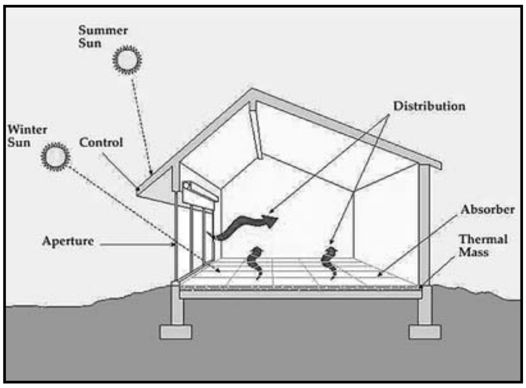
Passive cooling

The passive cooling techniques include building envelope and structure measures such as replacement of windows or the addition of reflective coatings to existing windows, use of solar shading systems, and the increased use of thermal mass.

They may also include more “active” cooling measures, such as natural and/or night ventilation, the use of ceiling fans and solar chimneys, and indirect evaporative cooling. In addition, measures used in the heating mode, such as additional insulation and varied temperature set points, may also be applicable. It should be noted that some of the issues concerning lighting, such as increased use of daylight will also have an effect on the cooling demand.

- Prevention of heat gains
- Modulation of heat gains
- Heat dissipation

The first two measures aim to minimise the heat gains and the air temperature inside the building, while the third aims to reduce interior air temperatures.



Prevention of heat gains

Prevention of heat gains is the first step towards improvement of the thermal comfort conditions in the interior of buildings and includes every measure that helps to minimise indoor heat gains.

Heat gains in a building can be classified as external and internal:

- External heat gains originate from solar radiation transmitted indoors through glazing or absorbed by the opaque elements and consequently conducted indoors, and the ambient heat conducted through the building fabric or transmitted by convection through ventilation and air infiltration.
- Internal heat gains originate from metabolic heat produced by occupants artificial lighting (a significant heat source in museum buildings), computers and increasingly from appliances.

The contribution of each type of heat gain depends on the design of the envelope and the use of the building.

Protection from heat gain involves the following design measures:

- Landscaping and use of outdoor and semi-outdoor spaces
- Building form, layout and external finishes
- Solar control and shading of building surfaces
- Thermal insulation
- Control of internal gains

Modulation of heat gains

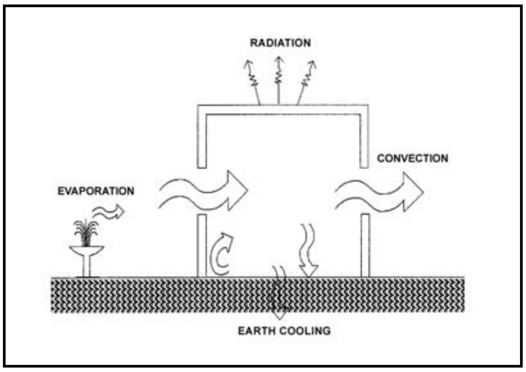
Modulation of heat gain is influenced greatly by its capacity for heat storage in the building structure which can be achieved through the use of materials of high thermal capacity (or thermal mass, as it is also called). High thermal-mass materials such as brick and concrete act to store both heat and cold as they heat up and cool down relatively slowly. This delay or ‘thermal lag’ can attenuate peaks in the cooling load and modulate internal temperatures allowing heat discharge at a later time (e.g. at night).

Thermal mass can also reduce the heat flow reaching the interior of the building as part of the stored heat in the envelope is reradiated and convected back to the external environment during the evening hours. During the evening, the thermal mass acts as a “cooling” storage that is gradually depleted during the day. The larger the swings in outdoor temperature, the more important is the effect of the thermal mass. The role of thermal mass attains its greatest importance in buildings that are in continuous use, such as museum buildings.

Heat rejection

Heat dissipation techniques deal with the potential for disposal of excess heat by natural means. Dissipation of the excess heat depends on two main conditions: The availability of an appropriate environmental heat sink for the heat to be rejected to and appropriate thermal coupling and sufficient temperature differences to permit the transfer of heat from indoor spaces to the sink. The main processes of heat dissipation techniques are identified in the table below:

Process	Heat Sink	Heat Transfer Mode
Cooling with ventilation	Air	Convection
Radiative Cooling	Sky	Radiation
Evaporative Cooling	Air	Evaporation
Ground Cooling	Earth	Conduction

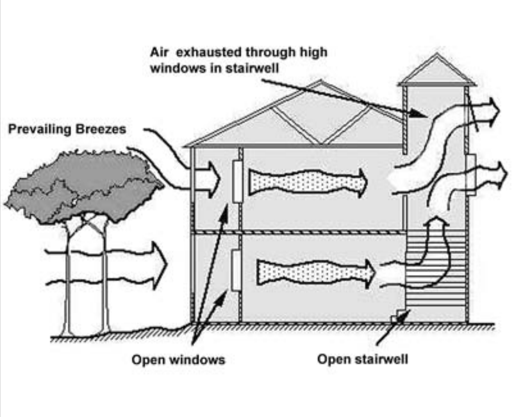


Heat dissipation strategies

2.2.3 Environmental Design Techniques to Optimise Performance

2.2.3.1 Thermal and air-flow systems

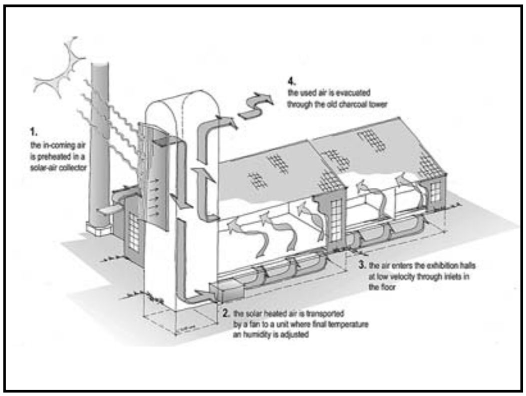
The use of hybrid or natural ventilation and night ventilation strategies either using designed openings and the automatic opening of the mechanically movable elements in the roof and walls is an alternative to the use of a mechanical air conditioning system.



Natural ventilation

2.2.3.2 Solar Heating with ventilation

The use of hybrid solar air heating and ventilation systems offer an alternative to air conditioning systems by supplying not only part of the heat demand, but also all the fresh air necessary.

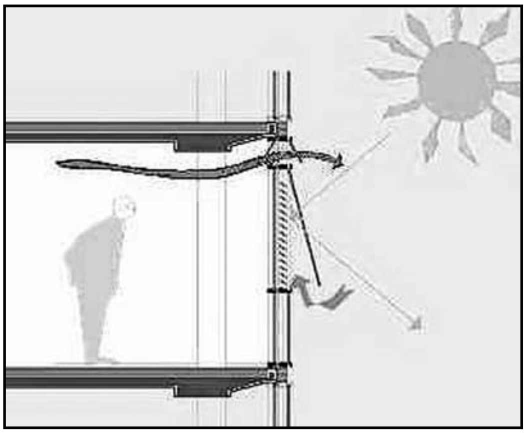


Kristinehamn solar air heating system

2.2.3.3. Cooling with ventilation

Ventilation of is a major cooling technique in buildings throughout the world. It is based on convection, where air flowing next to a surface carries away heat, provided it is at a lower temperature than the surface. When it passes over the human body, it increases the evaporation rate from the skin which enhances heat extraction.

Air movements through buildings result from the difference in pressure indoors and outdoors which can be achieved by *natural forces* imposed by wind-induced pressure differences or by temperature gradients (stack effect) or *mechanical forces* (pressure difference induced mechanically, e.g. by using fans).



2.2.3.4 Daytime ventilation

This can improve thermal comfort through higher indoor airflows which can provide a direct physical cooling effect even at temperatures as high as 34°C. Higher air speed increases the rate of sweat evaporation from the skin also minimising the discomfort from the feeling of wet skin. Thus, it is especially beneficial when the relative humidity of the air is high.

Although daytime ventilation can raise the temperature of the internal surfaces and air, its overall effect on comfort can be positive, provided that indoor comfort conditions can be experienced the prevailing outdoor air temperature, with through an acceptable indoor air speed. It is estimated that increasing the air velocity by 0.15 m/s-1 compensates for a 1°C increase in air temperature at moderate humidity levels (less than 70% RH).

The design objectives should be:

- to obtain a continuous air flow throughout the building
- to direct the air flow through the occupied zones
- to achieve high air velocities close to the occupants.

The structural materials should ideally be of low heat storage capacity.

2.2.3.5 Nocturnal ventilation

Air movement through the buildings during the night, when the ambient air temperature is lower, indoor air temperatures and may be said to store “coolness” in the building thermal mass.

The storage mass can be distributed in the structure, for example in the walls, floors, ceiling or in a specialised thermal store, such as a rock bed or water storage mass. The building is kept cool during the following day provided the windows are closed, as the cool structural mass can absorb heat that penetrates through the envelope or is generated inside the building. When the storage mass is outside the building, it can be used to pre-cool the ventilation supply air or to cool the building by a closed-circuit loop.

The effectiveness of nocturnal ventilation is linked to:

- the ventilation rate
- the storage volume or mass
- the area that comes into contact with the cool air flow
- the heat capacity and thermal conductivity of the storage material.

The design of the museum buildings should ensure a high ventilation rate through the building, especially over the storage surfaces.

2.2.3.6 Radiative cooling

Radiative cooling is based on heat loss by long-wave radiation emission from a body towards another body of lower temperature, which plays the role of the heat sink. In the case of buildings, the cooled body is the building and the heat sink is the sky, since the sky temperature is lower than the temperatures of most of the objects on earth.

Direct radiative cooling

The building envelope radiates towards the sky and gets cooler thus enhancing the heat loss from the interior of the building. The roof absorbs the largest part of the solar radiation during summer, has also the best view of the sky dome and thus is a very effective radiator. (On a hot summer day the roof of a building could reach 65°C at noon and at this temperature could reradiate almost 750 Wm^{-2} towards the sky).

The use of high thermal storage materials can increase the radiative potential of a building by delaying the transfer to its interior of heat which is radiated back during the night. Traditional architecture in hot, dry and sub-tropical climates shows examples of radiative cooling by using vaulted roofs. The surface of a vault is bigger than its horizontal base (three times bigger for a hemispherical roof), and thus there is a large storage surface during the day and radiative surface during the night.

Insulation of the roofs structure minimises the actual radiative cooling potential of the building, but application of movable insulation on top of the roof can enhance the radiative potential of the roof, as it is used to protect the roof from solar gains during the day but leave it exposed during the night.

2.2.4 Evaluation of Environmental Design and Performance

The environmental design evaluation strategy of the museums together with energy simulations and monitoring, aim to achieve the following:

- To assist designers in the final selection of the various renovation / retrofitting features to be applied by analysing the performance and effectiveness of each system.
- To predict or estimate the potential energy savings achieved by comparing initial and final

simulation results To assess qualitatively the environmental and energy performance with respect to energy conservation, thermal and visual comfort and indoor air quality.

- To investigate and assess the real performance of the energy strategies and features implemented by comparing the simulation results with the monitored energy consumption figures; and to evaluate the specific and overall energy and environmental efficiency of the final building designs.
- Finally, to compare actual results with initial targets or existing consumption data and to rate and classify each of the museum buildings according to a rating scheme based on the applied energy norms and performance standards.

2.2.4.1 Simulation phase

The evaluation of the energy features selected for a museum building can be performed initially by using precise simulation techniques to represent the main design objectives.

Various evaluation and simulation tools are available and many of them may be used in the design phase of a museum project for each of the major sub-systems, in particular:

- Microclimate
- Building envelope
- Heating / Cooling systems
- Ventilation
- Artificial lighting
- Indoor comfort
- Control systems

2.2.4.2 Monitoring phase

Monitoring activities are necessary in order to evaluate in practice the specific and the overall energy and environmental quality of the museum buildings. Thus, monitoring protocols and strategies must be defined and planned in order to have the necessary information for comparison with the theoretical results obtained during the evaluation simulation phase.

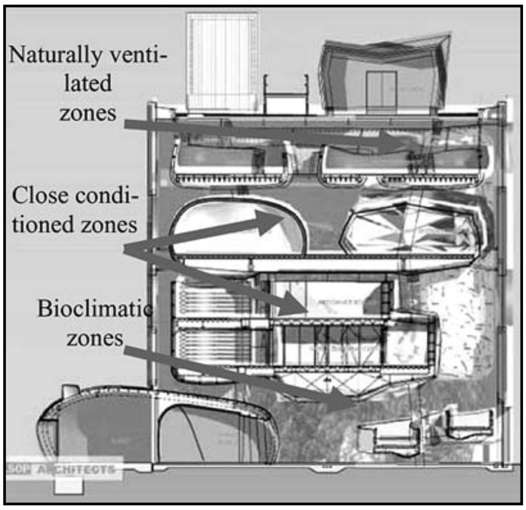
The monitoring phase for a museum building may start after its successful commissioning and can last for 12 months or more to allow for settled occupation drying out of wet construction material and optimisation of the museum building operation with continuous measurements of the outdoor environment, indoor environment, systems operation and energy use, e.g. space heating & cooling, electricity for ventilation & lighting, contribution from renewable energy sources, etc. The use of monitoring targets to verifying the project's final results helps ensure scientific appropriateness and comparative analogy to the simulations previously performed.

Finally, quantitative measurements may be complemented with the distribution of a qualitative questionnaire to find out how the visitors and staff perceive the thermal performance and indoor air quality according to the occupancy profile of each building.

2.2.5 Results, Lessons Learnt and Strategy with Respect to the Environmental Design

Although climate is a determining factor in the demand for heating and cooling of a museum, building type, occupancy patterns, activities and building design are equally important.

Moreover, the efficiency of passive cooling techniques is more dependent on climate (air temperature. relevant humidity, velocity and direction of winds) than are passive heating ones.



THEpUBLIC Arts Centre bioclimatic envelope

Passive solar heating will always make a positive contribution to the overall thermal performance of a building, whereas improper choice of a cooling technique could create a very unpleasant internal environment. In addition, thermal comfort requirements during summer are different for each climate type. Thus, hot dry climates require different cooling strategies to hot humid climates. Appropriate measures for prevention and modulation of heat gains can be effective in any climate and any type of building.

The overall concept behind a strategy for passive heating and cooling can be summarised in the following, steps:

- Control of the solar energy reaching the building and of the ambient air entering the interior of the building
- Proper dissipation of the internal heat gains from occupants, artificial lighting and appliances
- Control of the heat that penetrates the building envelope through appropriate methods (thermal mass, ventilation, etc.)
- Implementation of suitable bioclimatic architectural design according to the building type and its climate.

2.2.5.1 Shading devices

- Use of fixed or movable sun shading devices
- External shading devices are preferable and more effective than internal ones.
- In museums. special glazing with a low solar transmittance coefficient or, if required, high shading coefficient should be used.
- When designing the external shading devices, take into account the need to control solar gains in summer, as well as the heating and lighting performance of the building.

Herzog-Anton-Ulrich Museum glazed roof

2.2.5.2 Thermal capacity

- In warm climates such as those of the Mediterranean, materials of high thermal capacity should be used to help the building operate as a thermal storage bank. This will improve the building's performance during summer as well as during winter.
- Special care should be taken in order to provide night-time natural ventilation during the summer period, which is essential for the rejection of the stored heat by convection. This is the best, if not the only method for passive cooling during night.

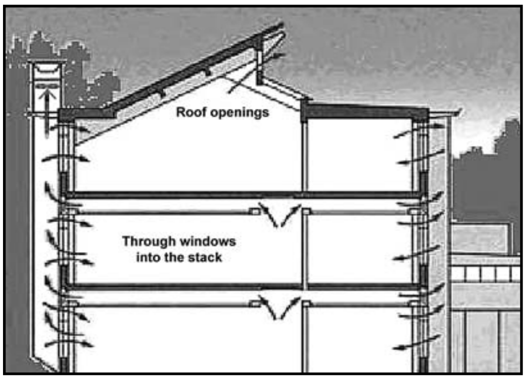
2.2.5.3 External surfaces of the building

Coatings - Light colours should be used in warm sunny climates with long hot summers to increase the surface reflectance and to avoid high surface temperatures.

- Glazing - In urban buildings with a given orientation, east or west, the most effective glazing types are the reflecting or the absorbing ones.
- Planting next to building skin and / or roof vegetation.

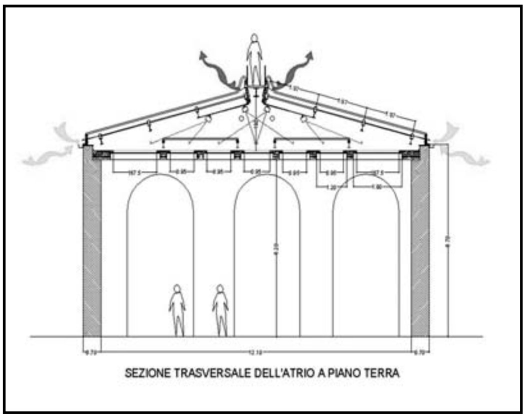
2.2.5.4 Ventilation strategies

- Openings: ventilation is mainly induced by wind forces and pressure differences around the building.
- Wind tower / stack effect: air motion through the building is controlled by buoyancy forces attributed to temperature differences between adjacent air intake and exhaust zones.



- Solar chimney / air collector: air is heated by the solar warming of a surface and can either be used to heat the building or induce ventilation due to temperature differential.

Kristinehamn solar air collector



Bardini ventilated roof

- Ventilated roof or wall construction
- Clerestorys and roof vents: the heated air which is collected near the ceiling is removed through the roof and window vent openings mainly by suction caused by the wind pressure differences around the building.

Delphi ventilation - automatic windows

To summarise, the applicability of passive heating and cooling strategies depends on:

1. *Climate and microclimate*
   High night ambient temperature, cloud cover, high humidity and wind speeds are the main factors affecting the efficiency of the different cooling approaches.
2. *Air pollution and noise*
   This restricts the use of some cooling techniques such as natural ventilation especially in the urban locations.
3. *Site topography and building regulations*
   In some cases these factors can restrict the design of museum buildings and limit the applicability of environmental design techniques.
4. *National regulations*
   These concern regulations relating to the heating and cooling needs of museum buildings. Even though there may be an emphasis on the heating needs of buildings, the issue of thermal comfort during the summer period deserves equal attention.

2.3 LIGHTING DESIGN

2.3.1 Why Lighting Design is Important

Museum visitors usually prefer to see objects which are displayed under daylight. The daylight may be provided by side windows or rooflights and may be highly controlled or partially controlled. The effects of daylight in a space are much more noticeable from side windows than rooflights but is more difficult to control to ensure avoidance of glare and poor viewing conditions. Highly controlled rooflights, may however, fail to give a good impression of daylight and it must be questioned whether they are worth the cost. An evaluation of energy payback is needed.

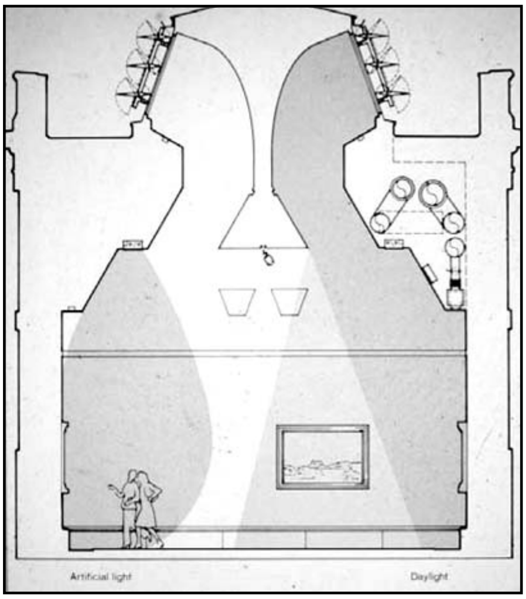
Daylighting and indeed artificial lighting pose specific conservation problems in Museums. We need light to see the objects but that light can damage sensitive objects. By ‘light’, we mean visible light and ultra-violet light. Controlling ultra-violet light is somewhat easier because it does not contribute to vision so ultra-violet filters can be used. However, most ultra-violet films used on windows, for instance, will become less effective with time. Therefore, continuous monitoring of ultra-violet light should take place wherever sensitive objects are displayed. Direct exposure to sunlight while potentially very detrimental to the object and our ability to see it is unfortunately still too common in European museums.

2.3.2 State of the Art in Lighting Design

The overall light exposure permitted on sensitive objects is the sum of the daylight and artificial light. With highly sensitive objects it is almost impossible to use daylight. Control of artificial light to levels below 50 lux precludes any daylight use. Where such objects are being displayed, especially in any large museum, areas should be provided where a view out is possible. These areas may contain less sensitive objects or may simply provide seating for the visitors. Such an approach can also help reduce the incidence of ‘museum fatigue’. With objects of medium sensitivity a highly controlled approach may be adopted requiring automatic shutter control of the louvres that control the daylight, and of artificial light. Such systems are extremely expensive both in their initial cost and maintenance. A more passive approach might be adopted where by daylight may provide between 40% and 70% of the total yearly lighting demand. Such a system would normally have differential louvre controls on the daylighting for summer and winter, and be relatively more transparent in winter than summer.


Automatic light control louvres on gallery roof


Turner Oil Room, Tate Britain, London



Automatic daylighting system for Turner Oil Room, Tate Britain, London. Source: K. Mansfield

2.3.3 Lighting Design Techniques to Optimise Performance

Vertical hanging space is often at a premium in museums particularly for paintings. Hence it is frequently found that vertical windows have been blocked up or covered in museums which have been created from refurbished buildings of other types. However, it is not simply the hanging space that causes problems with vertical windows. Objects displayed against windows are displayed against a high luminance (very bright) background, increasing the adaptation requirement of the eye so that much detail and colour in the object are lost.

Bastan Museum in Tehran, Iran

Museum at Ioannina, Greece

2.3.3.1 Rooms for sensitive objects

With lower levels of light, the use of a dark background reduces the adaptation level of the eye, thereby increasing the apparent brightness of the viewed object. For instance, in the 'Turner Watercolour' room at the Tate Britain Gallery in London where the vertical illuminance on paintings is maintained at 50 lux, a low reflectance, maroon background is used.

The choice of background reflectance and, indeed, colour plays an important role in the visibility of the objects. Backgrounds of high chroma (strong colour intensity) can impose their own colour on a room. Photographs may exaggerate this effect as the eye searches for a reference or 'white balance' within a room in an effect sometimes known as 'colour constancy'. Neutral surfaces (except white) tend to produce a gloomy, cold appearance. The best compromise is usually a low chroma background with a reflectance of 20% – 60%, chosen according to the necessity to reduce the adaptation level of the eye.

Turner Watercolour Room, Tate Britain, London

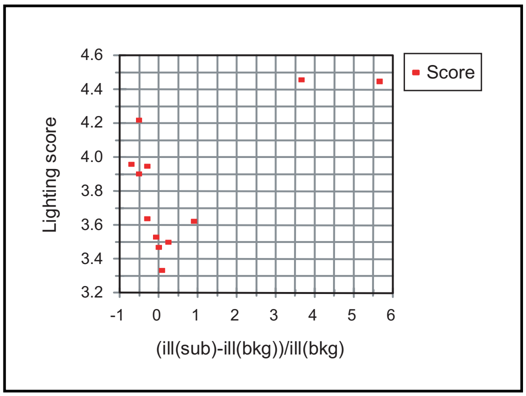
Bastan Museum in Tehran, Iran

Galleries exhibiting modern art have a tendency to use a white background where the reflectance may exceed 80%. This will often work with modern art consisting of strong primary colours, such as the works of Andy Warhol, but not necessarily so well with Picasso and, in particular, dark sculptures. Thus, it is a less exaggerated example of trying to view a dark object against a window. A similar statue is shown below against a low chroma mid reflectance background.

2.3.3.2 Changing wall reflectances

Care should be taken, however, if a design that was originally conceived with highly reflective walls is to be replaced with walls of lower reflectivity. This is because in schemes with high reflectivity the contribution of the reflected light to the total amount of light is very high and a reduction in that reflectivity will severely compromise the total amount of light in the room.

2.3.3.3 Lighting quality and visibility



Illuminance contrast versus lighting quality

During the JOULE "Retrofitting of Museums for Antiquities in the Mediterranean Countries" project an 'illuminance' contrast of objects against their backgrounds was measured in a variety of archaeological museums in the Mediterranean region. The illuminance contrast was regarded as a reasonable estimate of the normal luminance (brightness) contrast because the objects, which were mainly stone, had similar reflectance values to the wall surfaces. This was compared with visitors' estimations of lighting quality. It was noticeable that the lighting quality was mostly judged by the degree of contrast, regardless of whether the object was relatively bright or the background was relatively bright. Clearly if the background is relatively bright some detail will be lost in the object. However, as visitors are often unaware of this loss of detail, the museum curator has particular responsibility to guard against such poor visual effects.

Museum at Samos, Greece

2.3.3.4 Glass display cabinets

High brightness sources, either artificial light or daylight, may produce reflections in the glass of display cabinets thus affecting the visibility of objects within the cabinet. They may be particularly noticeable if the objects within the cabinet are poorly lit and it contains no additional light source. The perception of the 'veiling reflection' depends on the balance between the brightness of the reflection and the brightness of the object. The issue is quite complex, however. A low reflectance surface in the background of the cabinet can reduce the adaptation level of the eye and, in theory, improve the visibility of the object reducing the adaptation level of the eye may make the veiling reflection visible. Careful analysis is needed in each case.

Reflections of window in glass case in Bastan Museum, Tehran, Iran

2.3.3.5 Surface reflectance

Surface reflectance can have a major impact on the level of illuminance in the room for a given amount of light flux entering. The impact may be judged by Sumpner's formula, which gives the mean surface illuminance as F/A (1-R), where F is the amount of light flux entering the room, 'A' is the surface area of the room and 'R' is the reflectance coefficient. Changing the mean reflectance from 0.4 to 0.6 increases the illuminance by nearly 67%; and from 0.4 to 0.7 by 100%. Increasing the luminance of the surfaces by 0.4 to 0.6 increases the luminance by 100% and by 0.4 to 0.7 by 175%! A room with an average reflectance of 0.4 might be considered a mid-reflectance room, where a 0.7 reflectance room would have white surfaces and a light-coloured floor. The surface colour and reflectance is an integral part of the lighting scheme.

2.3.3.6 Contrast

Diffuse illumination, where light comes equally from all directions, will allow an object to be seen, but will do little to reveal the form or texture because of the lack of shadows. The gradation of the reflected light (brightness) over the surface of an object reveals its 3-D nature, while texture may be depressed or expressed by applying light at an appropriate angle. The degree of diffusivity in a space can be expressed as the vector /scalar ratio, where values between 1.2 and 1.8 give satisfactory modelling of faces. Where an 'unnatural' effect is required, specified on a scale ranging from subtle to dramatic, the following table acts as a guide.

Display Effect	Objective Display Illuminance ratio	Subjective Apparent Brightness ratio
Subtle	5 to 1	2.5 to 1
Moderate	15 to 1	5 to 1
Strong	30 to 1	7 to 1
Dramatic	50 to 1	10 to 1

2.3.4 Lighting Design Performance Criteria

It is common to divide objects into three categories regarding sensitivity to light: insensitive, medium sensitive and sensitive. The figures in the next table should be seen in the context that full appreciation of colour is not achieved until about 250 lux. The levels of light recommended for sensitive objects preclude the use of daylight. Some highly controlled daylighting systems (normally rooflights) exist to maintain 200 lux on the objects, but the lux-hour allows a more passive approach to maintaining conservation requirements. Some commentators have suggested that very sensitive objects, which may have to be lit at 10 lux or below (e.g. the Leonardo cartoon in London's National Gallery), may be viewed at higher levels, but with a restricted viewing time.

	Maximum Illuminance (Lux)		**Maximum accumulated yearly exposure (Lux-hours)**	
	UK	US	UK	US
Sensitive objects (*eg* watercolours)	50	50	150000	50000
Medium Sensitive objects (*eg* oil paintings)	200	200	600000	480000

Where objects are insensitive (e.g. stone statues that are not treated with light sensitive preservative), then higher levels of light may be used. Earlier research within the JOULE project, however, showed no correlation between absolute light levels and visitor estimation of lighting quality.

2.3.5 Results and Lessons Learnt with Respect to Lighting Design

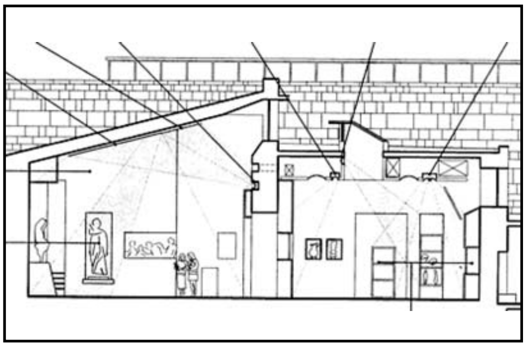
All of the projects in 'MUSEUMS', apart from the newbuilt THEpUBLIC Arts Centre in West Bromwich, UK, were either refurbishments of existing museums, or conversions of existing buildings into museums. Two major problems were encountered regarding daylighting. One was sunlight penetration, while the other arose where existing vertical windows provided high luminance light sources in the direction of view either because there were no blinds, or because existing blinds offered only poor protection. With artificial lighting, the concern centred on the replacement of existing fluorescent lighting which provided dull diffuse light, by more focused lighting sources in order to improve contrast between object and background.

2.3.5.1 Archaeological Museum of Delphi

The museum at Delphi had two distinct types of gallery. In most galleries the objects are not sensitive. The clerestory-lit galleries (e.g. the Apollo and the Athenians) tended to suffer from sun patches on the objects, particularly from the east-facing windows during the morning.

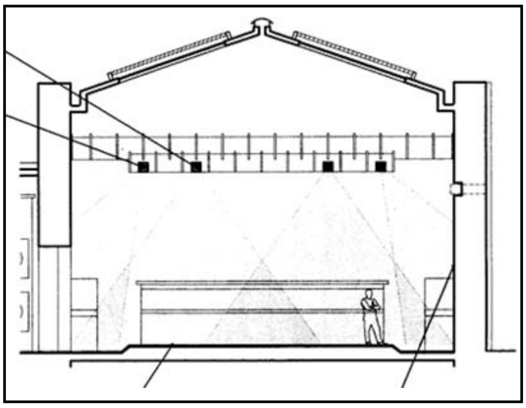
Model photograph showing sunlight problems in Apollo Room

The Siphnians room had a traditional rooflight, with light penetrating through the roof into the roofspace and then through diffusing glazing into the room.



Proposed solution for Apollo Room, Delphi

There was no control. An even level of light was produced in the room with poor contrast. In the vertical plane, the walls had a higher illuminance than the large objects in the room (generally placed toward the centre of the room). The clerestories were fitted with external shading, while east-orientated screened rooflights, were added. The artificial lighting strategy incorporates a combination of fluorescent and spot lamps with ceiling-reflected light.



Proposed solution for Siphnians Room, Delphi

The diffusing ceiling in Hall V (Siphnians Room) is being replaced by an egg-crate based internal system, with external shading louvres allowing no penetration of sunlight, reducing the luminance of the background while maintaining the illuminance on the objects.

2.3.5.2 Herzog-Anton-Ulrich Museum, Braunschweig, Germany

The Herzog-Anton-Ulrich Museum in Braunschweig has utilised a split, venetian louvre type blind system on the vertical glazing. Most objects are oil paintings, corresponding to 'medium sensitivity'. The bottom part of the blind remains generally closed, while the top part reflects light onto the ceiling. This maintains a low luminance in the field of view, while admitting reflected daylight from the ceiling. These systems are being introduced on the north-facing windows at present.

Two-part louvre blinds during installation at Herzog-Anton-Ulrich Museum

2.3.5.3 Kristinehamn Museum of Contemporary Art, Sweden

The Kristinehamn Museum of Contemporary Art in Sweden, consists of two main buildings. The older building, the former boiler station for the whole site (originally a sanatorium), is being converted into a large exhibition space. The gallery needs to be flexible to deal with a variety of displays, ranging from highly sensitive objects to those with no light sensitivity. The south-east-facing side has several large windows with an additional glazed area to the south-west. Heliodon studies showed that sun patches would be a problem from both sets of windows. The solution has been to adopt a double blind system. A diffusing blind and an upside down blind are fitted to the inside. The latter blind allows control of daylight by creating an adjustable clerestory.

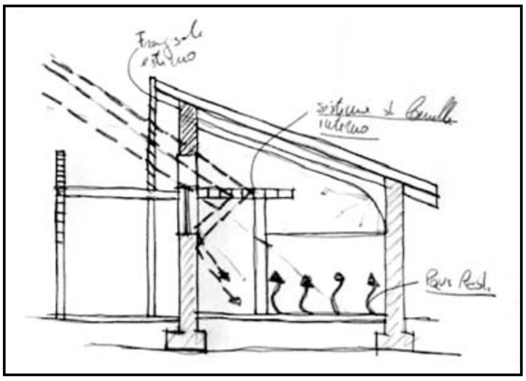
Kristinehamn Museum with blinds fully retracted

Kristinehamn Museum with blinds fully drawn

2.3.5.4 National Etruscan Museum 'Pompeo Aria', Marzabotto, Italy

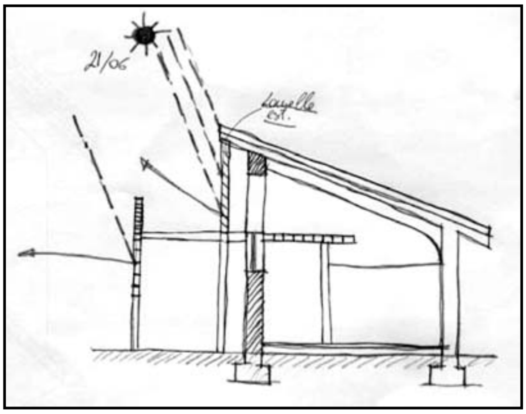
The new exhibition space of the 'Pompeo Aria' National Etruscan Museum in Marzabotto, has south facing vertical glazing that needs sun control with regard to both thermal gains and daylighting. The service/ energy solution chosen involved the use of an external wooden balcony, an observation point towards the archaeological area, that also connects to the new multimedia room.

Moreover, the balcony acts as an external shading system, designed to allow solar gains in winter and avoid overheating during summer season.



Archaeological museum 'Pompeo Aria': Winter sun

Internal baffles and louvres, together with a curved ceiling, diffuse daylight and allow a uniform illuminance inside the exhibition room and a more variable one in corridors.



Archaeological museum 'Pompeo Aria': Summer sun

The following images show RADIANCE simulations of the proposed solution under an overcast sky and a sunny sky on 21st March at noon.

Archaeological museum 'Pompeo Aria' RADIANCE Simulation: Overcast sky

Archaeological museum 'Pompeo Aria' RADIANCE Simulation: Sunny sky

2.3.5.5 National Archaeological Museum, Lisbon, Portugal

The National Archaeological Museum in Lisbon provided a similar problem. South-facing vertical glazing is at present covered with two layers of dark gauze together with an expanded metal security grid. This leads to a very low overall transmittance of under 2%. Under a mean external luminance of 6,000 cd/m^2 (a bright, overcast sky), only 30 lux was available on the floor. The historical character of the building means that limited works can be undertaken. The proposed solution uses a screen with a light shelf. However, it can be seen from the RADIANCE simulations that additional louvres will be required over the light shelf to prevent low angle sun.

The Museum is also creating a new sunken storage and administrative area in the large courtyard. This sunken area includes a patio to give light to the office areas. It is proposed that the circulation spaces in this sunken area will be lit by light pipes.

National Archaeological Museum: RADIANCE simulation: Sunny sky, June noon

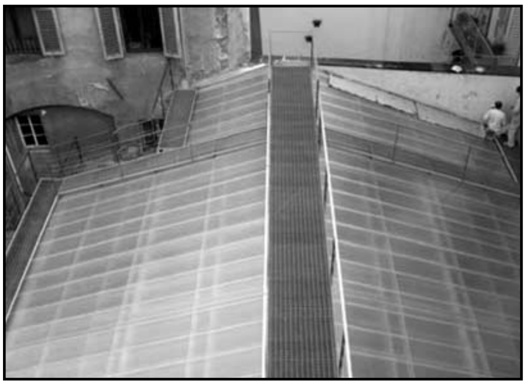
National Archaeological Museum: RADIANCE simulation: Sunny sky, November noon

2.3.5.6 Bardini Museum of Florence, Italy

The Bardini Museum in Florence suffered from poor artificial lighting and a low transmittance rooflight structure with poor daylight control. For the artificial lighting, a variety of tungsten and poor efficacy fluorescent lamps with low utilisation fittings are being replaced with modern, high efficacy improved colour-rendering fluorescent with high reflectance, low brightness (low glare), high utilisation fittings.

The original glass superstructure of the rooflight had poor solar control and is being replaced by 30mm twin-walled polycarbonate of improved transmittance.

Birds eye view of existing rooflight, Florence

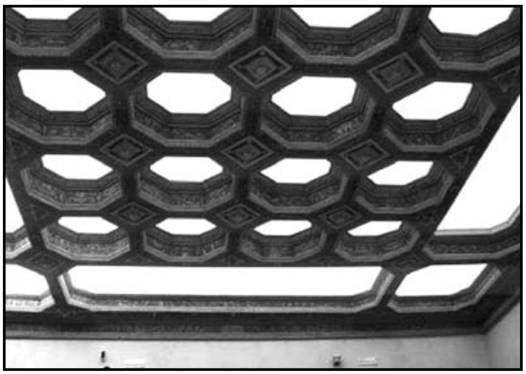


Birds eye view of new rooflight, Florence

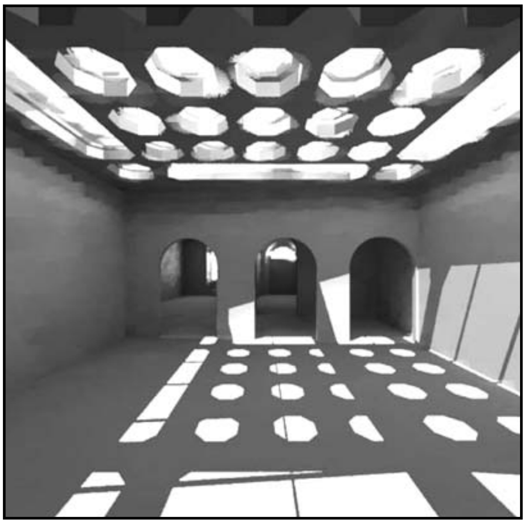
A wooden / glazed ceiling exists below the present superstructure. The bullet-proof glass is to be replaced by high-grade diffusing plastic, creating a more even illumination.

Simulations with RADIANCE have been carried out in order to compare the reflection coefficient of the original blue colour (0.35), which is intended for replication in the new museum rooms, with that of the cream colour (0.6) of the existing plastered walls.

Bardini Museum: Existing wooden / glazed ceiling



Bardini Museum: New wooden / glazed ceiling



Bardini Museum: RADIANCE Simulation

2.3.5.7 Slovene Ethnographic Museum, Ljubljana, Slovenia

The rooms in the Slovene Ethnographic Museum in Ljubljana were sidelit and a roller blind approach has been adopted for sun protection. This is linked to daylight and occupancy controlled artificial lighting consisting of T8 fluorescent for general lighting and tungsten halogen spots. Sensitive objects are placed away from the windows. The Adeline version of the RADIANCE software has been used to predict the lighting levels in the rooms under a variety of conditions.

Roller blinds in Slovene Ethnographic Museum partly raised

Roller blinds in Slovene Ethnographic Museum closed

2.4 ACOUSTIC DESIGN

2.4.1 Why Acoustic Design is Important

Museums may be characterised acoustically into two types: those with hard plaster surfaces including ceilings and are often naturally ventilated; and those spaces with air-conditioning where a suspended acoustic ceiling may hide duct work. Sometimes both types of space exist side by side in the same museum. In the former case the reverberation time can exceed 7 seconds, whereas it will generally be below 1sec where an acoustic ceiling has been installed. The acoustics are thus substantially different. In the 'MUSEUMS' project there was no problem with external noise from traffic or other transport or industrial sources in any of the individual projects. Noise problems, however, arise from the visitors themselves and their guides. With Arts centres, the acoustics become more complex. Besides noise from outside to inside, these centres often include performance spaces with loud amplified music. Both other areas of the building and, potentially, surrounding buildings need acoustic protection from such spaces. This will be even more necessary if events continue into the night.

2.4.2 State of the Art in Acoustic Design

A noise created in a room of reverberation time 0.5 seconds (eg a room with a suspended ceiling) is nearly 12 dB less than a room with a reverberation time of 7 seconds (e.g. a hard plastered room). As a 10dB increase is about a doubling of loudness, it is clear that these highly reverberant spaces constitute a potential noise problem. This problem may simply be annoyance, but if verbal acoustic information is to be transmitted, e.g. by guides, there is clearly a problem of intelligibility. The following table shows intelligibility as a function of distance from speaker. Noise levels exceed 70dB in museums with guides, such as Delphi, so it is not surprising that the guides begin to shout. This, of course, increases the background noise level. Control of reverberation is often a main issue in museum design.

Background Sound Level dBA	**Background NR**	**Maximum distance for intelligibility (metres):** for normal speech; raising voice by 5 to 6 dB can double distance
48	40	7
53	45	4
58	50	2.2
63	55	1.2
68	60	0.7
73	65	0.4
77	70	0.2
Over 77	Over 70	Too noisy for speech

2.4.3 Acoustic Design-Techniques to Optimise Performance

Control of reverberation is obtained by the use of sound absorbing materials. These may exist as porous type absorbers (mineral wool, open pore foam, sprayed plaster, sintered stone and aluminium mesh), panels and Helmholtz absorbers.

Porous absorbers are the most common type, absorbing primarily at the high and mid frequencies. Some useful low frequency absorption is obtained if used in a suspended ceiling or very thick layers. Their performance is limited if used in thin layers directly applied to a hard surface.

Panels are resonant absorbers and typical wood panels absorb primarily at the low frequencies.

Helmholtz resonators in their pure form (a cavity with a neck) are used in specialist applications, having highly tuned absorption generally at low frequencies. However, a cavity filled with porous absorber, and commercially often appearing as a perforated metal covering to a porous layer, exhibits absorption characteristics like a normal porous absorber, but with some loss at high frequencies and improvement at the low frequencies.

The choice of a particular absorber, nearly always a porous absorber or the Helmholtz resonator form of porous absorber, is very much connected to the aesthetics of the situation. The mineral wool absorber, generally covered with a finely perforated polymer finish that can be washed, or a fabric cover, can be formed into a variety of profiles but is often rejected on aesthetic grounds.

The perception of the finish depends on the distance from the viewer. These absorbers, however, tend to have a good acoustic performance. The perforated metal cover to the absorber can be used to give a 'high-tech' appearance and can usefully be employed in conversions of older buildings, as well as newbuild project. Spray-on porous plaster has been used in several museum refurbishments as it can have a minimal impact on the building appearance. It is difficult to produce a smooth finish, and this depends on the product, but the distance of view is important in the surface perception. The acoustic performance is limited by the thickness of the application (the thicker the better). Cleaning is not so easy and any paint application will reduce the effectiveness of the absorber.

Sound insulation between the outside and a room may not be a problem. However if there are entertainment spaces within a building, particularly if they are used at night, local authorities will normally place restriction orders on the amount of noise that is heard at the nearest inhabitable premises outside the building. It may be required that there should be no increase in the measured LAeq (the equivalent continuous noise level measured on the 'A' scale) after the building is developed compared to before, for night use. This is not quite as onerous as it may seem, as a single car passing outside can have a major impact on the measured LAeq and therefore allow some noise to emanate from the building. In addition, a similar requirement is placed at the low frequency octave bands because of the poor acoustic performance at low frequencies of insulating materials. The 'mass law' in acoustics means that the insulation of a particular structure is reduced by about 5dB for every halving of the frequency. This causes the noticeable bass noise outside many discotheques with the consequent noise complaints.

2.4.4 Acoustic Design Performance Criteria

In large spaces the control of reverberation to 1s or below should be a target. This needs to be considered in tandem with the desired aesthetic design. In small rooms reverberation times should optimally be 0.5s or below.

The management of external noise from buildings such as Arts Centres depends very much on the nearest affected property and times of use. The issue of entertainment noise is subject to much debate and disagreement. Attempts have been made to define the nuisance in terms of the relationship between the noise generated (LAeq) and the background noise level (LA90). In urban areas the major noise problem may be the people leaving the Arts Centre late at night. In some countries local municipalities apply their own regulations to this problem.

2.4.5 Results and Lessons Learnt with Respect to Acoustic Design Performance Criteria

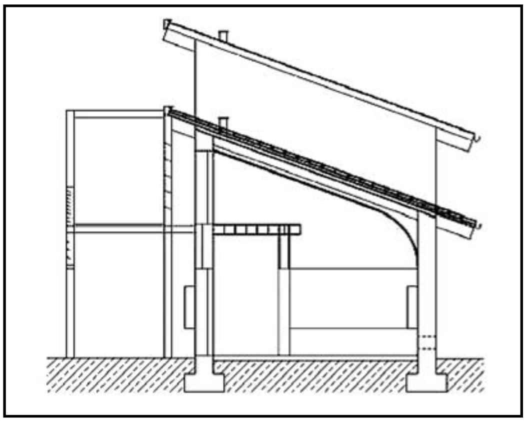
2.4.5.1 Archaeological Museum of Delphi, Greece

This very busy museum has guides and the acoustic problems were severe. The chosen means of reducing the reverberation time has been through the use of acoustic boards made from recycled blown glass granules. The following image shows the use of the material in the Charioteer room.

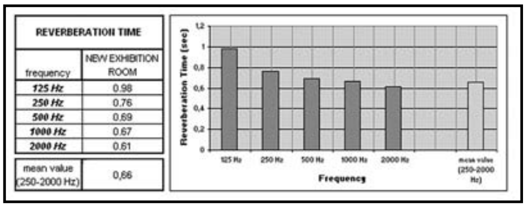
The new Charioteer Room in a previous development at the Archaeological Museum of Delphi

2.4.5.2 Herzog-Anton-Ulrich Museum, Braunschweig, Germany

The museum at Marzabotto is adopting a similar strategy. The following diagrams show the characteristics of porous plaster used on treated surfaces.



Section through Museum at Marzabotto showing treated surfaces



REVERBERATION TIME	
frequency	NEW EXHIBITION ROOM
125 Hz	0.98
250 Hz	0.76
500 Hz	0,69
1000 Hz	0.67
2000 Hz	0.61
mean value (250-2000 Hz)	0,66

Predicted reverberation time at Marzabotto

2.4.5.3 THEpUBLIC Arts Centre, West Bromwich

THEpUBLIC Arts Centre at West Bromwich, in the UK, has had more difficult acoustic problems to solve. Current external noise levels are about 70dBA but these are likely to reduce as the development takes place. The proposed external glazing system of 10-12-6 configuration provides a sound insulation (Rw) of 38dB, giving an average noise rating (NR) of 32. Levels will be higher in the Lobby and Bar areas when the entrance doors are open. A problem occurs where noise from the conditioned spaces enters the large non-conditioned circulation area and, from there, radiates to the outside. This is particularly important in terms of the multi-functional performance space, where electronic amplified music may exceed 110dBA. Control of the low frequency sound is particularly important.

The Institute of Acoustics Good Practice Guide on the Control of Noise from Pubs and Clubs places limits not only on the overall level of sound at the nearest habitable building, whether in terms of LA90 or LAeq, but also on the limits of noise in the low frequency octave bands. The multi-functional space uses a 'box within a box' type structure to address the issue of low frequency sound, in particular. Two dense concrete leaves, 100mm and 200mm, are structurally isolated with a 200–300mm airspace containing a mineral wool blanket and a lobby entrance has been introduced. Low frequency sound may still be a problem even with this level of insulation, so a sound limit may have to be applied to the music. The permitted levels will be determined by the local council but at night will be at, or close to, inaudibility.

With a large number of visitors, including many children, adequate sound absorption is necessary to control the reverberant sound. High performance acoustic absorbers will be applied to the inside of the external walls to help control reverberation in the large non-conditioned space. Most areas have sound absorbing ceilings. Entrances to the conditioned spaces will be highly absorbent.

2.4.5.4 National Archaeological Museum, Lisbon

The National Archaeological Museum in Lisbon presents a problem of high reverberation in a listed building. The measured reverberation time in the main downstairs gallery was nearly 4s at the mid-frequencies (at 500Hz). The proposed solution is to incorporate sound absorbers into the vertical shading panels that are being introduced as part of the light shelf system. In addition, absorbers will be introduced into any perforated metal decking system being used to create walkways within the space. The following table shows the measured reverberation times in the main downstairs gallery.

	Octave band Centre frequency (Hz)					
	125	*250*	*500*	*1000*	*2000*	*4000*
R.T. secs	5.0	4.6	3.9	3.5	2.9	2.2

2.4.5.5 Kristinehamn Museum of Contemporary Art

The Kristinehamn Museum of Contemporary Art has a high reverberation time in the old boiler room, i.e. about 5s at mid frequencies. A substantial amount of sound absorption has been necessary in this high large space with a volume of 3,000m^3.

Measuring reverberation time in the Old Boiler House at Kristinehamn

The following table shows the reverberation time in the old Boiler House at Kristinehamn.

	Octave band Centre frequency (Hz)					
	125	*250*	*500*	*1000*	*2000*	*4000*
R.T. secs	4.4	5.1	5.0	4.5	3.9	2.7

Only the ceiling was available for acoustic absorption materials, so a high performance acoustic tile system has been used as part of a suspended ceiling. Typically, such systems have a mid-frequency absorption in the range 0.5-0.8s, a performance about 2 or 3 times better than spray-on plaster. A British Gypsum tile with a decorative finish, Gyptone, has been chosen. The photograph below shows a typical application of Gyptone tiles.

Example of an installation of Gyptone

2.5 SUSTAINABLE SOLUTIONS AND MATERIALS

2.5.1 Why Sustainable Solutions and Materials are Important

The importance of sustainable solutions has increased rapidly in recent years and has now become one of the most important aspects of building.

Appropriate material and method assessment will lead to:

- Improved environmental qualities
- Less pollution
- Less energy consumption
- Longer life of buildings
- Improved health
- Improved indoor climate
- Better economy

Sustainable assessment is especially important in new and retrofitted museums because these buildings are very exposed to different kinds of emissions which can affect personnel, visitors and artifacts.

Natural stone pavement in Berlin

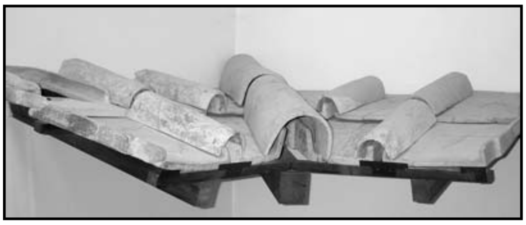
2.5.1.1 Historical heritage

The façade of the Archaeological Museum in Lisbon

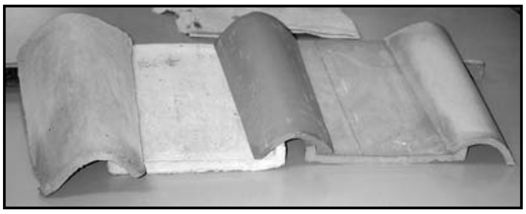
Museum buildings are often historically important buildings of then great value as part of our cultural heritage. In rebuilding and renovation a special effort must be made to preserve the original features. Sometimes materials which are not the best choice from a ‘sustainable building’ point of view may have to be used from this reason. In such situations, it is important to keep their use to a minimum and to take precautions to maintain the architectural and historical integrity of the building. On the other hand, the extensive use of traditional and natural materials in most historical buildings may be compatible with the use of sustainable materials.

2.5.1.2 Local tradition

Museum buildings are often an important embodiments of local traditions. Historic and ethnographic museums are often the only source of information about local culture and the buildings themselves may be good examples.



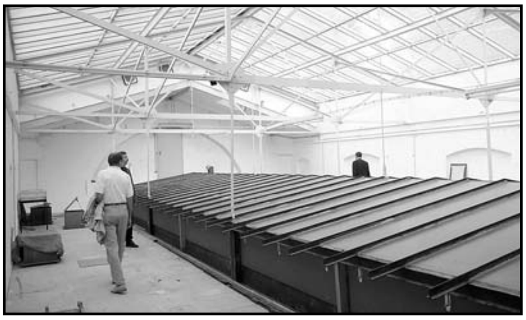
Old roof constructions of the ‘Pompeo Aria’ Museum, Marzabotto. The picture below shows the new tiles manufactured to resemble the old design



2.5.1.3 Indoor climate

Museums contain artifacts of high value. Because of this, the indoor climate - temperature, humidity, light - has to be kept within strict limits. This sometimes requires special materials and construction methods.

Existing natural ventilation systems in Herzog-Anton-Ulrich, Braunschweig. Above: Air inlet integrated in the floor. Below: Skylights for daylighting and extraction of used air



2.5.1.4 Safety

Museums often require high security. Fire regulations sometimes require that special compounds, paints and materials are used. These materials can be hazardous and may have to be treated with special attention and care. Safety precautions against burglary can also lead to extensive use of special materials.

Security measures, such as protection from burglary and fire, are important in museum buildings and may require special materials

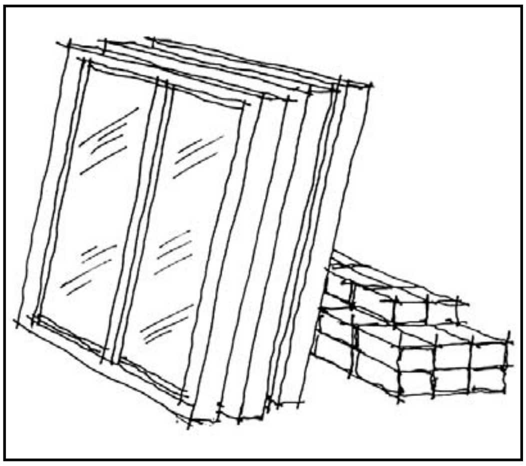
2.5.1.5 Public buildings

Since museums are well frequented buildings, it is extremely important that durable materials are retained and maintained in existing buildings and selected for new buildings. Durable materials are often local, traditional and natural materials.

The Archaeological Museum of Delphi is built of both durable and traditional materials which guarantee long life and low maintenance costs

2.5.2 State of the Art in Sustainable Solutions and Materials

2.5.2.1 Building materials today



Today there is an endless supply of building and construction materials on the market. In general the trend is towards ecological and healthy materials due to the increased knowledge and requirements of clients, but there is also a constant supply of new material products.

2.5.2.2 Potential problems with building materials

Waste of natural resources

The use of building materials should always be assessed for potential environmental risk. The initial strategy should be to reduce consumption and avoid unnecessary use.

Waste from building materials

Building materials should be capable of reuse and be recyclable. The building site should be arranged and the building project planned in such a way that waste can be sorted and collected. Recycled or reused materials should be selected whenever possible.

Building waste is sorted at the building site in the Kristinehamn Museum of Contemporary Art project

Deterioration

Some building materials will deteriorate faster than others. Natural and durable materials will often last longer with less demand for maintenance. The correct selection can prolong the life time of the building.

Dangerous materials

Some building materials may cause hazardous emissions during production, construction and use. Only building materials with no health risks should be selected. Products with unknown compounds should be avoided.

Energy consumption

Building materials consume energy during production, construction and use. Materials and products with low embodied energy should be selected.

Transport

Long delivery journeys mean energy consumption and cost. Locally produced building materials and products will reduce transport energy consumption. The use of such materials will also help to preserve the local building culture and industry.

2.5.3 Sustainable Solutions and Materials Techniques to Optimise Performance

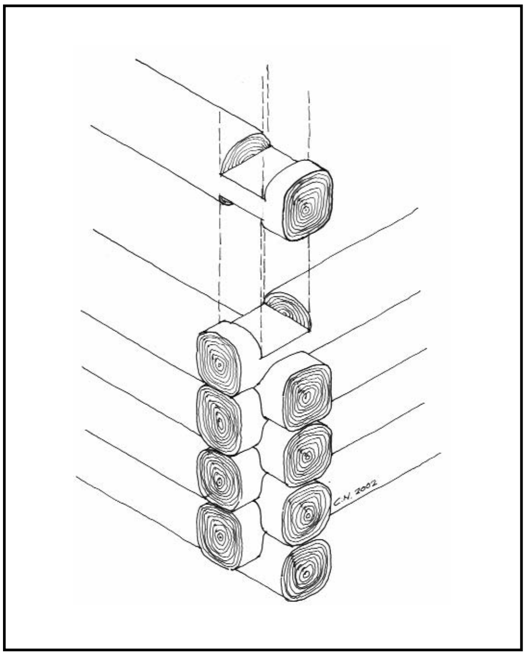
2.5.3.1 Design and selection rules

Due to the numerous construction materials on the market today it is very difficult, not to say impossible, to give detailed advice on the selection criteria for all materials. In addition, the qualities and characteristics of many products change constantly.

There are however, a number of general rules which may be useful:

1. *Design for durability*:

   A durable building will last longer, need less maintenance and spread its environmental impacts over a long period. It will also be more economical to run and consume less energy.



2. *Plan for demolition and reuse:*

   Keep materials separate. Materials which are glued together or fixed to each other are difficult to separate and reuse. Design the building so that materials can be easily separated and reused (car manufacturers do this regularly today). Make the structure adaptable to other uses and choose materials and components that can be readily reused or recycled.

3. *"The most ecological materials are the materials that are never used"*:

   Try to minimise the use of materials and avoid unnecessary use of materials. Avoid the use of materials for cosmetic purposes only.

4. *Investigate the options:*

   Try to find the appropriate building material and product for your purpose. Do not use materials or products because "it is the standard".

5. *Demand information from the manufacturer:*

   Manufacturers should always provide correct and clear descriptions of components and their environmental impact. Do not accept "secret components with obscure description names" a company that will not tell you what its product contains probably has something to hide.

6. *Use low-maintenance building materials with minimal environmental impact*

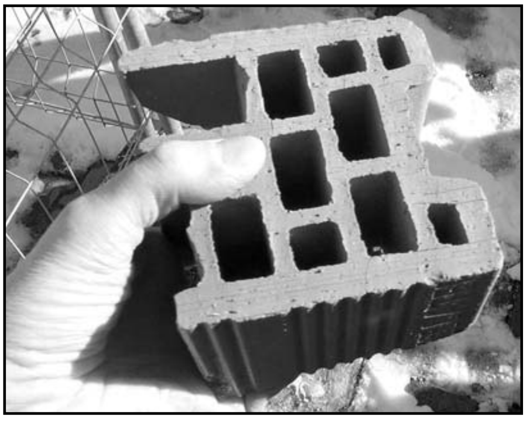
7. *Use building materials with low embodied energy*

8. *Use locally produced building materials:*

   Locally produced materials and products use less energy for transportation, and preserve the local building culture.

Top: An apartment building from the 1960s being recycled.
Middle and bottom: It can be deconstructed - but a closer look shows that the sealants contains large amounts of PCB which makes it difficult and expensive to reuse the components

The renovated ceiling of Bardini Museum is constructed using traditional techniques and materials



Locally produced building blocks from Marzabotto are energy saving, cheap and require minimum transport

9. *Use building products made from recycled materials:*

   Building products made from recycled materials need less energy in manufacturing, reduce solid waste problems, and save natural resources.

10. *Avoid ozone-depleting chemicals in components and materials especially mechanical equipment and insulation:*

    CFCs have been phased out, but their primary replacements–HCFCs–also damage the ozone layer and should be avoided where possible. Avoid foam insulation made with HCFCs. Reclaim CFCs when servicing or disposing of equipment.

Insulation made of recycled wood or paper is healthy and has low embodied energy

11. *Avoid materials which will lead to pollution and hazardous emissions:*

    Solvent-based finishes, adhesives and many other building products can release emissions into the air and ground water.

12. *Avoid potential health hazards such as, radon, mould, pesticides:*

    Follow recommended practices to minimise radon penetration and provide for future mitigation if necessary. Provide design detailing that will avoid moisture problems which could cause mould and mildew growth. Design insect-resistant detail that will require minimal use of pesticides.

13. *Recycling on the building site:*

    Centralise cutting operations to reduce waste and simplify sorting. Set up clearly marked bins for different types of usable waste (wood scraps for kindling, sawdust for compost, etc.). Find out where different materials can be taken for recycling, and educate the work force about recycling procedures. Organise a recycling plant on the building site where waste materials can be separated and sorted.

A well planned building site will make the recycling and sorting of waste easy

2.5.4 Sustainable Solutions and Materials Performance Criteria

2.5.4.1 Selection methods

Different methods for the selection of building materials include:

The *LCA (Life Cycle Analyses)* method is probably the most frequently used way to investigate the environmental effects of building components and materials. In order to use this method, however, you have to make the selection of materials before the assessment. This method is therefore not suitable for comparing selections in the early stages of the building design process.

The *EPM (Environment Preference Method)* method is tailored for use by architects and planners in the design process. The method was developed by the Dutch institute Woen Energie and is described in the "Handbook of Sustainable Building" (Anik, Boonstra, Mak, publishers: James&James, London). The EPM-method compares building materials and products currently on the market. Materials are ranked according to their environmental impact into four groups, according to use (i.e. windows, roofing, sealants etc.).

The method is not perfect. A ranking which is correct for one region, with its particular building traditions, may not be the correct for other regions. Products may vary between regions and countries. These disadvantages are however compensated by the fact that this method is very easy to use and requires no special skill. And, if used with care and common sense, the method can prove to be a valuable tool in the assessment of building materials.

The EPM method also functions as a check list and highlights issues which should be further investigated. This will reduce the risk of major mistakes.

The use of an assessment tool, however, does not replace the importance of rigor in the design process. A tool is just a tool, and the quality of the result finally depends on the user. It is the responsibility of every architect to be informed and updated on building materials in a constantly changing market.

2.5.4.2 Example of selection strategy

In this chapter, the method used for the material assessment in the MUSEUMS project is described.

The purpose of this activity has been to give general advice and to raise issues leading to further discussion. The project design teams are responsible for the selection of materials in the individual museums.

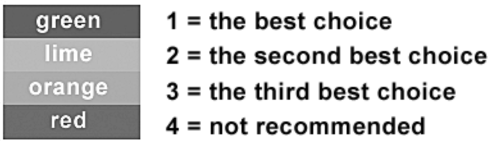
WEB-questionnaire

The EPM method as described in “Handbook of Sustainable Building” was used for the material assessment in the MUSEUMS projects.

A questionnaire (including 72 questions on building material selection) was presented to the project teams. The questions were arranged in building construction related groups:

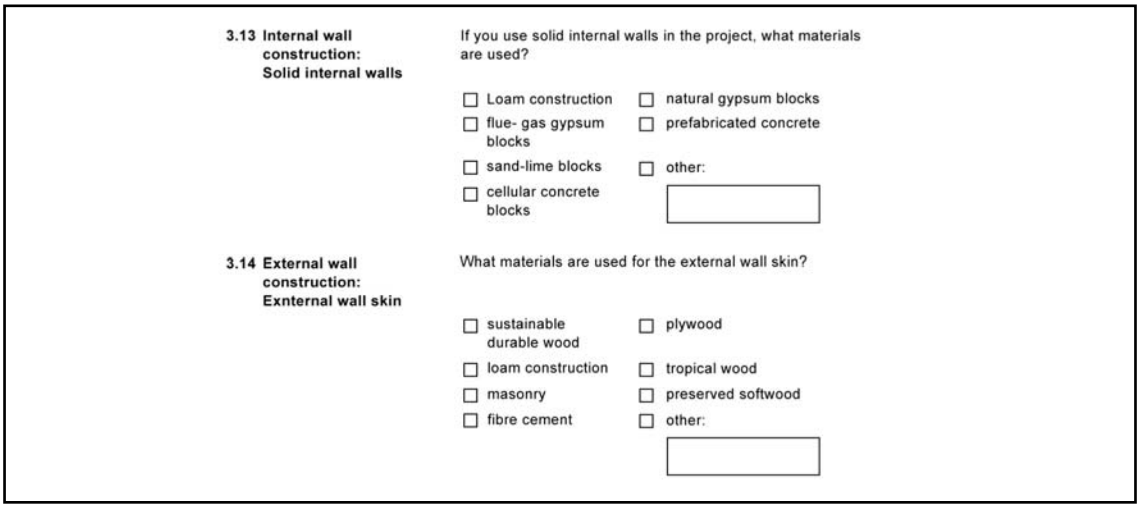
1. Building site
2. Preservative treatments
3. Ground coverings
4. External drainage
5. Landscaping
6. Foundations
7. Floor construction
8. Internal walls
9. External walls
10. Roof construction
11. External windows and doors
12. Internal windows and doors
13. Cladding systems
14. Stairs
15. Roof coverings
16. Glazing
17. Stone
18. Sealants
19. Plaster
20. Tiling
21. Flooring
22. Ceiling
23. Paints
24. Fixtures
25. Wall and floor coverings
26. Gutters and drainpipes
27. Waste
28. Sanitary plumbing
29. Heating installations
30. Electrical installations

For each construction, the projects were given a number of alternative solutions ranked in four groups:



green	**1 = the best choice**
lime	**2 = the second best choice**
orange	**3 = the third best choice**
red	**4 = not recommended**

Each ranking was given a colour in order to give a graphic illustration of the choices made


3.13 Internal wall construction: Solid internal walls

If you use solid internal walls in the project, what materials are used?

☐ Loam construction
☐ flue- gas gypsum blocks
☐ sand-lime blocks
☐ cellular concrete blocks
☐ natural gypsum blocks
☐ prefabricated concrete
☐ other:

3.14 External wall construction: Exnternal wall skin

What materials are used for the external wall skin?

☐ sustainable durable wood
☐ loam construction
☐ masonry
☐ fibre cement
☐ plywood
☐ tropical wood
☐ preserved softwood
☐ other:

Example of the questionnaire (2 questions from a total of 72) which the projects answered

Answers

The project teams were able to access and complete the questionnaire on the internet.

Analyses, evaluation and comments

The material selections have been analysed for each project. The selected materials have been sorted in a matrix by group depending on the ranking. Comments and recommendations were sent back to the project team if material with low ranking (third best choice or not recommended) was chosen.

The results from the questionnaires have been presented and discussed during regular MUSEUMS partners meetings.

Experience

The EPM method proved to be a valuable tool and was well designed for use over the internet. It was possible to evaluate and to illustrate the results by

			green	lime	orange	red	
3.27	External windows: window sills	Aluminium			■		
3.28	Internal window frames	Wood					Depends on what kind of wood
3.29	Internal doors	Wood					Depends on what kind of wood
3.30	Internal door thresholds	Wood					Depends on what kind of wood
3.31	Internal window sills	Softwood	■				
3.32	External wall cladding	Plaster					See 3.44
3.33	Internal stairs	Stone		■			
3.34	External stairs						
3.35	Internal balustrades / railings						
3.36	External balustrades / railings						
3.37	Glazing type	Argon-filled LE-glazing	■				
3.38	Installing glazing	Dry glazing	■				
3.39	Thresholds	?					
3.40	Sealing joints	PUR foam				■	Try to avoid PUR if possible.
3.41	Sealing cracks	PUR tape				■	EPDM or mineral wool are preferable.
3.42	Elastomeric sealants	Silicone sealant	■				
3.43	Plastic sealants						
3.44	Plaster works	Lime mortar		■			
3.45	External wall rendering	Mineral render	■				
3.46	Fitting tiles	Water-based adhesive			■		
3.47	Floor screeds	?					
3.48	Bathroom and toilet floors	Ceramic tiles		■			
3.49	Wall and ceiling framing systems						
3.50	Wall and ceiling panelling systems	Natural gypsum		■			
3.51	Internal joinery	European wood	■				
3.52	External joinery	Painted European wood		■			
3. 53	Internal paintwork (wood)	Untreated wax	■				
3.54	External paintwork (wood)	Water-based acrylic paint			■		
3.55	Wood / stone joints	Iron read lead			■		
3.56	Surface preparation (walls)	None					
3.57	Interior paintwork (walls)	Whitewash	■				
3.58	Exterior paintwork (walls)	Mineral paint	■				
3.59	Ferrous metal paintwork	?					
3.60	Kitchen units / cupboard						
3.61	Work surface	Beech	■				
3.62	Wall coverings	?					
3.63	Floor coverings	Ceramic tiles	■				
		Wood	■				
3.64	Gutters	Copper				■	
3.65	Gutter linings	?					
3.66	Drainpipes	PP	■				
3.67	Internal waste systems	PP		■			
3.68	Water supply	PP	■				

The answers were analysed and comments were sent back to the demonstration projects the use of matrices and colours for different rankings. The method is recommended for use in the early design process.

2.5.5 Results and Lessons Learnt with Respect to Sustainable Solutions and Materials

2.5.5.1 Material assessment process

The experience from the material selection process is very positive. The communication between the experts and the projects partners through the internet based questionnaire worked very well. Information received from the partners was compiled into tables and returned for further assessment.

This procedure led to deeper and dedicated discussions about material selection with good results.

2.5.5.2 Natural materials

Most of the MUSEUM projects are historical buildings which are built of natural materials such as stone and wood. Natural materials have been also used for the renovation in most cases. In some new build projects, such as the Delphi extension, natural materials, such as marble, have been used for façades and floors.

2.5.5.3 Traditional materials

Interesting examples of new use of traditional building materials can be seen in the archaeological museum of Marzabotto where new roof tiles and bricks have been manufactured using local traditional techniques. The Bardini Museum uses traditional roofing techniques modified with cork insulation.

2.5.5.4 Historical aspects

The historical and cultural aspects of material selection were discussed during the project. It was agreed that respect must be paid to the fact that museum buildings are often an important part of the cultural heritage and that historical and aesthetical aspects play an important role. In some cases materials which would not be the best choice from a sustainable point of view must chosen with limited and controlled use for cultural and aesthetical reasons.

2.5.5.5 Recycling and reuse

In some projects existing materials were repaired rather than replaced.

2.5.5.6 Dangerous, unhealthy and ecologically unfriendly materials

Materials which cause hazardous emissions have been avoided through the selection process. Extruded polystyrene insulation (XPS), which is a very common insulation today, has been replaced by EPS (expanded polystyrene) which is less harmful. There is also a very limited use of PVC in the projects.

2.6 HEAT RECOVERY, ENERGY STORAGE AND ACTIVE SOLAR SYSTEMS

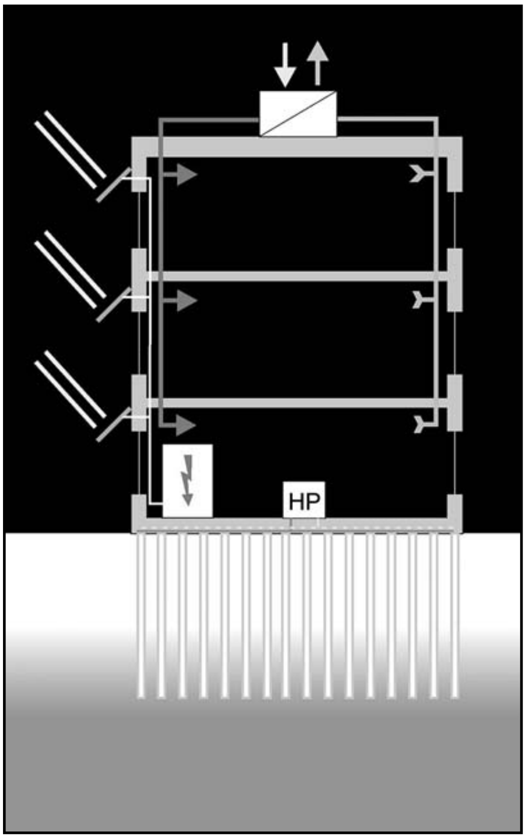
2.6.1 Integration of Heat Recovery, Energy Storage and Active Solar Systems for Improvement of Indoor Air Quality, Energy Efficiency and Optimisation of Operation Costs

The contrasting conservation requirements of exhibiting objects and the comfort requirements of the museum visitors is a general problem in museums. These diverging requirements usually lead to complications in the definition and the improvement of the indoor air quality and thermal comfort. Historical construction methods often make it difficult to integrate building services such as air duct or active solar systems and the preservation or protection of these monuments often restricts the variety of solutions put forward.

Because of this, integrated planning and the input of experts as early as possible is important for the design and retrofitting of energy efficient museum buildings.

Heat recovery, energy storage, and active solar systems are suitable means to help achieve energy efficient buildings and to reducing their operating costs. In detail it means to reduce the annual energy demand for heating and cooling, the electricity consumption and, as a consequence, the CO_2 emission of the buildings. The integration of heat recovery systems or components can lead to a reduction in thermal ventilation losses and a reduction in the energy demand. Energy storage can be inserted to absorb excessive heat gains or recovered energy for a period of time until this surplus energy can be used. The use of internal energy storage in walls, floors and ceilings, etc. can enable an improvement in indoor air quality and thermal comfort with relatively low additional costs. The use of renewable energy such as active solar leads also to a conservation of natural resources. Systems such as solar air and water collectors usually have to be combined with energy storage systems to hold the energy until later when it is needed. Photovoltaic elements also lead to a reduction of primary energy consumption and CO_2 emissions.

The integration of existing structural elements such as walls and floors as energy storage components and the implementation of heat recovery and active solar systems can lead to economically and ecologically optimised solutions for museum buildings. The specification of system components should derive from an integrated design process to achieve optimised solutions. Due to the complex requirements of indoor climate and monument conservation the specific design solutions are usually required.



2.6.2 State of the Art in Heat Recovery, Energy Storage and Active Solar Systems Design

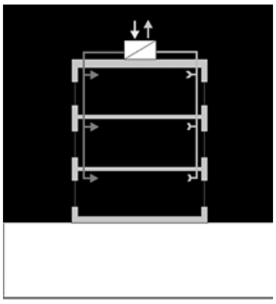
It is essential in energy efficient buildings to reduce thermal losses. The improvement of thermal insulation and the airtightness of the building in combination with controlled air changes will reduce the energy required. This can allow the use of energy optimised low temperature heating and high temperature cooling systems.

Integration of heat recovery is a sensible measure in the case of existing ventilation systems for energy saving and reduced operation costs. “Air-to-Air”, “Air-to-Water” or central or decentralised systems may be used. Central air to air systems are usable in new and existing museums buildings which have integrated air duct systems. The exhaust and supply air should to be located close to one another. Standard heat recovery components include recuperators and regenerators.

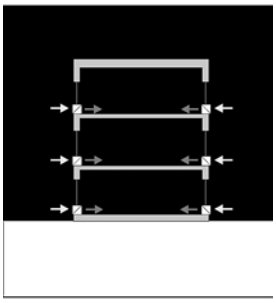
Decentralised air-to-air systems are particularly suitable for retrofitting existing museum buildings where it is possible to add fresh air to circulating air. In this way the air change rate can be minimised to minimum level required for health and air quality. The air conditioning can be realised as a four-wire-system with cooling and heating coils. Generally air-to-water systems are less efficient than air-to-air systems, but central air-to-water systems are favourable where distant adjustment of supply and exhaust air flows is required or in the case of simple exhaust air systems. In the latter case the recovered heat can support low-temperature systems such as floor and wall heating.

The use of construction elements or natural storage capacities in the environment for thermal storage offers another way to increase the energy efficiency of a new or existing building. The use of the thermal mass in ceilings, floors and walls to absorb heat from the room air is often the most simple option. Night-time ventilation may be used to expel excess heat. In the morning, pre-cooled building mass can, in combination with a reduced air change rate stabilise the indoor climate and avoid overheating of the spaces. The system efficiency depends on the thermal capacity of the construction material. Old museum buildings with large a construction mass are especially suitable. The advantages of this solution are in simple system configuration, low capital costs and low energy consumption. In new buildings concrete cores may be used for energy storage with active cooling or heating systems. Water filled tubes, may for example, integrate into the ceiling construction.

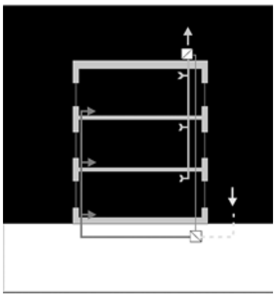
Energy 'piles' and borehole heat exchangers use the surrounding ground for heat exchange and thermal energy storage. Heat exchanger piles are often used as part of the building foundations. Both systems require plastic tubes in which a fluid circulates to exchange heat with the environment. In most cases the heat carrier fluid is water or a water-glycol mixture. One advantage is the parallel use of foundation piles as both a heat duct and foundation system. The extra costs of construction are reduced with the integration of the tubes in the reinforcement mesh and the



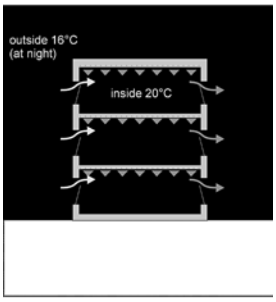
Central air to air system



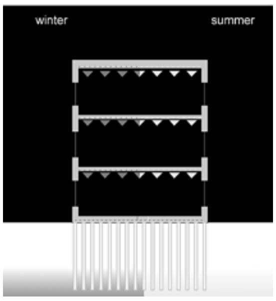
Decentral air to air system



Central air to water system



Activation of thermal masses by ventilation

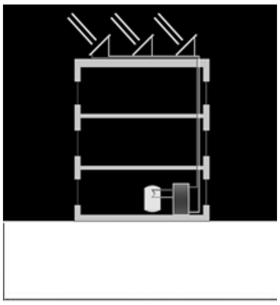


Concrete core activation and heat exchanger piles connection of the different vertical "U-tubes" arranged in the piles.

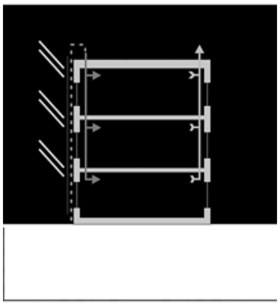
Energy generation with active solar systems is possible with renewable energy. Solar assisted space heating, solar domestic water heating, solar air heating and solar cooling are typical uses of solar thermal energy. The value of a solar-assisted heating system depends on the thermal efficiency of the building. Buildings of low-energy-demand (heat demand up to 70 kWh/m²) are suitable in connection with low temperature heat distribution systems such as floor or wall heating. Due to the reduced heat demand in summer, solar assisted space heating is normally not economic for museums. Where further heating is needed or additional energy consumption units are added to a district heating system the integration of a solar system should be considered. In this case the roof of the museum can be used for the arrangement of the collector array if a suitable roof area is available. Economic solar hot water systems begin with units supplying a daily hot water demand of 500 l. Where there is a low hot water demand and dispersed usage, as in most museum buildings, the integration of solar thermal systems is not recommended. Instead, decentralised electric water heaters should be installed to reduce investment costs and standby and distribution heat losses.

Solar air collectors transfer energy directly to the air flow inside the collector. In an open loop system the pre-heated air can be used as supply air for building ventilation. Another possibility is the integration of the solar air collector in a closed loop. In this case the circulating air is used as a heat carrier for energy transfer to the building structure, as in a hypocaust system. Solar cooling systems use direct coupling of the cooling demand and the available solar energy as both rise simultaneously. Heat delivered by a solar collector generates warm air to dehumidify and to cool a water absorbing medium (evaporative cooling). This cooling energy is transferred to the air of the ventilation system. Unlike solar heating, absolutely no storage is needed.

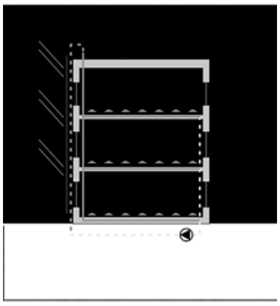
In addition to the use of solar thermal energy, photovoltaic systems transform solar energy into electrical energy. The electrical energy can be used in the building for many purposes or it can be fed into the grid. The fabrication of PV-elements in different forms, colours and sizes offers a wide



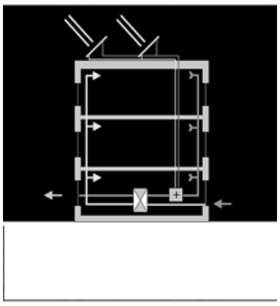
Solar tap water system



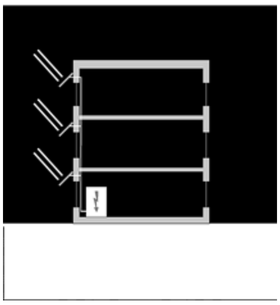
Solar air collector, open loop



Solar air collector, closed loop



Solar cooling system



Photovoltaics integrated with a shading system range of possibilities for their architectural integration. Their double function as shading devices and energy collectors leads to a reduction in the additional investment costs for the integration of PV-elements.

2.6.3 Heat Recovery, Energy Storage and Active Solar Systems-Design Techniques to Optimise Performance

Different conditions must be complied with to improve indoor air quality and thermal comfort. The different climatic requirements of people and exhibits must be identified as in the latter case sealed spaces and/or showcases for the artifacts may have to be used.

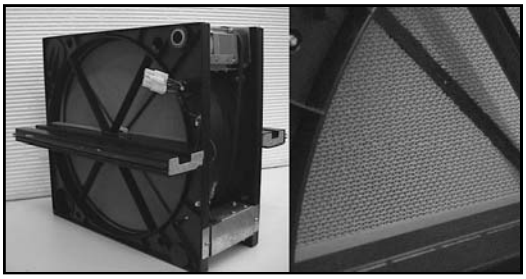
The need to preserve and protect the building façades, in particular those of historical significance will have a great impact on the selection and design of energy efficient elements for museums and may restrict the variety of possible solutions.

Some applications and combinations of components are outlined in the following examples:

The integration of heat recovery and therefore the reduction of ventilation losses can lead to a reduction in the heat demand of buildings and offers the possibility of integrating low temperature heating and high temperature cooling devices. Controlled ventilation and an airtight building envelope are preconditions for the installation of heat recovery systems. Standard air-to-air heat recovery components include recuperators and regenerators. Regenerators can be used for heat exchange as well as humidification and dehumidification of the supply air. The heat exchange between the two air flows in regenerators is realised by alternative passing through the heat exchanger. A moisture exchange between the two air flows is possible driven by the partial pressure gradient between supply and exhaust air. In the recuperator, the two air flows are totally separated so the exchange of moisture is not possible. The outside air must be pre-heated during frosty weather to avoid condensation and freezing in the recuperator (exhaust air).

One advantage of centralised heat recovery systems is in the simple integration of components such as other heat producing appliances, heat pumps. An earth (buried pipe) heat exchanger for pre-heating or pre-cooling may also be provided. In summer, the earth heat exchanger achieves a supply air temperature of 15-20°C lower than air temperature. In winter, use of the earth heat exchanger can avoid condensation and freezing in the recuperator. The disadvantage of the combination with an earth heat exchanger is in the inefficiency due to the small temperature gradient difference between the two air flows.


Recuperator


Regenerator

The use of ceilings with embedded coils can offer a useful heating or cooling facility with additional energy storage. Where concrete core is used the medium temperature is approximately 20°C (corresponding to the required indoor temperature). In a self regulating system which depends on the temperature gradient between water and indoor air, the ceiling may be used effectively for cooling or heating. Available ambient energy may be stored in concrete cores in conjunction with energy piles. In summer the low temperature of the ground may be used for direct cooling. If coupled with a heat pump which generates higher temperatures, the system may also be used for heating in winter. Generally, the heating power of concrete core storage systems will not completely fulfil the total heat demand of a building. Therefore, the system is normally supplemented by a conventional space heating system.

External energy elements such as energy piles, may be used to store heat energy over a defined time period.

Ceiling with a system of plastic tubes for concrete core heat storage

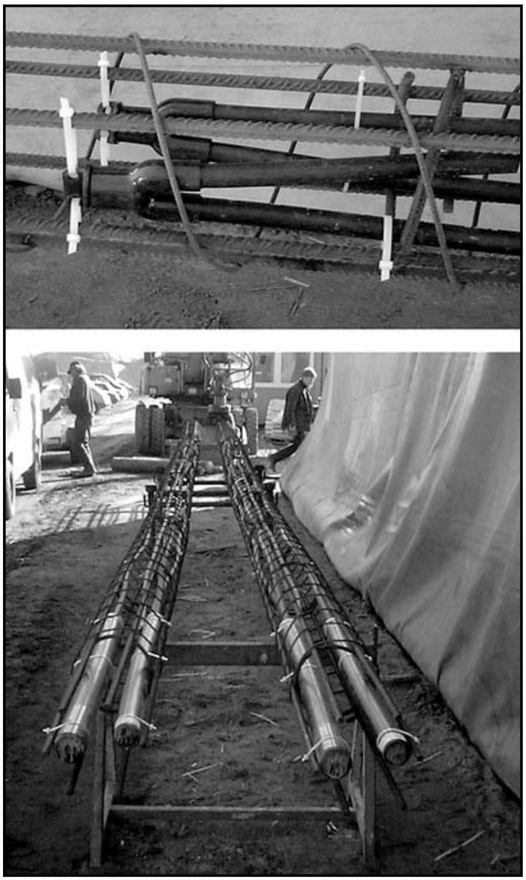
The choice of active solar systems is independent of the age of the building, however the preservation or protection of historic monuments must be considered. Integrated solutions can offer multiple functions, e.g. a photovoltaic façade can generate power and protect the building against weather (rain, wind, solar irradiation).

The first step in designing active solar systems is to check the availability of suitable solar surfaces on the roof and façade, the demand for energy and what proportion can be reliably supplied by solar heating / cooling or photovoltaic power. Collector arrangements with angles of 15-50° and vertical elements with orientations from south-west to south-east are usually suitable.

The use of active solar systems for energy supply in museums is usually restricted to the integration of photovoltaic elements, solar air collectors and solar cooling. In some cases, solar energy may also be used for space and hot water heating.

The integration of solar thermal collectors depends on the space, heating and hot water demand and is not common in museums. However, in some cases, simple absorbers systems are suitable. These systems are generally used for swimming pools, but they are also suitable in low temperature systems where the wall is used for heat storage.

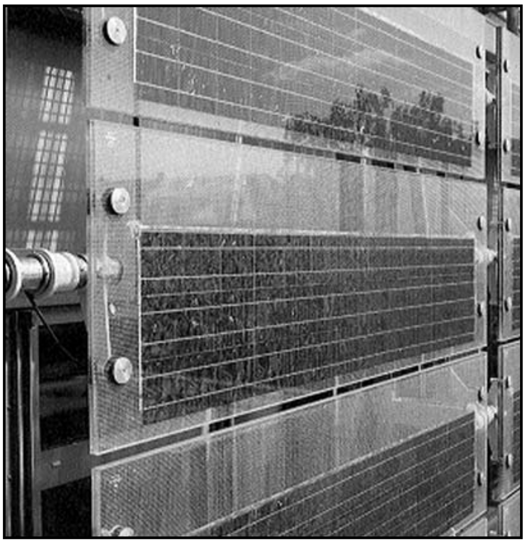
Flat plate and evacuated tube collectors are normally used to supply higher temperature hot water or space heating. Evacuated tube collectors are more energy-efficient than flat plate collectors and can be easily oriented to the required angle, but are generally more expensive. The collector of a solar heating system can be used for cooling in summer as well as for heating in winter.



Reinforcement and U-tubes of energy piles

Another sensible application for the use of active solar components within the energy strategy of a museum is the use of solar air collectors which pre-heat the air before it enters the building. The absorbed heat energy is transferred directly to the air flowing through an open loop system so that pre-heated the air can be supplied for building ventilation. These systems can be an optimal addition to low temperature systems and systems with a high thermal inertia. Heat recovery is not necessary in the case of solar air collectors.

Another possibility is the integration of the solar air collector in a closed loop. Here the circulating air is used as a medium for energy transfer to the building structure, as in a hypocaust system. The structure warms the enclosed spaces by radiant heat. In this case a powerful and rapid response heating systems is needed as a back up. The low density and heat capacity of air (compared to water as heat carrier) demands large duct dimensions, which have to be considered in the overall building design.



Hybrid system – providing shading and photovoltaic power

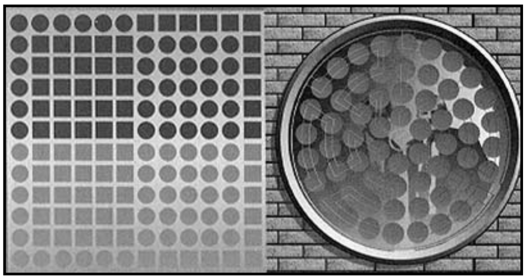
Solar air collectors integrated in to the façade or roof of a building can also act as building insulation.

Hybrid systems such as photovoltaic façades, which generate power and protect buildings against weather conditions; roof elements with integrated photovoltaic cells; and photovoltaic cells integrated in shading systems are now available.

Translucent photovoltaic modules

Photovoltaic elements are now available in different colours and forms and translucent elements are also possible. Therefore the integration of photovoltaics as an element of architectural and lightning design is facilitated.

Because of the integration of building and system engineering and the many dynamic boundary conditions such as temperature and moisture, the design and optimisation of energy systems often needs to be be defined by computer simulation. Tools allow the investigation of system behaviour under different load levels and offer the opportunity to optimise the system configuration. Simulation results can give greater confidence in the design and are an important tool for the development of efficient and well suited concepts for the complex demands on indoor air quality and thermal comfort in museums.



Photovoltaic elements in different colours and forms

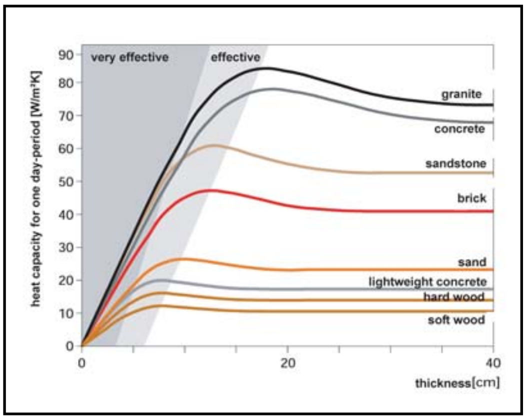
2.6.4 Heat Recovery, Energy Storage and Active Solar Systems Design Performance Criteria

Ventilation losses in energy efficient buildings can amount to over 50% of the total thermal losses of the building. To reduce these losses and to achieve a low level of energy use in the building (net heat demand lower than 60 kWh/m²) the integration of a heat recovery unit is normally required. Central air-to-air heat recovery devices of a variety of sizes and forms (recuperators, regenerators, heat pumps etc.) can be integrated into a ventilation system to process supply and exhaust air. Normally, an energy recovery rate of 70 to 90% can be expected by using recuperators (channel counter flow units). Regenerators used as “enthalpy wheels” can also achieve humidity recovery levels of 50 to 60%. In any case the COP (Coefficient of Performance) of heat pumps should be greater than 3 for efficiency.

The thermal efficiency of construction depends on the capacity and on the thickness of the construction material.

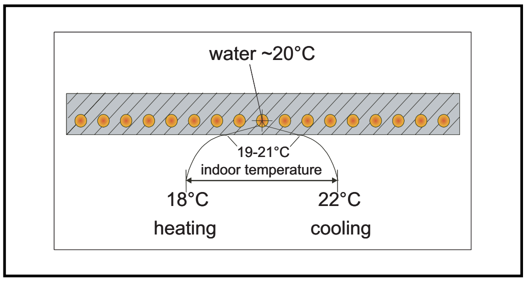
Low thermal capacity and/or thin constructions can be covered with a plaster incorporating a phase change material. The plaster stores energy at a specific temperature (or temperature range) without the temperature rising until the phase change has occurred. This effect is adjustable by the choice of material in a range between 23 and

26°C. The latent heat capacity is around 110 J/kg. Therefore, phase change materials can allow light-weight constructions to behave thermally like heavy-weight constructions.



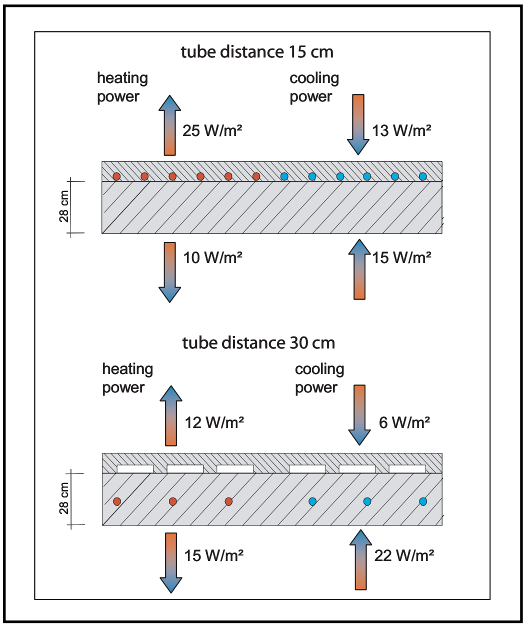
Influence of material type and thickness on the storage efficiency

Depending on the need for cooling or heating, the water temperature range for concrete core thermal storage is about 18 to 28°C. Water temperatures corresponding to the required indoor temperature achieve a self regulating effect. The storage mass cools or heats depending on the temperature gradient between water and indoor air. In order to adjust water and indoor temperatures the temperature spread between outflow and inflow should be 2 to 5 K.



Effects of self regulation for thermal activated constructions

In addition to the temperature gradient and the water flow, the cooling or heating power depends on the position and distance of the tubes in the storage mass. In the case of an activated ceiling, the tubes may be placed at the top, at the bottom or in the core. The separation distance of the tubes is generally 15 to 30cm. In situations with such boundary conditions the cooling or heating power may reach a value of between 5 and 40 W/m².

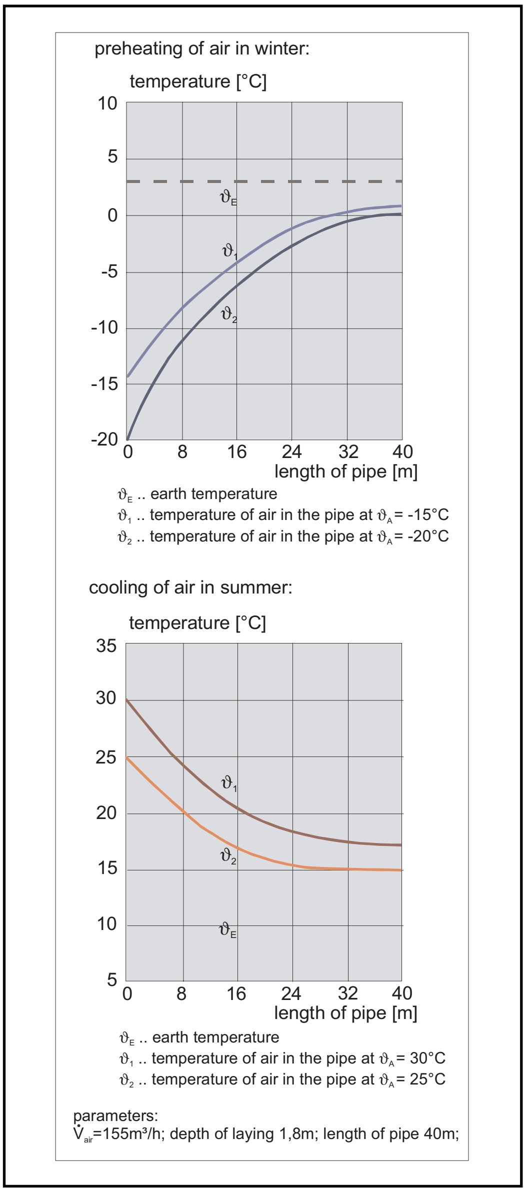


Cooling and heating power depending on the tube position and separation distance (steady-state condition $\Delta_{log}T = 5$ K), IndustrieBAU 2/99

Energy piles and borehole heat exchangers exploit the surrounding earth as a storage medium for heat and cold. For energy piles, the number and depth of the piles usually depends on building structural needs. In the case of separate piles for energy transfer purposes only, important considerations are the distance between the piles (greater than 5 to 6m), their depth (they usually range 30 to 150m) and, of course, the relevant parameters of the ground (thermal conduction, ground water flow, humidity) which must be taken into account within the design. The diameter of the tubes used for the circulation of the fluid is usually about 26 to 46 mm. The size of the tubes depends on the depth, the arrangement of the piles, the corresponding heat transfer rate and the resulting pressure drop. Depending on the ground parameters, a medium heating or cooling power in the range of 50 to 70 W/m can be expected. To be sure of the long-term availability of the ground temperature simulation studies should be carried out.

Earth heat exchangers can be used for pre-heating or -cooling of fresh air before it enters the ventilation unit or the building. The main influences on the optimisation of the heating or cooling power of the earth heat exchanger are earth type (thermal capacity, humidity etc.), its disposition (under or beside the building, depth) and the length of the channels. For optimised efficiency the depth of the earth heat exchanger should be between 1.8 to

2.4m. The channels must be positioned in a frost free zone of the ground. To achieve high heat or cold transfer within an earth heat exchanger and to avoid unwanted high pressure losses, the diameter of the channels should be sized for the flow rate. The corresponding flow velocities should be about 1.5 to 3m/s. With a length of about 35 to 45m a temperature level of 0°C can be reached at the end of the earth heat exchanger at ambient temperatures of about -15°C. In summer the air can be cooled down to a temperature level of below 20°C at ambient temperature of 25 to 30°C.

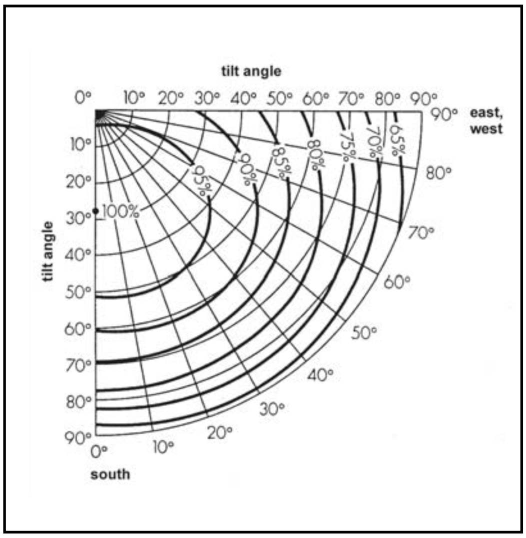


Possible air outlet temperatures in ground heat exchangers

In addition to the angle and the orientation of the collector the annual energy gain depends on the annual global irradiation and on the area of the collector. Shading by adjacent buildings, trees and other collectors must be considered when planning solar collecting arrays.

Hot water solar systems can be economical when the daily hot water demand is above 500 litres. Therefore, in most cases only museums with cafeterias or restaurants are suitable. To achieve an annual solar fraction of about 50%, 1m² collector area per 50 litres of daily hot water demand (water delivered at a temperature of 45°C) should be installed. The store volume should be 60 litres per square metre. The efficiency of the solar air collector system depends on numerous factors such as the annual global irradiation, the type and area of the collector and the air change rate of the building. The efficiency of solar air collectors increases with low temperature gradients between outflow and ambient air, and with an increasing airflow rate. In general solar air collector systems can generate 100 to 350 kWh heat per year for heating and ventilation.

The efficiency of photovoltaic systems depends on the type of solar cells installed (amorphous silicon, polycrystalline silicon or monocrystalline silicon cells). The ratio between generated power and solar radiation lies in a range of 5 to 18%. Therefore, the efficiency of the solar cells depends on their orientation and angle and the annual global irradiation.



Influence of the angle of the solar collector on the solar collection

2.6.5 Results and Lessons Learnt with Respect to Heat Recovery, Energy Storage and Active Solar Systems Design

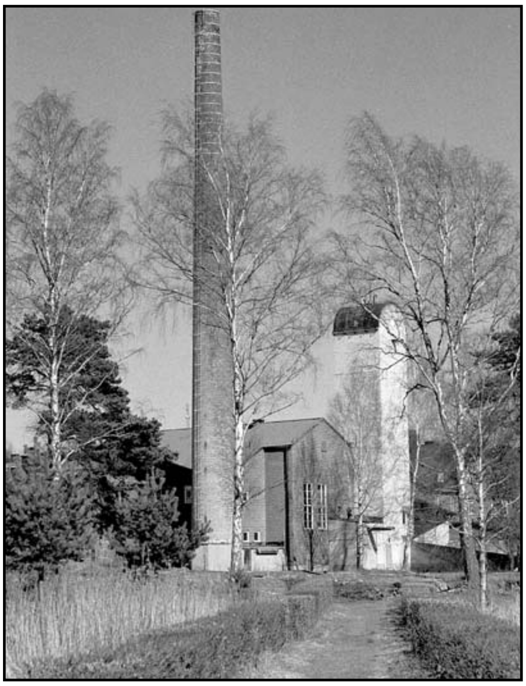
Energy storage, heat recovery and the use of active solar systems should be integrated in the overall energy design strategy of the building to best contribute to reduced energy consumption in museum buildings.

Knowledge of the operational characteristics of the different measures available is important for the development of efficient concepts and successful system integration. The integration of energy storage devices such as energy piles or in construction elements can greatly improve energy consumption and thermal comfort. The use of active solar components for energy-efficiency in museums is confined to solar air or photovoltaic collectors. Heat recovery units can be incorporated as distributed or central systems. Different solutions may be applied and can contribute to the reduction of energy consumption. The special requirements of exhibition rooms and the range of indoor air requirements for exhibits and visitors within the museum has to be understood. Tools for system and building simulation should be used to assess the parameters of thermal comfort and indoor air quality and be used to fine tune the efficient energy design.

Several advanced energy designs using active solar components, heat storage and ventilation systems were realised and monitored within the museum project.

Solar air collectors and a heat recovery system have been installed at the “Kristinehamn Museum of Contemporary Art”, Sweden. The museum is in a former hospital which was renovated during the 1960s and opened as an art gallery in 1977. A nearby, former boiler house was rebuilt and incorporated to provide more exhibition space. Due to insufficient thermal insulation innovative, cost effective solutions for heating were necessary to allow the building to be properly used in winter.

A south facing air collector with an area of 48m², has been mounted on the former charcoal tower for pre-heating of ventilation air in winter. External air flows through the collector. The solar heated air is drawn to the bottom of the tower and through the basement by fan. Solar energy is stored in the thermal mass of the building structure. The tempered air is then used for ventilation of the exhibition halls. The exhaust air is evacuated through the tall charcoal tower (See illustration on following page). When the museum is closed, the exhibition halls are ventilated by recirculating air.



The Kristinehamn Museum of Contemporary Art, Charcoal tower

Secondary rooms such as offices, libraries, cafeteria and shops are ventilated conventionally by a system with a central air-to-air heat recovery unit.

Solar air collector installed to the charcoal tower

The main energy supply for the underfloor heating in the exhibition halls and in the secondary rooms, and for boost heating the ventilation air are provided by district heating.

“THEpUBLIC Arts Centre” at West Bromwich in the U.K. shows that the design of building’s energy system should be part of the overall building design. From the outset in this example a heat recovery system is well integrated in the building design.

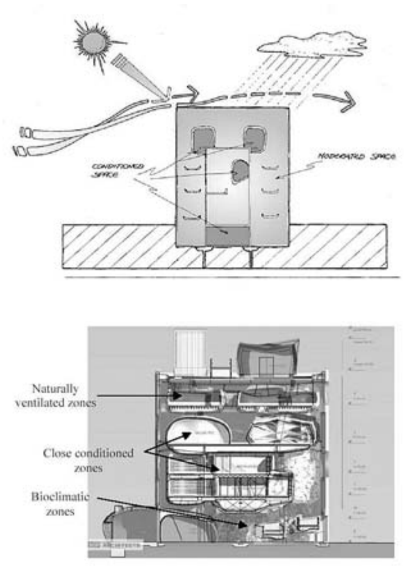
At present, the THEpUBLIC Arts Centre is under construction. It will be a modern, flagship building containing a gallery, studio spaces, shops, restaurant facilities, public areas, conference rooms and other multi-functional spaces.

A number of distinct comfort requirements exist due to the diverse nature of the spaces. These can be broadly distinguished into three groups:

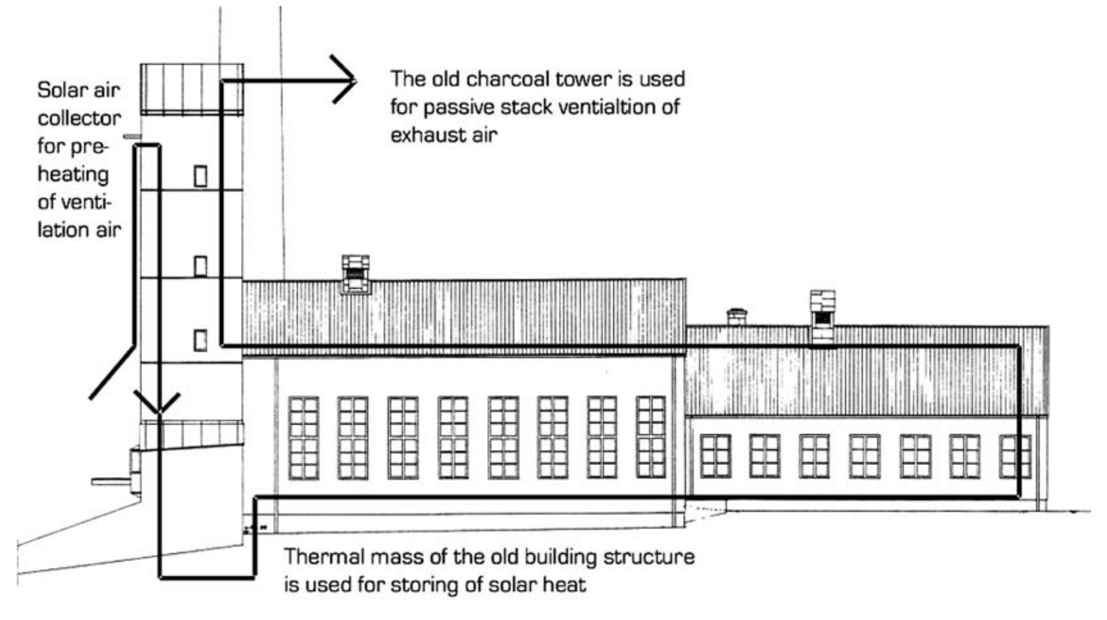
- Areas requiring close control (exhibition type spaces).
- Areas with less stringent environmental requirements, where natural ventilation and heating are proposed (offices and circulating spaces).
- The bioclimatic areas such as general public areas and some exhibition spaces, where minimal heating is proposed.

The bioclimatic areas are located within the “bioclimatic enclosure” which takes the form of an intelligent building skin. The close control areas lie entirely within the bioclimatic enclosure and therefore do not experience the outside climate but rather the modified conditions created by the bioclimatic enclosure. A heat recovery mechanism is specifically based upon the “box within a box“ strategy. Appropriate exhaust air from the closed conditioned spaces is released into the bioclimatic zone.

Borehole heat exchangers will be installed at THEpUBLIC Arts Centre for pre-heating and pre-cooling the closely controlled spaces, and some of the naturally ventilated spaces.



“Box within a box” strategy of the different climate zones



Principle scheme of the solar air heating at the Kristinehamn Museum of Contemporary Art

2.7 HVAC SYSTEM DESIGN

2.7.1 HVAC in Museum Buildings

Museums must control their indoor environments with two separate objectives:

- To satisfy the need for optimal conservation of the exhibits;
- To satisfy the needs of staff and visitors in terms of comfort and health.

Although natural conditions are suitable for many spaces and many museums, at least during part of the year in some locations, a state-of-the-art museum with exhibits requiring carefully controlled environments must usually use some type of HVAC system. Environmental control can thus represent a significant share of the energy consumption in a museum building and, therefore, HVAC design should always merit careful consideration. It is necessary to select a system that meets all the objectives and, at the same time, is energy efficient, optimises energy consumption and minimises environmental impact, with a sustainability perspective.

Reaching this objective is not an easy task. There is a wide range of HVAC systems, options and components, and the best solution for each specific case is anything but obvious in almost every single building. Unless there is some systematic procedure for searching for the best solution, the quality of the final design is never a certainty. This is a complex task in any building, but it becomes especially challenging in buildings with a large variety of different requirements for different types of spaces, such as in Museums, where it is common to have rooms for different types of exhibits, cafeterias and shops, auditoria, laboratories and working rooms, storage areas, offices, etc. Each type of space may require a different solution, and they must all be integrated into a harmonious final global system.

The complexity of the task is increased when the Museum building has an historic value and thus poses restrictions in terms of the possible solutions that can be implemented. Retrofitting cases pose special challenges, as the building was originally planned for a different use and must be converted to its new function while at the same time respecting its architectural values. Unconventional solutions and ingenuity are often required to overcome the difficulties.

This chapter describes the steps of a methodology to design optimised HVAC systems for museum buildings. It is however general enough so that, with small adaptations, it can be followed for the design of HVAC systems for most other types of buildings. The various steps of the methodology are illustrated with examples drawn from the HVAC designs developed within the eight buildings that are part of the MUSEUMS project (for more details, see Chapter 3).

2.7.2 An Optimised Methodology for HVAC Design

2.7.2.1 Step 1 - Define clear objectives for the indoor environment

It is essential to define carefully the desired indoor requirements for the environment in the Museum. This depends on two sets of concerns:

- occupant requirements for comfort and in-door air quality, defined by well known national and international standards and regulations (e.g. ASHRAE's standards 55 and 62, or ISO 7730).
- Conservation of exhibits, discussed elsewhere in this Handbook.

These requirements should be expressed in terms of desired variables (temperature, humidity, CO_2 or other gaseous contaminant concentration such as NO_x or SO_x, particle concentration, etc), set-points permitted, fluctuations allowed, and even acceptable rates of fluctuation, if applicable or necessary. Required ventilation rates must also be clearly identified.

Some specific issues that should be addressed can have a significant impact on the requirements for the indoor environment:

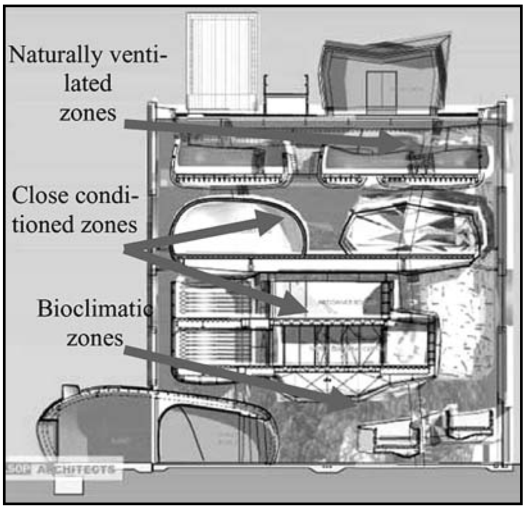
- The use of special conditioned spaces or display cases if any particular object(s) would mean requirements resulting in unnecessary energy consumption for a larger space.
- The placement of objects with identical requirements in the same rooms or exhibit cases.

If the objectives for the indoor environment are very demanding and restrictive, there will be a need for more complex mechanical systems and sophisticated controls, and little room for natural solutions. So, requirements should be realistic, pragmatic and carefully defined. Their definition will have a major impact on the building and on the HVAC systems to be selected for it.

The museums described in Chapter 3 of this Handbook offer some excellent examples of how these principles have influenced the choice of HVAC systems and reduced their corresponding investment costs. A few examples are listed next:

- Almost every museum has a complete HVAC system, including at least heating, cooling and ventilation, even in the coldest northernmost climates, because their typical exhibits require closely controlled environments.

  The two notable exceptions are Marzabotto (Italy) and Lisbon (Portugal), both focussing on archaeological exhibits (mostly stone, metal and other durable materials) that can withstand more flexible environments, unlike paintings or other sensitive materials exhibited elsewhere. Both museums do not have air-conditioning in the main exhibit rooms, with heating mostly required for visitor comfort rather than for strict exhibit conservation.
- The new THEpUBLIC Arts Centre museum in the UK adopted a layered structure of the spaces, concentrating together those that need air-conditioning and those that can accept natural ventilation, thus reducing investments in full air-conditioning of every space:



The target temperatures in each type of zone show clearly the hierarchy of tolerance ranges that allowed this type of solution:

Space Type	**Temperature Setpoint [ºC]**		
	Winter	**Spring Autumn**	**Summer**
Bioclimatic Zones	15-20	15-22	20-26
Naturally ventilated occupied zones	18-20	18-22	20-26
Conditioned Zones	20±2		

Temperature setpoints in the various zones of THEpUBLIC Arts Centre Museum

2.7.2.2 Step 2 - Define a sustainable strategy for meeting the environmental objectives

As discussed in Step 1, very strict requirements for the indoor environments almost always mean an active HVAC system. But it is often possible to consider a certain degree of environmental flexibility, in which case natural solutions for conditioning might and should be considered. Natural, passive means to provide the needed internal conditions should be explored to their fullest extent, both at the building level and at the systems level. At the limit, the need for an HVAC system should be assessed. A possible compromise is to have an HVAC system for when it is unavoidable, and run the building with HVAC off, under free-floating conditions, as often as possible.

When a design team is assembled, the normal tendency is simply to consider a conventional building with HVAC and to proceed without second thoughts. This is exactly the type of practice that must be avoided. Designers must think differently and try the unconventional to achieve better and better energy-efficiency.

The integration of renewables, including passive systems, daylighting and natural ventilation to reduce building energy needs, as well as solar thermal or PV collectors, wind, geothermal sources, etc., to provide for the remaining building needs, should receive careful consideration. Energy Certification of buildings, as mandated by the Directive 2002/91/EC of the European Parliment and of the Council of 16 December 2001 on the Energy Performance of Buildings, will certainly play a major role and provide an incentive for the search for greater energy efficiency.

The eight projects described in this Handbook provide excellent examples of the search for optimum energy efficiency through exemplary design strategies. They all involved carefully drafted strategies to maximise the contribution of Renewables:

- The new THEpUBLIC Arts Centre organised the spaces into three types, one fully naturally ventilated and another with a strong bio-climatic input. Only in the third type of space is conventional HVAC is required.
- The museums in Delphi (Greece), Kristinehamn (Sweden), Marzabotto and Bardini (Italy) and Lisbon (the old building) all use natural or hybrid ventilation in at least part of the buildings, including the possibility of simply opening the windows in some cases.
- Night ventilation strategies have been implemented in Delphi and Marzabotto.
- Ceiling fans are used to extend the summer periods that do not require air-conditioning in Delphi.
- Ventilated roofs increase air movement in the museum in Marzabotto.
- Almost every museum maximised the contribution of daylighting to reduce electricity consumption, to reduce cooling loads and, in a few cases (Marzabotto and the Herzog-Anton-Ulrich, in Braunschweig, Germany) completely avoid air-conditioning altogether.
- Additional insulation has been specified for almost every building, at least in roofs. For architectural reasons, it was impossible to do so in the walls of old buildings with protected façades.

2.7.2.3 Step 3 - Select the most appropriate type of HVAC system for the building

There are so many types of HVAC systems that it is impossible to even try to list the best options alone for each possible case in a short document such as this. The list of topics to follow, should be taken into consideration in selecting a system that meets the desired criteria.

List of important issues in HVAC system selection*

- type of building (e.g., thermal inertia)
- architectural integration and aesthetics
- desired level of air movement
- local restrictions
  (e.g., no water pipes indoors…)
- noise levels

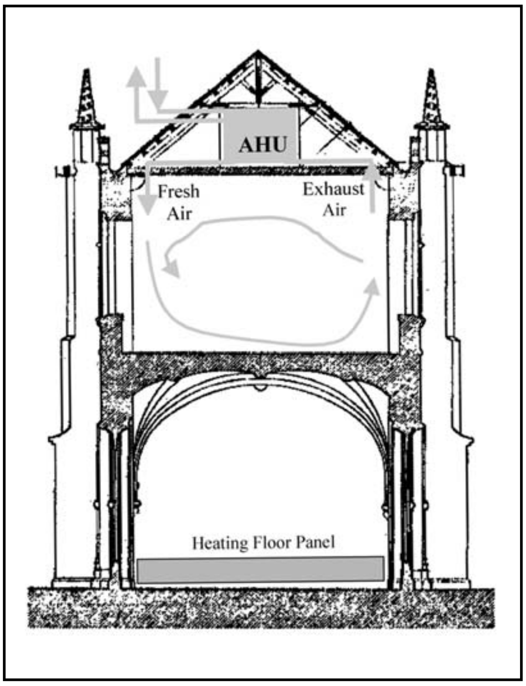
** Examples only, not meant to be complete.*

For example, buildings with high thermal inertia that are to be environmentally controlled on a non-permanent basis should have a system with fast reaction time (air heating or cooling). Conversely, if the same building is controlled 24 hours a day, then slow-responding systems are also a possibility (e.g. floor heating systems).

Embedded systems, e.g., pipes in the floor, ceiling or walls, may be the best solution when aesthetical considerations recommend the absence of visible terminal units. Examples of all these techniques can be found in several museums described in this handbook:

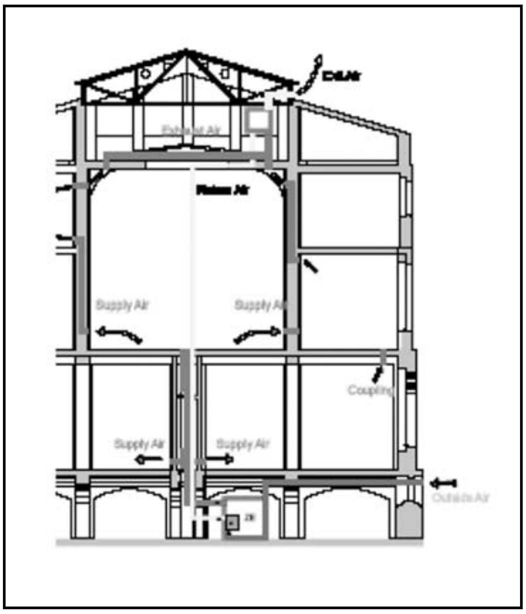
- A special wall-heating system has been devised for the Slovenian museum, once again to take advantage of the high inertia of the envelope and to reduce aesthetical impact inside the spaces;

- Floor heating was adopted at Lisbon, in the high-inertia downstairs galleries, where forced air movement and the presence of air-heating terminal units were both undesirable, while forced air-systems were adopted for the upstairs galleries where inertia is lower and no restrictions existed;



Herzog-Anton-Ulrich Museum, Braunschweig

- In Braunschweig, an original shaft system for air distribution, that had been disabled in various previous interventions during the last century in a prime example how original designs can be unknowingly destroyed, was restored to full use. This represents one of the best examples how to take advantage of specific physical limitations in an old building:

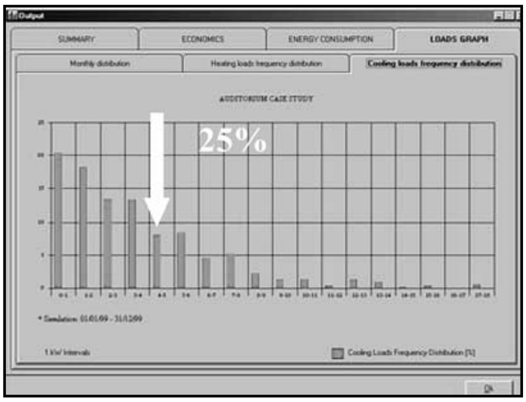


Herzog-Anton-Ulrich Museum, Braunschweig

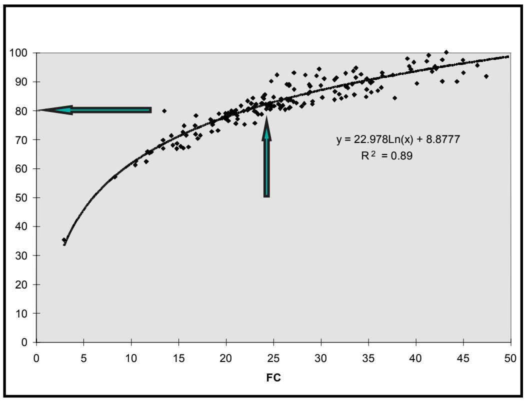
2.7.2.4 Step 4 - Size the systems using dynamic simulation

Every building is a complex thermal system. No steady-state simulation tool can adequately describe its behaviour. Sizing an HVAC system that is able to meet all the loads properly and does not waste resources requires detailed knowledge of the building behaviour and of mutual interactions.

In complex buildings, such as museums, knowledge about indoor temperatures, building heating and cooling loads, energy needs and indoor air quality levels should always be obtained by performing a dynamic simulation of the building. There are many suitable software packages, e.g., ESP-r, DOE, ENERGY+, HVASCSIM, TRNSYS, IDA (which is a program similar to TRNSYS used by consultants and researchers in Sweden, Finland and Switzerland and was used for the Kristinehamn Museum of Contemporary Art) etc., available to perform such task. Traditional manual methods based on quasi-steady state conditions or rules of thumb, often used by designers as an everyday routine procedure, inevitably will lead to significant oversizing, with corresponding over-investment in terms of initial cost and space requirements. Over-sizing will also result in lower overall energy efficiency of the HVAC system, as it will run at part-load for longer than would a correctly sized system.

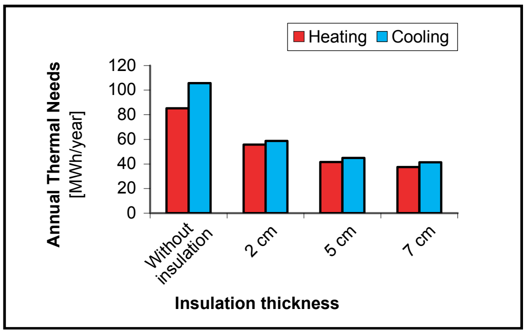


A single stage unit sized to meet 100% of the load of a building, as simulated above, will run most of the time at under 25% of the nominal load. Under these conditions, the operating efficiency of a typical chiller unit decreases by about 20%.



It is thus essential to know the load distribution of the building and its HVAC system, to allow a correct distribution of the power steps to be installed and thus optimise the operating efficiency.

A detailed simulation also has the added advantage of quantifying annual energy needs, an essential piece of information for carrying out the life cycle cost studies that are required for systems selection and optimisation, as described later. The dynamic software model can also be used to perform sensitivity studies to improve the design options, to model different life styles and building use patterns, if necessary.



Annual thermal needs for different roof insulation thickness - the case of the Lisbon Museum

The inputs to the design tool must be looked at critically. Energy designers cannot passively accept any envelope design if this means excessive solar gains, with probable overheating or large cooling needs, lack of insulation, with excessive heating requirements, leaky envelopes, etc., as well as excessive lighting loads derived from a non-optimised electric lighting system. The HVAC designers should interact with the rest of the design team in the search of the best possible compromise, using the dynamic simulation results as proof of the need for improved solutions, when applicable.

One of the obstacles that designers must face for dynamic simulation is the availability of a suitable hourly data file for the museum location. Credible data, e.g., TMY or TRY data, are not always easily available. Ideally, real weather data for a typical year is the best option. If this is not available, then a synthetic year can be used, as long as it provides all the information required by the software. The quality of the weather data used may have an important impact in the results and, thus, in the conclusions obtained from the studies. For HVAC studies, the requirements are essentially good temperature and solar radiation data but outdoor humidity levels are also fundamental especially when HVAC has control over humidity. For modelling natural ventilation and/or infiltration, reliable wind data (speed and direction) is also desirable, but this is probably the most difficult information to obtain for most sites.

2.7.2.5 Step 5 - identify possible energy sources for heating and cooling

Often, local limitations restrict alternatives to conventional sources of energy, i.e., electricity, natural gas, fuel oil, etc. But unconventional low-energy solutions should always be analysed for possible use, given their obvious advantages in terms of the environmental impact. For guidance, the tool “Selection Guidance for Low Energy Cooling Techniques”, IEA ECBCS Annex 28, can be used. It contains indications of whether to use one technique or another, including conventional air-conditioning, according to the local conditions. The economics of the options should be carefully evaluated on a life-cycle cost basis, as discussed later. Environmental costs should be factored in the calculation. In particular, the following alternatives should be studied:

- renewable energy (solar thermal, PV, geo-thermal, etc.)
- low energy alternatives (aquifier, river, sea, lake, ground, evaporative cooling, etc.)

This design procedure is also now required for large non-residential buildings by the European Directive, on the Energy Performance of Buildings. According to this Directive, district heating and cooling solutions, as well as the use of heat pumps, should be studied and promoted.

The eight projects described in this Handbook are a mix of cases in terms of applicability of these low-energy techniques:

- In many existing museums, often located in old city centres, it was impossible to adopt any such techniques due to the many restrictions that apply. Conventional solutions are therefore used at most sites, as might be expected;
- THEpUBLIC Arts Centre, in the U.K., a new building, uses a borehole water system for cooling and water supply;
- The Lisbon museum studied the possibility of using the local aquifier for heating and cooling, but the costs proved to be too high;
- The Swedish museum, at Kristinehamn, uses solar thermal energy for preheating the incoming outdoor air and district heating mainly based on biomass for space heating.

A variety of energy sources was adopted in the museums, according to local conditions, traditions and availability.

District heating was selected at two sites (Ljubljana and Braunschweig), a particularly efficient alternative where as it is available. Heat pumps were adopted at the Bardini museum, in Florence.

2.7.2.6 Step 6 - identify possible efficient components and working strategies

Engineers should make the HVAC systems that they design as energy efficient as possible. For Museums of medium to large size, a BEMS (Building Energy Management System) will almost certainly be mandatory, serving not only the HVAC but also lighting, security, etc. This option may also make other advanced components economically feasible, e.g., variable ventilation by CO_2 control or equivalent (occupancy in Museums tends to be quite variable etc.), heat recovery, free-cooling and energy storage. Their economic feasibility can be evaluated with the detailed simulation tool used for design.

As these issues are discussed in other chapters in this Handbook in more detail, they shall not be further discussed here, but this reference must be made in its proper context in the design process for HVAC.

2.7.2.7 Step 7 - apply life-cycle cost analysis to select the most appropriate system

The correct strategy for design of the HVAC system must be based on a life-cycle cost analysis. This is the only acceptable way to optimise the system. The solution with the lowest initial cost is seldom the most appropriate.

To apply the life-cycle methodology, first, select the cheapest solution that satisfies all the requirements identified (thermal loads, environmental conditions, specific requirements, etc.). Systems that do not satisfy any of these requirements should not be considered as a possible solution.

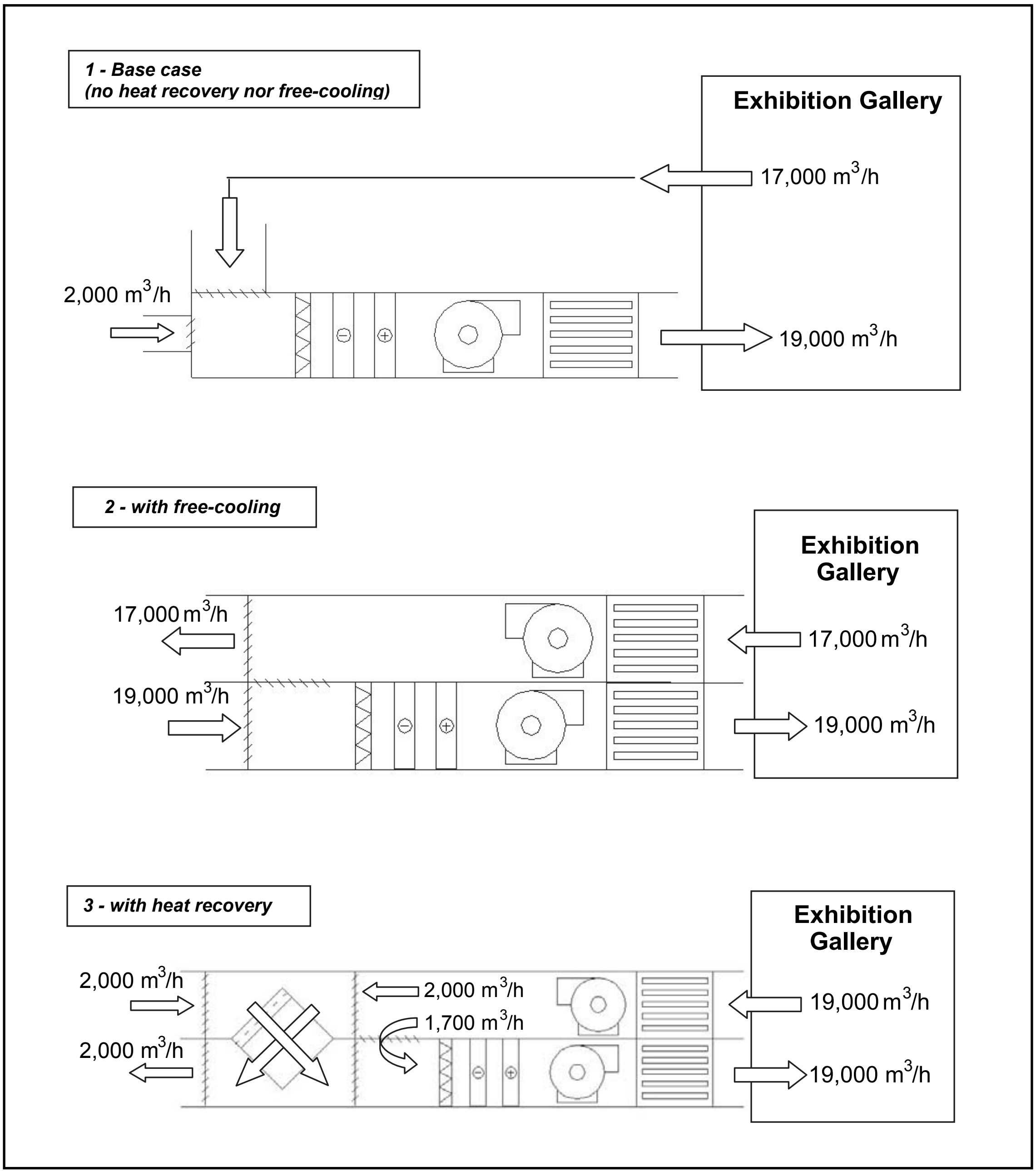
Then assess possible improvements one by one in terms of life-cycle cost. Consider additional investment cost relative to the cheapest system, and the energy and environmental savings that they provide. All costs should be considered, including the cost of removing the system at the end of its useful life (demolition). Criteria for economic acceptability (return on investment, payback, etc.) should be established beforehand. Every alternative meeting these economic requirements should be integrated into the final design. Of course, the budget limitations of the building owner must always be taken into account, but there should be an effort to systematically include all the economically attractive alternatives.

The study of the various alternatives should be based on the detailed simulations. They can highlight the energy savings associated with each option. The corresponding costs must be realistic and be established with as much detail as possible. An example on the next page illustrates this procedure. In the case of combined improvements, the interactions between them cannot be neglected select the best single improvement in the package (the one with the best economic performance) and then look for the best marginal return on investment for the second improvement, and so on.

2.7.2.8 Step 8 - detailed design

The HVAC system should be carefully specified in terms of performance requirements. Energy-efficient components should be specified in every case. Every important performance detail must be specified (flow rate, efficiency, noise level, etc.) for each major item:

- energy equipment (boilers, chillers, etc.)
- fans and pumps
- pipe networks with low pressure drops
- duct work (air-tightness, low pressure drops, etc.)
- terminal devices (fan-coils, air diffusers, chilled beams, etc.)



Comparison of Air Handling Units with and without heat recovery or free-cooling

Investment [Euros]	Base-Case	Heat Recovery	Free Cooling
AHUs	25,500	36,814	32,260
Air ducts	2,255	3,966	12,039
Others (sensors, actuators)	0	180	180
Total Investment	27,755	40,960	44,479
Extra Investment		13,205	16,724

Investment difference between the three alternatives analysed

HEAT RECOVERY		
	Heating	**Cooling**
	[kWh/year]	[kWh/year]
Base-Case Solution	**41,553**	**44,905**
Solution with Heat Recovery	**28,485**	**44,905**
Thermal Annual Energy Savings	13,068	-
	31.4%	-
Thermal Annual Energy Savings [Euros/year]	484	-
Fan energy increase [kWh/year]	2,387	-
Fan energy increase [Euros/year]	144	-
Total Energy Savings [Euros/year]	**340**	-
Investment [Euros]	**13,205**	-
Simple Payback Period [years]	**39**	-

Heat recovery analysis

FREE COOLING		
	Heating	**Cooling**
	[kWh/year]	[kWh/year]
Base-Case Solution	**41,553**	**44,905**
Solution with Heat Recovery	**41,553**	**35,957**
Thermal Annual Energy Savings	-	8,948
	-	19.9%
Thermal Annual Energy Savings [Euros/year]	-	317
Fan energy increase [kWh/year]	-	2,385
Fan energy increase [Euros/year]	-	143
Total Energy Savings [Euros/year]	-	**174**
Investment [Euros]	-	**16,724**
Simple Payback Period [years]	-	**96**

Free cooling analysis.

These examples correspond to a real case-study for the Museum in Lisbon. They clearly show that the extra costs required were not acceptable. A mild climate and short operating hours made the systems too expensive for the relatively small energy savings that they produced. For example, other scenarios with longer hours of operation (S1 to S4), and thus higher energy savings, improve the situation for heat recovery. The hypotheses made can have a strong influence upon the conclusions.

HEAT RECOVERY ANALYSIS [HEATING]						
		S0	**S1**	**S2**	**S3**	**S4**
Base Case	KWh/year	41,553	57,889	84,388	108,347	359,176
With Heat Recovery		28,485	32,678	40,094	52,919	130,978
Thermal Energy Savings		13,068	25,211	44,294	55,428	228,198
Fan energy increase		2,387	2,825	4,082	7,703	23,161
Total Energy Savings	€	265	764	1,396	1,672	7,315
Simple Payback	years	**50**	□ **14**	**10**	**8**	**2**

Often, many such details are not specified with precision and the system ends up being selected on a lowest-cost basis by the contractor, resulting in undesirable lower performance.

The designer must also define all the control algorithms for the whole installation. For example, simply defining that a system should have free-cooling or CO_2 controlled variable ventilation and leaving it up to the contractor to implement the strategy can lead to totally different results relative to those that the designer may have envisaged. The specifications should be detailed in terms of performance sought and control points.

There is a strong interaction with the overall specification of BEMS systems, described elsewhere in this Handbook.

Finally, provisions for maintenance must be foreseen in the detailed design. Placement of sensors (or locations for connection of sensors) to monitor performance of the components, setting aside access for maintenance (e.g., for duct cleaning, fans, pumps), etc., must be specified in the detailed design phase before construction takes place.

2.7.2.9 Step 9 - specify careful commissioning and maintenance procedures

In the brief for the contractor, which is often sent out to tender, there should be a detailed description of all the tests that must be carried out to verify the performance of each component and of the system as a whole. All the specs in Step 8 should be verified in-loco before the installation is accepted. Often, this step is bypassed, totally or in part, for various reasons: cost, time needed to carry out the tests; need to get the installation operational in a hurry, etc. However, this means that problems may arise later when it is too late or too costly to correct. The quality of the final system must be ensured at all cost.

Commissioning is still an evolving science and there is still room for progress. Further reading can be obtained in the results of Annex 40 of the ECBCS of the IEA. The responsibility of the designers is not complete when the system is built and commissioned according to the specifications. The system must be able to operate efficiently and satisfy design criteria for many years after that. Thus, maintenance is a requirement which is as important as good sizing and component selection.

Actual maintenance plans for major equipment can only be drawn up following the selection of the specific machines and components used in the system. This means that it is a task for the contractor to set the actual procedures in a second phase of the project. But the essential elements for maintenance must be foreseen during the design itself, as already stated in Step 8.

Finally, it is necessary that the building owner actually implements a regular maintenance plan, as designed. Sometimes, this is bypassed for budget reasons, with serious consequences for the systems performance and energy efficiency in the long run.

Maintenance must become more seriously considered by building owners and authorities. It should be regarded as an investment, as a way to reduce costs, both operational costs (greater efficiency) and hardware costs. Failure to apply proper maintenance procedures invariably results in the need for component replacement and shorter system life.

2.7.3 Conclusion

HVAC usually plays a fundamental role in any museum, and it is responsible for a significant share of running costs and annual budgets. Thus, HVAC demands serious attention during the design phase, and a permanent dialogue between the engineer, architect, lighting designer and other members of the design team (BEMS, acoustics, etc.). HVAC design is, and must always be, an iterative process, to obtain an optimised building design with an optimised HVAC system.

The guidelines and methodology presented in this chapter aim to achieve optimised HVAC systems in both the design and operational phases. They outline a series of steps that should be carefully followed. Any shortcuts and deviations from this methodology may result in a less than ideal product in the end, with undesirable consequences for the museum.

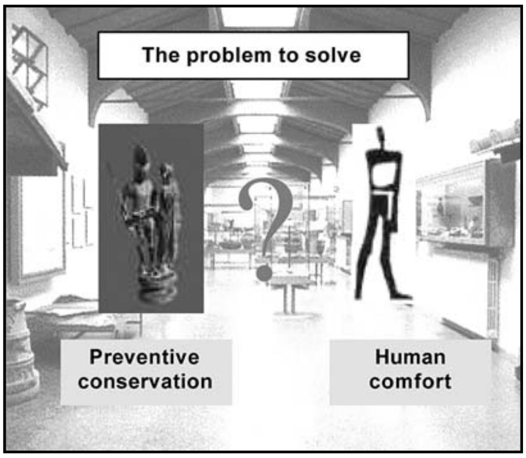
The design of the HVAC in the eight museums described in this Handbook followed, more or less, this procedure, showing that it is feasible and can produce good results. These were exceptional projects as they benefited from special support and funding that is not generally available for most other buildings. However, taking into account the investment that any new or retrofitted museum (or any other important non-residential building) always requires, much improvement could be obtained if it were followed as a rule rather than as an exception.

2.8 INDOOR CLIMATE - SPECIFICATIONS AND STANDARDS

2.8.1 Why Indoor Climate, Specifications and Standards are Important

Climate control inside museums is complex as it has to satisfy two different kinds of requirements:

- appropriate conditions for preventive conservation;
- appropriate conditions for human comfort.

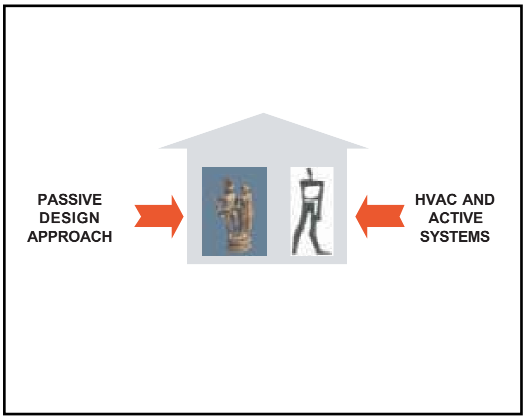


Museum indoor climate control: contemporary satisfaction of preventive conservation requirements and human comfort ones

In a museum, and more generally in any space dedicated to exhibition, one cannot design the internal microclimate without considering how this will effect the exhibits. The optimum conditions under which each object of art should be exhibited, in terms of lighting and climate control, is called preventive conservation. A museum curator is responsible for pursuing preventing conservation measures in selecting appropriate conditions for each specific exhibit.

It is very important that the architect and museum curator consider energy-efficiency and environment impact as part of a holistic design strategy. Defined conservation climate values and the acceptance of their range of variation should be related to the ability of the building to operate in a passive manner and its capacity to moderate microclimate changes.

Such values should consider the building “user model”, i.e.. typical operations hours, number and frequency of the visitors, etc. They should also include other aspects such as financial ones.



Balancing passive and active strategies for climate control: a great challenge

When dealing with exhibit conservation one must remember that the acceptable range for the proposed conservation microclimate values is very short for some categories of exhibit. This may create an impression that passive climate control, which allows many variations, is not appropriate and that the only way to solve the problem is by means of artificial systems. This is not completely correct. We should consider that some objects were during their lifetime, subject to many climate variations without being damaged, often being stored in areas that have no climate control.

Dedicated HVAC systems are only necessary for very sensitive exhibits needing special care. In those cases, it is necessary to consider the issues related to maintenance and possible malfunction of HVAC systems which could make the system more damaging than useful.

The indoor climate of today’s museums is more critical than in the past because of increasing pollution. Today air pollution and thermal loads due to large numbers of visitors create a more aggressive environment.

2.8.2 State of the Art in Indoor Climate - Specifications and Standards

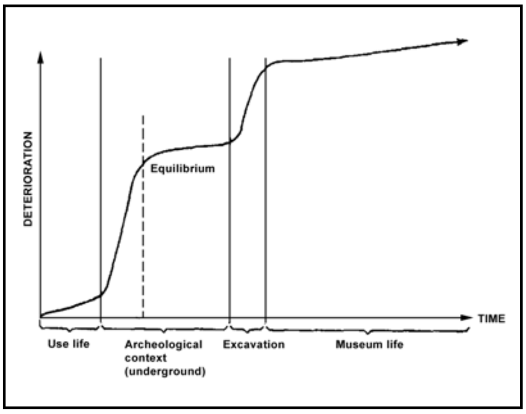
As already mentioned, indoor climate control inside museum buildings requires special attention from a preventive conservation view point. This requires not only an “historical responsibility” toward future generations, but also consideration of economic issues. It is clear that it is more convenient to prevent any deterioration by means of an appropriate strategy, instead of restoring the exhibits once damaged.

Museums must satisfy two classes of specifications and standards from the exhibit protection point of view:

- safety requirements
- conservation requirements.

The safety requirements are related to exhibit protection from fire, earthquake, thefts and vandalism, etc. Conservation requirements refers to micro climatic issues in the preservation of the exhibit's original characteristics.

Preventive conservation is the branch of the conservation science that studies lighting, air quality and climate control for the optimisation of conditions under which each object of art should be exhibited. We know that every object has a defined period of life and we know that protection means trying to reduce the deterioration curve.



Example of deterioration diagram of archaeological exhibits

It is important to define a set of recommended values for each exhibit that can be viewed in relation to human comfort values. This can be useful when assessing the compatibility of the microclimatic environment both for visitors and exhibits, or the necessity to modify the display environment by means of showcases. Poor climate control can cause much damage to exhibits.

2.8.2.1 Thermal aspects

Climate control should address temperature, relative humidity and Equilibrium Moisture Content.

It is important to note that proper conservation values depend both on single values and on the range of values acceptable for daily and seasonally variations.

Air temperature may cause chemical reactions in materials with the following effects:

- increasing photochemical reactions (discolouration from excessive light);
- increasing organic material deterioration due to chemical reaction, even without light exposure;
- increase in physical and chemical deterioration due to evaporation processes that may cause mechanical stress in the material;
- volumetric expansion of the material mainly in the case of organic materials);
- increasing biological activity of micro-organisms, especially in organic material.

Specialists agree that air temperature is only a danger for conservation when it is particularly high or particularly low: such conditions are not so common in museums.

The influence of temperature control is important when combined with relative humidity. According to conservation specialists, relative humidity is the most important parameter when evaluating if a museum environment is appropriate for conservation. Moisture in the air influences the exhibit's moisture content, and may be different from that required for conservation.

Specialists have indicated the best conservation values for some categories of material, especially for organic ones, that may be damaged by inadequate humidity control.

For high relative humidity values (R.H. greater than 75%) some of the following effects may be observed:

- mould formation on organic material such as paper, parchment, leather;
- corrosion of iron, copper alloy and other metals;
- water on the surface due to condensation;
- dimensional changes that may affect the surface texture (very problematic for paintings);
- salt formation on glass surfaces;
- deformation and decaying of wood and paper materials.

Where relative humidity values are low (R.H. less than 5%), exhibits can dry out causing problems related to an increase in brittleness and fragility.

It is very important to clarify that thermal control must take account of daily and seasonal variations.

Temperature and relative humidity influence the moisture content of materials. The value of Equilibrium Moisture Content (EMC) defines the quantity of moisture in materials in relation to the temperature. EMC is defined as the moisture content measured in saturation conditions as a percentage of the object's dry weight, for a defined temperature.

2.8.2.2 Lighting aspects

Light influences the deterioration of exhibits in different ways. For exhibition reasons, lighting can not be avoided, but it is necessary to minimise the damage it can cause as much as possible.

Deterioration due to light may be summarised as following:

- increased photochemical reactions with many consequences, but mainly discolouration;
- increased material fragility, especially if combined with high temperatures.

Lighting properties to be controlled are:

- illuminance (lux),
- yearly exposure (lux h/year)
- UV radiation (W/lm).

2.8.2.3 Air quality aspects

Deterioration due to airborne dust may be summarised as following:

- chemical reactions between air pollution and the material of the artefact, that may cause alterations of its original physical and chemical properties;
- deposition of dust on surfaces that impairs both visual perception and conservation.

To define optimised air quality for conservation, it is necessary to divide polluting agents according to their physical constitution: solid polluting agents (dusts and aerosol) and gaseous polluting agents. Air quality values that need to be controlled include: gaseous polluting agent concentration (mg/m^3) and solid polluting agent concentration (Eurovent efficiency).

2.8.2.4 Recommended values for conservation - Exhibit categorisation

The definition of recommended values for the Conservation Performance Programme requires a classification of the typologies of objects that can be found in a museum as each object has its own conservation requirements that depend not only on the material of which the exhibit is composed. Each object should be treated as an individual case, requiring particular attention.

Proposing general recommended values for preventive conservation, which are useful to designers for a comprehensive overview of the problem, implies a general classification of the most characteristic objects. For a preliminary general approach, the objects may initially be grouped according to their most typical characteristics. Then with the help of experts of conservation and restoration, it may be necessary to research each exhibit.

This general classification aims to simplify the classification process initially, while still taking account of the following aspects: exhibition requirements, educational issues, safety criteria, level of interest in the object, etc.

Some important aspects in classification consistly appear in the literature. The "Comité de l'ICOM pour la Conservation" (Groupe de Travail n. 17) in 1987 suggests considering the following:

- The type of material from which the object is made: (This is most important as it is influenced by relative humidity control and differs for organic and inorganic materials;
- Fabrication techniques: The same material can be manufactured in different ways, differing with the level of knowledge of the historical period or where different methods were tried. Fabrication techniques may imply different material chemical compositions; material density and shape may also influence deterioration processes;
- Historical object: Some objects may have been conserved in places without thermal control but in spite of that, they may have reached an equilibrium with the environment. This occurs frequently with archaeological exhibits. As the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) suggests for such situations, it is

better to maintain the same microclimate conditions.

- State of deterioration: Alterations and movement of the object within its life may have changed the original material characteristics, implying a need for different conservation treatment.

Issues for the definition of correct preventive conservation (drawing: Gael De Guinchen, ICCROM)

The constituent material seems to be the most important aspect in setting up a comprehensive classification of objects with regard to microclimatic control.

The classification may be carried out by dividing objects into 10 main exhibit categories. Each one is divided into secondary categories, with a total of 50 sub-categories:

Paper objects:

I paper, papier-maché, tissue paper
II stretched paper, wall paper, oriental parchments
III prints and drawings
IV philatelic collections, miniatures
V books and manuscripts
VI documents and archives material

Textiles:

I generic fabric
II clothes and costumes
III tapestry

Paintings:

I watercolours, drawings, pastel
II frescoes
III enamelware, varnish
IV oil paint
V tempera, gouache
VI generic paintings, canvas

Vegetable material:

I wood, wood sculptures
II painted wood, painted wood sculptures
III furniture, musical instruments
IV botanical collection
V ethnographic collection, generic vegetable objects

Animal material:

I anatomical collections, biological collections
II ivory
III horn, bones, turtle shell material
IV leather
V insects, mummies
VI furs, feather
VII parchment

Metals:

I weapons, armour, pendulum clocks
II silver
III copper, bronze, brass, lead
IV iron, steel
V common metals
VI coins
VII gold
VIII pewter, tin

Photographs and films:

I records
II movie films
III photographs
IV recording tape

Glass objects:

I stable glasses
II unstable glasses
III ancient glasses

Ceramics objects:
I earthenware
II majolica
III china

Minerals:
I volcanic material
II gems
III alabaster
IV stones
V marble

Different publications propose preventive conservation requirements according to specific situations for the above mentioned categories. The ICCROM Library, Via San Michele 13, Rome, contains the world's most extensive collection of resources about every aspect of heritage conservation in a wide variety of languages (www.iccrom.org/eng/library.htm). In the case of museum rehabilitation and retrofitting, once the monitoring has been performed it is necessary to find some deviation indicators if it is noticed that some environmental values are different from the ideal conservation values. Such indicators are useful to understand how the indoor climate may potentially damage exhibits. This is done by calculating for each parameter (e.g. R.H., etc.) the percentage of time for which monitored values differ from the parameter acceptance range. This can be easily done by looking to the parameter “per cent cumulate frequency diagram”, calculated for the reference period (often on a hourly basis).

2.8.3 Indoor Climate - Specifications and Standard Techniques to Optimise Performance

When designing a new museum or retrofitting an existing one, the opportunity exists for making choices to create an indoor environment with the correct conditions for exhibit conservation and, at the same time, providing a comfortable place for visitors. In order to improve the use of passive strategies, it is very important to perform a careful analysis to define conservation requirements and to determine climate targets without wasting energy. This is a significant challenge but, in order to define the targets correctly and select the best solutions, a methodological approach is necessary. The design process, for new constructions, retrofitting and rehabilitation of existing buildings requires a number of experts to be involved: the architect, the mechanical engineer, the museum director, the museum conservator, the exhibition designer, etc. Each one has their own experience and has to be involved in the decision making process in order to achieve common targets. It is thus necessary to define a common language to focus on comfort and conservation targets. The architect, as the person that controls the design process, may need instruments to interface with the other experts, particularly in conservation matters. There is a need for methods and instruments that are useful to building designers, owners, and building management and maintenance personnel, to analyse and to solve specific problems to achieve desirable results.

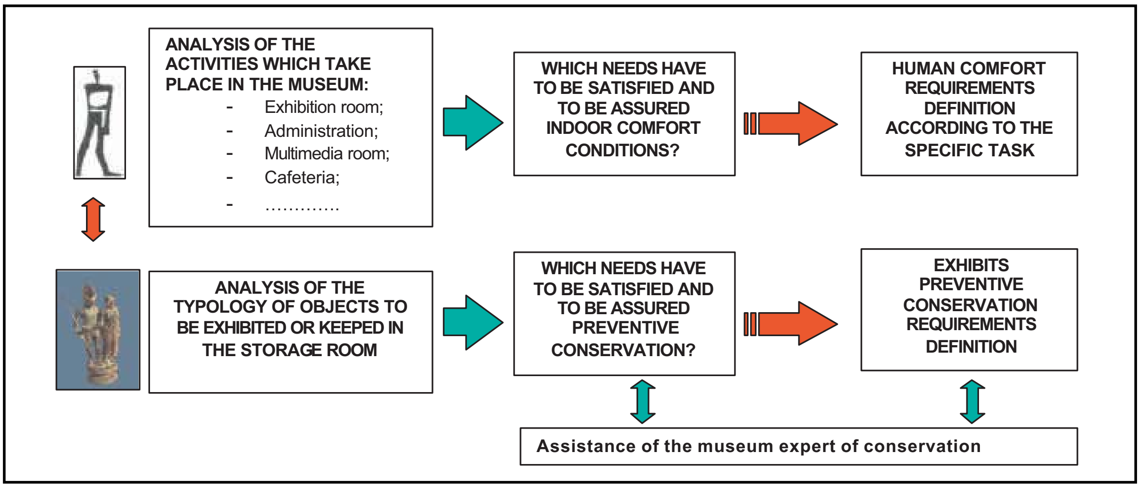
2.8.4 Indoor Climate - Specifications and Standard Performance Criteria

A method is briefly described here and some useful instruments are proposed to help ensure the expected performances. The method is addressed to architect and museum designers to help them to define a methodological approach to decision making in the management phase, and to obtain sufficient background knowledge on the subject. These instruments should help the designer to consider the conservation requirements of exhibits from the preliminary design stages, and give them sufficient knowledge to deal with the requirements of preventive conservation for each specific situation.

Such a method, can allow the indoor climate to be controlled according to previous targets, and takes account of the different requirements for conservation and human comfort. It is possible to define a set of specific requirements for each aspect of the design (thermal, air quality, visual and acoustic). Some concern both people and exhibits, while others relate solely to exhibits (e.g. seasonal temperature variation) or people (e.g. acoustic requirements).

The way to define requirements is similar for exhibits and people. In the beginning one starts with the classification of exhibits and follows on to the activity that has to be performed in each space. For both one must initially define the needs (for preventive conservation or comfort) and then the specific requirements.

This procedure follows the analogy existing between the need for human comfort and for an



Logical path for definition of requirements

optimised environment for the conservation of objects. It is therefore possible to define general rules allowing the subdivision of the issue into simpler steps in order to evaluate compatibility.

In order to assess human comfort requirements it is necessary to make an accurate analysis of all the activities that will take place in a museum and to establish the relationship between them with regard to the need for technical equipment, space organisation, etc. Once the activities and their relationships are known, it is possible to define the levels of comfort required by people involved in each activity. The results may be shown in a table that sets out the comfort requirements that must be addressed (thermal, air quality, visual and acoustic) for each homogeneous area derived by the activity analysis, that can be found in a museum (office, cafeteria, permanent exhibition rooms, laboratory, conference room, etc.).

The exhibit conservation performance programme can be obtained with a similar approach. The exhibits are initially divided into categories of objects with similar conservation requirements. This may be difficult because the process depends on many factors including the constituent material, the fabrication technique, the objects history and state of deterioration, all of which influence the classification in different ways.

Once the objects are categorised, it is possible to define the range of parameters for conservation. The results may be reported in a set of tables omitting the Conservation Performance Programme. Shown horizontally are the requirements for conservation, including thermal, lighting and air quality issues; Each category of artefact category that will be exposed in a museum is shown vertically. The table is filled in showing the best conservation conditions for each category resulting from a comparison of a data-set found in the scientific conservation literature. These tables are effective for generic categories of exhibits without the need to consider the influence of the conservation history of each exhibit that could affect the suggested values.

REQUIREMENTS		Units	Terracotta	Copper, Bronze, Brass, Lead
Thermal issues	Temperature control	°C	$18^\circ C < t < 24^\circ C$	$18^\circ C < t < 24^\circ C$
	Temperature daily variation control	°C	$\delta t < 3^\circ C$	$\delta t < 3^\circ C$
	Temperature seasonally variation control	°C	$\Delta t < 9^\circ C$	$\Delta t < 9^\circ C$
	Main temp. of radiant surfaces control	°C	$17^\circ C < t_{mr} < 21^\circ C$	$17^\circ C < t_{mr} < 21^\circ C$
	Relative humidity control	%	$0 < R.H. < 45\%$	$20\% < R.H. < 45\%$
	R.H. daily variation control	%	$\delta R.H. < 5\%$	$\delta R.H. < 5\%$
	R.H. seasonally variation control	%	$\Delta R.H. < 10\%$	$\Delta R.H. < 15\%$
	EQ. Moisture content control	%	/	/
Lighting issues	Illuminance level control	lux	$50 < E < 250\ lx$	$E < 300\ lx$
	Maximum yearly exposure control	lux h / y	$Expo < 80\ Mlx\ h/y$	$Expo < 5\ Mlx\ h$
	U.V. radiation control	W/lumen	$UV < 75\ \mu W/lm$	$UV < 75\ \mu W/lm$
Air quality issues	Gas pollutant concentration control	varied	$SO_2 < 10\ \mu g/mc;$ $NO_2 < 10\ \mu g/mc$ $O_3 < 2\ \mu g/mc$	$SO_2 < 10\ \mu g/mc;$ $NO_2 < 10\ \mu g/mc$ $O_3 < 2\ \mu g/mc$
	Solid pollutant concentration control	varied	*Eff 85% on Eurovent 4/5*	*Eff 85% on Eurovent 4/5*

Preventive conservation parameters selected for the Archaeological museum 'Pompeo Aria' of Marzabotto, according to relevant literature and the museum conservator expertise

The parallel between best microclimate values for comfort and for conservation makes it possible to make a direct comparison of the values and, for each case, microclimate compatibility can therefore be evaluated. In this phase, the contribution of the curators is very important because they can define appropriate conservation parameters for each object according to its specific requirements.

The methodology previously summarised may be divided into logical steps within the design process:

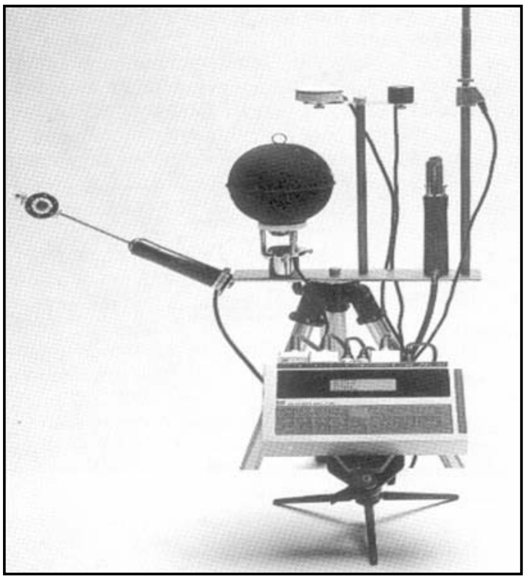
1. Analysis of all the activities taking place in the museum and grouping of spaces with similar environmental requirements;
2. Selection of human comfort values (the occupant comfort performance programme for each group of spaces);
3. Classification of museum exhibits;
4. Selection of conservation values from the Conservation Performance Programme;
5. Selection of the best microclimate values for preventive conservation and evaluation of the compatibility range;
6. Comparison between microclimate values for preventive conservation and occupant comfort (in the permanent exhibition area) and evaluation of possible compatibility;
7. Comparison between conservation, comfort and microclimate values and evaluation of compatibility with monitored results (for retrofitting actions);
8. Definition of retrofitting and/or design priorities and possible design scenarios.

If compatibility is not guaranteed and the related diagnosis is known, it is possible to proceed with different design scenarios for rehabilitation. The evaluation of compatibility with microclimate and occupant comfort requirement targets and exhibit conservation requirements may define different solutions.

1. Total dominance of the recommended values: In this case, the suggested range of values for occupant comfort and for museum exhibits is fully adhered to.
2. Partial adherence in this case, the range of recommended values for occupant comfort and artefact is less stringent and implies a more complex technical solution. In this case, object conservation becomes a priority.
3. No adherence when it is impossible to satisfy adequately both the occupant comfort requirements and those for artefact conservation, the curator and the design team are obliged to use solutions that create separate and different microclimates.

It is clear that this kind of methodology can not solve all of the problems that arise, but it is a practical approach for designers in order to set design targets, without wasting too much time on details.

Climate control in 'Pompeo Aria' Museum



BABUC/A Multidata logger used for monitoring in the 'Pompeo Aria' Museum

2.8.5 Results and Lessons Learnt with Respect to Indoor Climate - Specifications and Standards

The correct definition of indoor climate values is of great importance for occupant comfort, exhibit conservation and energy savings. The design strategy requires a comprehensive, holistic approach in order to optimise the use of passive and active systems. Sometimes an accurate analysis of the exhibits and of a model of museum occupancy (number of persons, occupancy pattern, activities, etc.) makes it possible to reduce the heating and cooling loads and to design the HVAC system without over sizing.

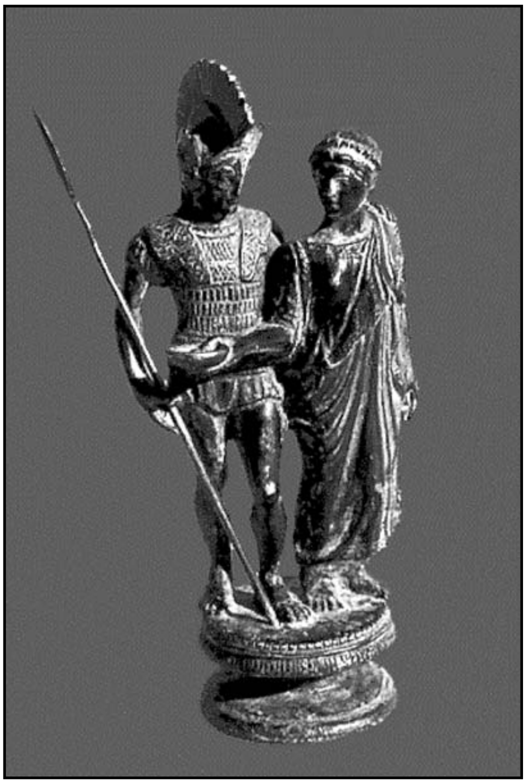
Indoor view of the existing exhibition of the 'Pompeo Aria' Museum in Marzabotto

This methodology has been successfully applied to the MUSEUM buildings and has led to different design solutions to overcome the problems and solve specific needs.

2.8.5.1 National Etruscan Museum 'Pompeo Aria', Marzabotto, Italy

Here the methodology has been applied to the retrofitting of the National Etruscan Museum 'Pompeo Aria' in Marzabotto. The work has been performed using the following steps:

- Classification of museum exhibits
- Selection of conservation values starting with a literature analysis
- Selection of the optimal microclimatic values for preventive conservation and evaluation of a compatibility range, together with the help of a specialist in conservation
- Comparison between microclimate values for preventive conservation and occupant comfort as well as the evaluation of possible compatibility
- Comparison between conservation, occupant comfort and microclimate values and evaluation of compatibility with monitoring results
- Definition of rehabilitation and retrofitting design priorities and design scenarios.



Bronze statue, 'Pompeo Aria' Museum in Marzabotto

Correct definition of comfort and preventive conservation targets has been a very important phase of the work. Climate control is pursued as much as possible by passive means during the cooling season and by controlling the heating system operation during the heating season. This option is possible because the exhibits do not have specific conservation needs.

The radiators located under the showcases in the existing museum area were replaced by a radiative heating system which will provide a more uniform temperature distribution and reduce temperature stress on the exhibits.

The show cases required for security purposes will also be used to control the microclimate locally. This will be done mainly by means of hygroscopic salts to keep the relative humidity under control. Showcases will be naturally ventilated.

REQUIREMENTS		Units	BRONZE and TERRACOTTA EXHIBITS	OCCUPANT COMFORT VALUES (exhibition area)	COMPATIBLE?	
					YES	NO
Thermal issues	Temperature control	°C	$18°C < t < 24°C$	$17°C < t < 24°C$	X	
	Daily temperature variation	°C °C	$\delta t < 3$ °C $\Delta t < 9$ °C	/ /	X X	
	"Operative temperature"	°C	/	$18\ °C \leq t_{op}^{winter} \leq 20\ °C$ $22\ °C \leq t_{op}^{summer} \leq 25\ °C$	X	
	Main temp. of radiant surfaces	°C	/	$17\ °C < t_{mr} < 21\ °C$	X	
	Surface temperature	°C	/	$14°C < t_s < 25°C$ $t_s < 70°C$ (heating sources)	X	
	Relative humidity	%	20% < R.H. < 45%	35% < R.H. < 45%	X	
	R.H. daily variation	%	δR.H. < 5%	/	X	
	R.H. seasonally variation	%	ΔR.H. < 10%	/	X	
	EQ. Moisture content	%	/	/	X	
	Air speed	m/sec	/	$0,1 < v_a < 0,25$ (m/sec)	X	
	Thermal inertia factor	m^2/m^2	/	$i \geq 0,5\ m^2/m^2$	X	
	Non symmetric distribution of average radiant temperature	/	/	$\Delta t_{mr}^{vertical} < 5°C$ $\Delta t_{mr}^{horizontal} < 10°C$	X	
	Floor surface temperature	°C	/	$19\ °C \leq t_{fs} \leq 28\ °C$	X	
	Head-foot temp. difference	°C	/	$\Delta t_{hf} < 3°C$	X	
Visual / Lighting issues	Illuminance level	lux	50 < E < 250 lx	200 lx < E < 300 lx	X	
	Maximum yearly exposure	lux h / y	Expo < 5 Mlx h / y	/	X	
	U.V. radiation	W/lumen	UV < 75 µW/lm	/	X	
	Daylighting	lux/lux	/	DF > 2%	X	
	Glare		/	G = 1,15	X	
	Correlated colour temperature	K	/	3000 K ≤ TCC ≤ 4000 K	X	
	Colour rendering		/	Ra > 85	X	
Air quality issues	Gas pollutant concentration	varied	$SO_2 < 10$ µg / mc; $NO_2 < 10$ µg / mc $O_3 < 2$ µg / mc	/	X	
	Solid pollutant concentration	varied	Eff 85% on Eurovent 4/5	/	X	
	CO and CO_2 concentration	%	/	CO < 0,003% $CO_2 < 0,15\%$	X	
	Ventilation	l/(sec people)	/	r > 7,8 l /sec pers.	X	
Acoustical issues	Sound level pressure	dB(A)	/	$L_{Aeq} \leq 55$ dB(A)	X	
	Reverberation time	sec	/	$T \leq 1,5$ sec	X	

Comparison between microclimate values for preventive conservation and occupant comfort and evaluation of possible compatibility

2.8.5.2 Herzog-Anton-Ulrich Museum, Braunschweig, Germany

The museum has two main façades orientated north and south. The layout of exhibits takes account of the different lighting and thermal behaviour patterns occurring in south and north oriented rooms. This represents a simple way to control the impact of the external climate.

The stability range for relative humidity has been carefully evaluated allowing for some variation. Only objects which need very careful protection require such strict control.

While using passive and bioclimatic design techniques for indoor climate control, to the greatest extent possible, it is accepted that the range of climatic variations is too great and in most cases is acceptable. It should be however noted that some objects were in contact with many climatic variations without deteriorating at the beginning in their existence and often, in the more recent past, during their storage in areas where the microclimate was not controlled.

Peter Paul Rubens (1577 - 1640), Herzog-Anton-Ulrich Museum, Braunschweig, Germany

2.8.5.3 Archaeological Museum of Delphi, Greece

The museum hosts three main categories of exhibits: metals (copper and gold), ceramics (terracotta) and minerals (marble). Except for some specific exhibits it appears that there is potential compatibility between the requirements of preventive conservation for exhibits and those of user comfort. This means that exhibits can share the same indoor microclimate. For specific exhibits, UV exposure has been controlled by means of special protective film on windows and skylights, and with the correct choice of artificial light installation.

Some daily and seasonal variation of thermal parameters is considered acceptable. This represents a good compromise in order to try to minimise the use of artificial systems, such as HVAC.

Charioteer statue, Archaeological Museum of Delphi, Greece

2.8.5.4 Kristinehamn Museum of Contemporary Art, Sweden

The indoor requirements defined for user comfort inside the Kristinehamn Museum appears suitable for many collections that have not got any specific conservation needs. These requirements are met without a HVAC system. As the museum has mostly temporary exhibitions stringent indoor requirements e.g. 19-21°C and 43-47% only apply for the rare occasion that sensitive objects of art are borrowed.The windows filter UV light. There is also a back-up mechanical system for cooling, humidifying and dehumidifying.

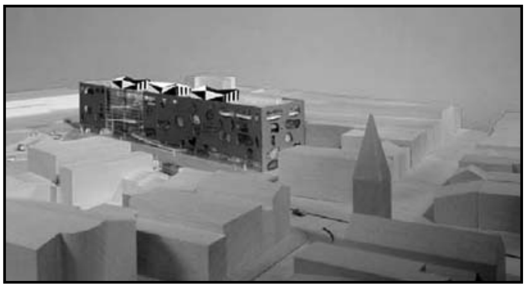
Kristinehamn Museum of Contemporary Art, Sweden

Outdoor exhibitions (sculptures) need controlled preventive conservation conditions in the Kristinehamn climate. For wooden or stone sculptures, it may be necessary to set up a maintenance programme to include cleaning and protective treatment.

2.8.5.5 THEpUBLIC Arts Centre, West Bromwich, United Kingdom

The objects which will be exposed in THEpUBLIC Arts Centre are not specified in detail yet. But they will mainly be contemporary art modern materials. The conservation targets for those materials should be defined according to the importance of the exhibits. Apart from special exhibitions (for example video installations) the occupant comfort requirements should be in line with the preventive conservation limits.

In order to prevent colour deterioration it is important to provide glazing with UV protection, as it can represent a large percentage of the façade.



Model of THEpUBLIC Arts Centre, United Kingdom

2.8.5.6 National Archaeological Museum, Lisbon, Portugal

The museum hosts an area for temporary exhibitions. This means that it is impossible to predict which kind of exhibits will be displayed. The correct definition of the preventive conservation target is, therefore, difficult. Such spaces need to be flexible and adaptable to different situations and exhibits, and should be capable of being fine tuned according to future requirements.

To do so it is important that the architects and climate engineers are informed from the beginning by the museum conservation and management personnel in order to get as much information as possible concerning the exhibits to be displayed. Sometimes, as in the case of archaeological museums, one can assess the kind of exhibits that will be shown by looking at the actual collections, but in other cases this is not possible. In such situations it is necessary to find solutions that can be easily adapted to different comfort and conservation scenarios in order to fully address all of the requirements. The Lisbon museum has an underground exhibition area in which a stable climate throughout the year is predicted. This space will be suitable to exhibit sensitive objects.

5th century of Hegira (1009-1106), Arab mortuary lettering. Fragment, Frielas. Lisbon, National Archaeological Museum

2.8.5.7 Bardini Museum of Florence, Italy

The difficult task of controlling climatic conditions in historical buildings is often largely due to the need to maintain the architectural and historical integrity of the building. They can offer an excellent location to show collections in an impressive context, but the possibilities for intervention are limited, sometimes because they were not originally conceived for exhibition purposes and because of the artefact conservation requirements of today. Many compromises need to be made in such buildings as the installation of a HVAC system may not be compatible with the architectural characteristics. This situation is very common in Italy, as is the case in the Bardini museum.

The museum is seldom crowded, which provides an opportunity to avoid or reduce the use of an artificial systems to rapidly adjust indoor climate conditions.

"La carità", Tino di Camaino, Bardini Museum, Florence, Italy

The use of natural ventilation integrated in the windows is potentially a good strategy to control indoor climate here. The use of night ventilation is also feasible, as inside velocity is not an issue. However, this could be a very useful technique during the summer by helping to cool down the building envelope and obtaining the maximum advantage of the thermal mass which is usually a characteristic of ancient buildings.

2.8.5.8 Slovene Ethnographic Museum, Ljubljana, Slovenia

The museum has various exhibits that require special care, including ancient organic materials.

Slovene Ethnographic Museum, Ljubljana, Slovenia

It is very important that conservation targets takes account of energy saving and environment impact issues, as part of a coherent architectural design and artefact conservation. The defined conservation climate values and the acceptance of their range of variation must first be related to the ability of the building to moderate the external climate in a passive manner, and its capacity for accommodating microclimate changes. Moreover the design team should consider the building user model operations hours, the number and frequency of visitors as well as financial constraints.

2.9. BUILDING ENERGY MANAGEMENT SYSTEM AND INTELLIGENT COMPONENT DESIGN

2.9.1 Why Building Energy Management Systems and Intelligent Component Design are Important

The integration of intelligent components can provide an important contribution to the achievement of high environmental requirements in museum buildings. Nowadays, building devices and components are designed to be self-regulating as far as possible, requiring minimal intervention by the occupant in order to operate heating, cooling or daylighting systems. Automatic intelligent controls are useful to help optimise building performance so that energy use can be improved and the desired indoor microclimate can be maintained at all times.

Several Intelligent Building Management System options are now on the market. The latest generation are modular with a digital output and can accommodate a wide range of appliances and buildings of varying appliances, from individual simple to the most complex and geographically distributed ones.

An integrated management system generally enables a building to be operated more easily and with greater efficiency, therefore helping to reduce operating costs. Instead of using a variety of devices, the operator can often perform all activities from a single management station, keeping training costs to a minimum and reducing the likelihood of incorrect operation. Furthermore, if control of all the systems in the building is brought together in a single management station, faults and alarms can be identified and dealt with immediately, for better protection of people and property.

2.9.1.1 Intelligent Components and their control system

A number of control systems are available for lighting, air conditioning and heating, to help optimise daylighting, temperature and humidity levels etc. Controls systems for optimised building energy management apply mainly to three fields:

- thermal control systems,
- artificial lighting and solar radiation control systems,
- ventilation and air quality control systems, integrated within building automation control systems (for ventilation, overall energy consumption) or special components, or operations.

Moreover, quite sophisticated intelligent systems are now available, as Building Energy Management Systems (BEMS), which integrate and manage a large number of sensors (fire alarms, smoke ventilation, security, HVAC systems), according to requirements.

2.9.1.2 Design Standards

The basic elements of an intelligent control system are one or more sensors to measure the parameters required for the implementation of any required control strategy. Once this information has been processed by a controller, appropriate commands can be sent to the actuators.

The controller will instruct the actuators based on programmed algorithms and in response to the input to the sensors.

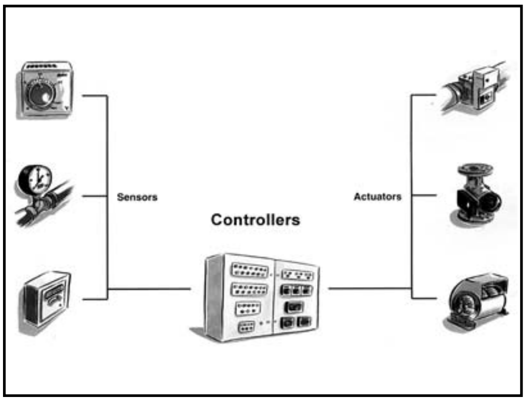


Diagram of a BEM system

Sensors

Sensors are of vital importance because effective automatic control depends on the quality and correct interpretation of information they provide. Sensors measure the parameters required for any control strategy, including indoor and outdoor temperatures, CO_2 or air quality, wind velocity and direction, rain, solar radiation and humidity and can be used to help determine the local management of each room or zone according to the internal specified physical conditions.

Controllers

Controllers receive and read data from the sensors and send orders to the actuators by means of a strategy programmed into the memory of the controller.

Actuators

Actuators are used to adjust mechanisms and operate switches, valves etc.

With regard to the control of passive solar gains, for example, the actuator may be an electric motor that adjust the position of screen elements, using input data from the sun or other control variables. Many examples of sunshades can be adapted for use with automatic control systems with power packs and control sensors. Various types of programmable control units are available for curtains, venetian blinds and roller blinds etc.

2.9.2 State of the Art Building Energy Management System and Intelligent Components Design

In planning a BEMS for museum or exhibition building, several parameters must be considered to achieve a well designed and functioning system, to provide a good overview of what is happening and to achieve well defined effective control strategies. Museums need special design attention to achieve the required comfort conditions for exhibit conservation without resorting unnecessarily to additional artificial systems. An advanced control system can ensure that artificial devices consistently produce the desired microclimate.

2.9.2.1 Comfort combined with lower energy consumption

The operation of building services and administration systems using a Building Energy Management System makes it possible to save energy in new ways, without sacrificing comfort. Optimum comfort combined with lower energy costs make buildings more attractive to users and increases property values.

These components allow clients the flexibility and freedom to choose from the leading suppliers of other building services such as lighting control, electrical distribution systems, fire, security, etc. and to integrate their equipment into the management system.

2.9.2.2 Integration is a good thing, but get the balance right

There are two approaches to integration: “as much as possible”, or “as much as necessary”. The latter is recommend - integration within limits - to ensure the best cost/benefit ratio. It's also ensures that individual systems, although integrated, remain as autonomous as possible. This means that each system can be expanded or replaced individually with few, or ideally, no adjustments - another way of protecting capital investment.

This kind of solution can take advantage of all the benefits these subsystem offer when integrated, such as centralised monitoring and command, a common user interface for the whole system, alarm evaluation and many more facilities, without the disadvantages of project specific integration solutions, including high initial cost and high maintenance costs.

2.9.2.3 Supreme comfort

Pleasant environmental conditions are of fundamental importance when it comes to our sense of well-being in a building. Clearly, these conditions do not always exist naturally; thus they need to be controlled and continuously monitored. It is important to choose a highly integrated Building Energy Management System that is designed to ensure ideal conditions throughout a building.

A museum visit may require a long stay indoors, in a closed environment. It is therefore necessary to allow users to spend this time in maximum comfort and safety. No matter how often, or for how long we are in a building, a BEMS must often satisfy the most demanding requirements at all times and be designed in compliance with economic criteria which set new standards for the future. It also needs to incorporate an energy efficiency system which ensures that the amount of energy made supplied to any part of the building is never more than is actually needed. That applies to all buildings, whatever their size.

2.9.2.4 Effective environmental protection

With regard to with sustainability, it is always important to work in harmony with the environment. Therefore, the choice of intelligent components systems and services, taking account of all the relevant environmental factors, is preferable The result can be a substantial reduction in energy consumption and, significantly lower operating and energy costs.

2.9.3. Building Energy Management Systems and Intelligent Component Design Techniques to Optimise Performance

A modern computer-based Building Energy Management System is therefore vital for the efficient management of buildings, and the means of display and operation is especially important. Such a system is used for continuous monitoring, energy optimisation and adaptation to the changing needs of users over the entire lifetime of a building. Building automation systems that control heating, ventilation, and air conditioning have become common in new construction and are now included as part of many retrofit projects.

The current practical approach to the problem is limited both by the number of input and output variables taken into account and in the control strategy adopted. The sensors used are often photometric and measure light intensity, or at most, uniformity of light intensity. Actuators are almost always on/off controls on lighting units. Energy management programmes are mainly based on rather than real time data.

It therefore seems that the principal need is to supply the control system with data from the ‘field’ which it is controlling in real time, data not only on light intensity but also on all other comfort factors (light contrast, uniformity, temperature, humidity and glare). The control system would then be able to compare this data with comfort standards and instruct the various devices concerned (sun blinds, lighting units, etc.) to take the corrective action necessary if a comfort parameter goes beyond its limits of acceptability.

Automation building systems may offer incremental energy savings and in addition to these savings, which are usually large, they offer other benefits including:

- detailed reports of occupancy and energy use
- enhanced operation schedules
- diagnosis of lighting system problems
- a wide array of manual control options and where appropriate other occupants and building managers
- the ability to monitor and control lighting, heating, ventilation etc. throughout a building or even throughout a multi-building facility
- the ability to minimise peak demand, thereby reducing energy costs where energy utility rate structures are based on peak demand and real-time pricing.

Modern building automation systems are distributed control systems, which means that their computing hardware and software are distributed as a network that comprises microprocessor-based control modules and standard personnel computers (PCs). For example, BEMS can be used to monitor and control various operations in order to achieve the optimum efficiency of various components and the overall system.

This system is very important for museum buildings, which have various types of zones and different operating conditions and schedules.

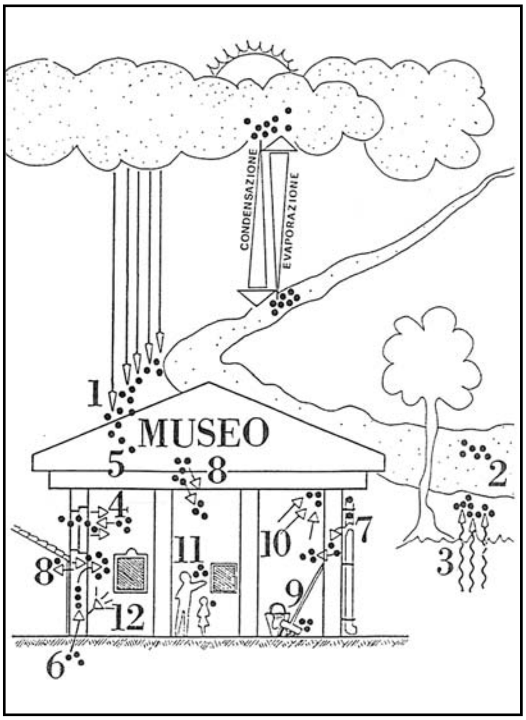
2.9.3.1 Control for thermal conditions

Temperature sensors

Thermal control in the museum environment is a crucial part of conservation; as for example, inappropriate air temperatures can cause chemical reactions on artifacts.

Moreover, accurate measurement and control of temperature can result in high energy savings (5-10%), compared with an average heating installation and the cost of such a control system is relatively low. The sensors, positioned inside and outside of the buildings, send temperature data to the controller that interprets them and regulates the HVAC system through actuators to adjust environmental conditions according to requirements.

The intelligent regulators of the system that operate in the building check that changes happen according to what is required in the indoor environment. In museum buildings, optimal conditions for both the exposed artefact and user comfort must be satisfied. Optimizers are a more advanced feature connected to internal and external sensors that can operate time switches. They assess previous operational responses and current conditions to determine the optimum time for turning on the heating system, for example, in order to reach the desirable indoor temperature at a specified period, taking account of thermal lag times.



Humidity sources

Humidity sensors

It is often thought that the ideal solution for the preservation of exhibits in museums is an air conditioning system which can regulate temperature, relative humidity, air speed and quality in every single room according to the different needs of exhibits and occupants. Many of the museum exhibits are much more sensitive to humidity variations than to temperature ones, even where temperature is very important, for example, for film and wax artefact preservation. All materials tend to expand with a temperature increase, but for hygroscopic ones the thermal expansion is shorter compared to that caused by an increase in relative humidity.

This air conditioning solution is easy to achieve in new buildings, designed for exhibition use, whereas there may be technical, artistic and economic problems that are not always easy to overcome in ancient museums. Here, it is often the case that the only way to achieve suitable, stable conditions is to provide a system with a high energy consumption. Systems for the control of humidity constitute one of the greatest expenses in retrofitting projects.

Buildings adapted to become museums may have restricted flexibility. Exhibition spaces in old buildings not designed for that use can be quite different in terms of structural, thermal and lighting characteristics.

To obviate these difficulties, stand-alone appliances are sometimes used to control local microclimate conditions, particularly RH. Sometimes, to maintain required humidity values, it may be necessary to introduce water vapour to the space in an efficient manner.

CONTROLS (systems):	
▪ Active centralized	− Humidifier systems − Dehumidifier systems (using deionising water)
▪ Active localized	− Humidifier by condensation − Humidifier by absorption (constant maintenance, especially if in dusty rooms)
▪ Passive	− Stabilising elements (silica gel and art-sorb but in circumscribed volumes)

Control system typologies

Besides those listed in the table above, other appliances may be used to control humidity levels:

- Humidifiers for heating
- Humidifiers for evaporation and rapid ventilation
- Humidifiers for heating and rapid ventilation
- Humidifiers with atomisers
- Dehumidification by condensation
- Dehumidification by absorption

Humidity measurement and control is useful for museums, especially in facilities using a variable flow ventilation system. Moisture data can be obtained from the mechanical ventilation system to adjust system operating modes according to indoor conditions and, above all, to maintain adherence to conservation requirements.

Control of lighting system

Lighting can affect many exhibits. It is important to control illuminance, annual exposure to light and UV radiation to avoid damage to exhibits.

Control systems can be used to control lighting; however, high initial and maintenance costs, the apparent complexity of these systems, and concerns among occupants about the operation of lighting systems and other building systems have limited such applications.

The technologies and systems used to control lighting and environmental plant are important to the process of the design, construction and operation of a museum buildings with respect to energy savings and natural light usage. The selection and/or the practicability of the control system can help optimise design decisions, but it can equally make them ineffective.

The use of automated lighting controls such as timers, occupancy sensors and photosensors help reduce deterioration caused by lighting on exhibits and may offer energy savings.

Existing systems have not gone much beyond the concept of supplementary lighting i.e.. measuring the level of daylight and supplementing it with artificial light. A system based on this concept makes it possible to keep the level of illumination in the room at the design level as daylight varies, and the coefficient of uniformity at pre-selected values. It also permits a considerable saving of electricity, longer life for lighting equipment, and simple management of reserve lights. A system based on this concept may incorporate some of the following:

- Continuously controlled lighting units,
- Computerised panels for on/off switching of a large number of lighting units,
- Central computers to manage a number of computerised sub-panels,
- Timer-controlled switching systems.

An intelligent lighting control system incorporates on schedules and lighting sensors (photo sensors and occupancy sensors, operating either singly or in combination).

Schedules

Much of the energy saving produced by a building automation system comes from scheduling the operation of electrical loads. For instance, the lighting in a museum building can be programmed so only occupied spaces are lit. Different schedules can be programmed for individuals circuits or groups of circuits (zones). Each different zone also can have a unique schedule for weekdays, weekends, or special events. Some systems automatically adjust a lighting zone's schedule to account for seasonal variations e.g. in the availability of daylight etc., according to the exhibit. A building automation system using fuzzy logic can dynamically adjust schedules based on typical occupancy patterns.

Lighting sensors

1. Photosensors:

A photosensor is an electronic control device that adjusts the light output of a lighting system based on detected illuminance. While some photosensors simply switch off and on, there are specific photosensors with a dimming electronic ballast to adjust the light output of fluorescent lighting systems over a continuous range. These photosensors are most commonly used in daylight applications to dim electric lighting when total illuminance exceeds a preset level.

There are essentially two types of photosensors:

- A photosensor used for switching sends a binary signal to the direct digital control network when the amount of light it detects reaches a certain (adjustable) threshold. The building automation system can then turn off lights or set them to a lower level.
- A photo sensor used for dimming sends a continuously variable signal indicating how much light it is detecting. With this information, a building automation system can gradually dim lamps as daylight increases or gradually increase power to the lamps as they age to maintain constant illuminance (light level).

The use of photoelectric cell sensors can be used to control electrical lighting, based on the availability of daylight levels in the space. The objective is to achieve an optimal balance between daylighting, use of electrical lighting, cooling and heating load.

If such a system is not provided, electric lights will tend to stay on, as can be seen in many museums and so the unnecessarily high illuminance can deteriorate objects more rapidly and cause problems with colour rendering and glare. Photoelectric control is best used in areas such as corridors, atria and entrance halls where occupants do not expect to control the lighting.

2. Occupancy sensors:

These sensors can be used to turn the lights off when the space is unoccupied of periodically occupied.

Their typical operating method is to detect the movement of mass by sensing reflected beams. The most common types uses infrared rays. A system that turns lights off when the room is unoccupied and leaves the occupant to turn the lights on if required is likely to be the most efficient. Energy can be reduced with this system compared to a conventional presence detection system by eliminating the possibility of the lights coming on by small movements such as those due to wind, even when the room is unoccupied.

Occupancy sensors use passive infrared, ultrasonic, or a combination of these technologies, which combine these two technologies, such as 'microphonic', in-one sensor.

- Passive infrared (PIR) technology:
  this relies on "line of sight" coverage to detect occupancy by sensing the difference in heat emitted by humans in motion from that of the background space. These sensors use a pyroelectric detector located behind an infrared-transmitting lens to detect motion. The lens is etched with an optical pattern that divides the field of the pyroelectric detector into wedge-shaped segments.
- The occupancy sensor responds when it detects a heat source crossing from one segment to another. Because infrared occupancy sensors must have a direct line of sight to the motion, they should not be used where furniture, partitions, or other objects are positioned between the sensor and the motion. Every time an occupant moves, the time delay circuit is reset. Each sensor provides for a adjustable time delay from 30 seconds to 20 minutes. After a period of time the sensor will automatically time out, turning lights off.
- Ultrasonic technology:
  This utilises the Doppler principle to detect occupancy by emitting ultrasonic sound waves throughout a space. UT sensors transmit pressure waves at frequencies of 25-40 kHz. These ultrasonic waves are similar to sound waves except that they are at a higher, inaudible frequency. The ultrasonic values travel through the air and are reflected from room surfaces and objects back to a receiver in the occupancy sensor. Motion within the space changes the frequency of the reflected vibrations. The receiver detects this change and turns or maintains the lamps on. Unlike passive infrared occupancy sensors, ultrasonic occupancy sensors are sensitive to the motion of inanimate objects, such a blowing curtains. However, these sensors do not need a clear line of sight to an occupant and are preferred for spaces with partitions or other obstacles.
- Dual technology (DT):
  these sensors employ both PIR and ultrasonic technologies. DT sensors will activate lights when both sensing technologies detect occupancy, but will continue to hold lighting on as long as only one technology detects continued occupancy.

In evaluating the characteristics of these systems, and reviewing the physical characteristics of the space under consideration, designers should be familiar with:

- room space, size and shape
- location(s) of occupant activity and in-activity
- location of walls, doors, windows and curtains
- ceiling height(s)
- partition heights and locations
- location of large objects that would obstruct or alter a sensor's coverage i.e.. shelves or large equipment
- location of HAVC ducts & fans
- areas with high levels of sunlight
- location of obstacles

Special attention should be paid to high levels of vibration and/or air flow, extreme temperature conditions, and unusually low levels of activity, because these issues may lead to alternative technology solutions. For occupancy sensors, the simple payback period is less than for photo-electric cell sensors, for the same energy savings.

Solar radiation control system

Controllable sun screening is desirable to prevent excess solar transmission in summer. However, it should be capable of allowing the transmission of daylight to minimise the use of artificial light under overcast conditions. This complex issue involves the balancing of daylight, comfort and energy efficiency in general, and of particular relevance for museum buildings. Intelligent control allows for a balance of control that can be overridden by occupants for private spaces.

It has been shown that removing totally the user control causes irritation and a significant reduction in occupant tolerance to the internal environment. In the exhibition spaces, intelligent control will be necessary for special exhibits that require particular lighting.

Lighting, blinds and other shading devices, are moderated by the quantity of solar radiation, occupant presence and room temperature detected by sensors.

Ventilation and air quality control system

The purpose of ventilation is to maintain indoor contaminant concentrations to an acceptable level. This can be achieved in most cases by increasing the air ventilation rate. Generally, in museum buildings, the air quality values to be addressed and controlled for exhibit conservation are:

- gaseous polluting agents
- solid polluting agents

Many museum buildings, both new or refurbished, are naturally ventilated. In order to maintain good indoor air quality and summer comfort in noisy or polluted environments, an intelligent ventilation control system must be used. Wind sensors are necessary for the automatic control of natural ventilation or to avoid damage to shutters and awnings. The automatic sensors for ventilation operate fans, high level opening windows, grids and ducts. These include room presence detectors, CO_2 concentration monitors, and multi-gas pollution sensors.

The sensors for air quality control are designed to be sensitive to a wide range of gases such as VOCs, solvents, vapours and many other toxins. For this reason the sensors are ideally suited to ‘general air quality’ sensing. Typically, these sensors are supplied in a pre-characterised state at a standard range of 0 – 100 ppm of a typical VOC (Toluene).

Alternatively these sensors can be set to operate at lower and higher VOC levels (0-1,000ppm). It should be noted that the choice of either sensor should be optimised to target ‘general air quality’ odours. These sensors stabilise in less than 1 minute and there after zero drift is less than 1% / year.

The humidity response is small and the sensors can operate in a range of ambient temperatures. Power consumption is typically about 0.6W. Physically small, the sensors are constructed by depositing a thick film layer of gas sensitive material onto an alumina substrate which incorporates a thick film heater. To give the gas response, the sensing chip is constantly heated to approximately 400°C.

An automatic building control system can be used to control the following passive measures in a museum:

- natural ventilation, including the opening and closing of high level vents e.g. atria vents, and air inlet vents; implementation of the fire control strategy
- night ventilation, including window opening and closing, and fan assisted cooling.

2.9.4. Building Energy Management Systems and Intelligent Component Design Performance Criteria

Pleasant environmental conditions are of fundamental importance when it comes to our sense of well-being in a building. These conditions do not always exist naturally. They need to be controlled and continuously monitored.

A efficient BEMS must be designed in compliance with economic criteria which set new standards for the future. Actuators are used to adjust mechanisms and operate switches.

Designers can use the list of do’s and don’ts (on the following page) as a quick reference tool in determining the correct application of a sensor. It should incor-porate an energy-efficient system which ensures that the amount of energy made available anywhere in the building is never more than is actually needed.

For a quick overview of the design process, the second chart illustrates the principal steps involved in developing and implementing an occupancy sensor application.

Do	Don't
Use ultrasonic sensors in areas screened by partitions or furniture	Use ultrasonic sensors in spaces with heavy air flow
Use PIR in enclosed spaces	Install ultrasonic sensors in spaces where the ceiling height exceeds 4 metres
Create zones controlled by different sensors to manage lighting in large areas	Use PIR sensors in spaces where there are fixtures or furniture that obstruct a clear of sight
Use dual technology sensors for areas with very low activity levels	Install PIR sensors so that their line of sight continues beyond doorways
Install sensors on vibration - free, stable surfaces	Install sensors within 2.5m of HVAC outlets or heating blowers
Position sensors above or close to the main areas of activity in a space	Control emergency or exit lighting with sensors
Mask the sensor lens to define coverage of the controlled zone even more accurately	Install PIR sensors in spaces where there are extremely low levels of occupant motion
Integrate sensor use with other control methods (i.e scheduled control, daylighting)	

When	What	Who
Design phase	Identify all control needs in the building.	Client and design team
	Identify set-point, tolerances, relevant technical norms and standards etc.	Client and design team
	Plan the daily operation of the building divided into manual operations and automated operations.	Client and design team
	Choose the most suitable control algorithms and choose parameters representing the values of desired set point as close as possible.	Design team and eventual BEMS consultant
	Identify critical parameters and set-points which have to be carefully analysed to identify relevant set-points and control algorithms.	Design team, especially the engineers and BEMS consultant
	Planning of alarms, reporting and documentation routines, with care on balancing the amount of alarms according to their impact on safety of the building and exhibitions and impact on comfort and energy consumption.	Client and design team
Tendering	Ensure specification of tendering documents to incule of service contracts where a certain amount of service hours should be included to be a competitive factor in the bid by the BEMS companies.	Engineers and eventual BEMS consultant
Commissioning	Make sure that the system really works in the specified way without exemptions before the system is accepted. Include in the contract a one-year service period to check the functionality under all climate conditions.	Client and design team

2.9.5. Results and Lessons Learnt with Respect to Building Energy Management Systems and Intelligent Component Design

2.9.5.1 Bardini Museum of Florence, Italy

In the Bardini Museum project, a BEMS has been used to regulate thermo-hygrometric conditions and daylighting control.

The control systems

The control system for optimised indoor climate for preventive exhibit conservation and user comfort will include:

- Temperature and Humidity sensors: these combine previous operational responses and current conditions to determine the optimum time for turning on the heating system in order to reach the desired indoor temperature at a specific time.
- Occupancy sensor: These are used to turn lights off when the space is unoccupied or periodically occupied. The most efficient type turns lights off when the room is unoccupied and leaves the occupant to turn the lights on if required, eliminating the possibility of the lights coming on by small movements, such as those caused by wind.
- Lighting sensors: Make it possible to keep the level of illumination in the room at the design level as daylight varies. It also provides for a considerable saving of electricity, longer life for lighting equipment and simple management of reserve lights.

2.9.5.2 Archaeological Museum of Delphi

The BEMS controls the operation of all major and auxiliary systems and features which affect the thermal and visual comfort as well as the indoor air quality of the building, such as daylighting, artificial lighting, automatic windows & blinds, ceiling fans, main A/C units, ventilation units, etc. and aims to optimise their energy and environmental performance.

- The control systems for artificial lighting: The artificial lighting in the various spaces of the building is controlled through several measures such as turning on or off of lights, adjustment of artificial lighting levels and antiglare panels in

Installation / System	Control points
Heating Boilers	Start / Stop Malfunction
A/C Chillers	Start / Stop Malfunction Water flow-rate
FCU, 3-Way Valves (winter/summer)	Motor-drive (ON / OFF) Malfunction
Circulators - Pumps	Start / Stop Malfunction
A/C Unit KKM-1	Start / Stop Inflow-air fan operation Return-air fan operation Return-air fan operation Humidifier valve 3-way valve servo / cold 3-way valve servo / hot Damper analogue servo in mixing box Malfunction, overload, filter change, etc.
A/C Units KKM - 2 / 3 / 4 / 5	Start / Stop Inflow-air fan operation Return-air fan operation Return-air fan operation Humidifier valve 3-way valve servo / cold 3-way valve servo / hot Damper servo (on-off) in fresh / recycled air mixing box Damper analogue servo in mixing box Malfunction, overload, filter change, etc.
Outdoor Conditions	Ambient temperature reading Ambient relative humidity reading
Alarms Panel	Status ON / OFF Malfunction
Fire Protection Panel	Malfunction 10 digital outputs from the A/C units (KKMs in case of fire problems)
Sewage Pumps	Status ON / OFF Malfunction
Automatic Blinds / Shutters (x20)	Start / Stop Adjustment with solar intensity Malfunction
Electrically Operated Windows (x16)	Start / Stop Adjustment with CO_2 concentration Adjustment with indoor temperature Malfunction
Artificial Lighting (12 zones)	ON / OFF Adjustment with illuminance levels Operation with presence detectors
Ceiling Fans (x18)	Start / Stop Malfunction
Electrical Panels (Low Volt.)	Status ON / OFF Current load (A) Voltage load (V) Frequency datalogging Cos Φ datalogging Electrical consumptions (kWh)

The controlled operations and check-points for the Delphi Museum, Greece order to program different "light scenarios" related to different users' environmental demands.

- Electrically operated blinds and shutters and automatic windows can control both the natural ventilation, as well as daylighting of the museum exhibition spaces. A number of electrically operated blinds shutters and windows have been installed. Their operation is achieved by switches or impulse relays installed in the distribution panels.
- Central A/C units automation:
  Each central A/C unit is linked to an electronic, programmable controller, which with the help of temperature and humidity sensors, adjusts the indoor comfort conditions in the museum spaces during the winter and summer periods as well as the inflow air temperature to the A/C units.

  The controller also automatically operates the bypass to the heat recovery unit during the intermediate seasons with simultaneous adjustment of the fresh and re-circulated air ratio up to 100%. Finally the starting up and operation of the fans is achieved through the controller. These controllers are directly linked to the central BEMS of the building, which also controls the operation of all the other main and auxiliary machinery (chillers, boilers, pumps, etc.).
- Start-up of chillers and boilers, operation changeover:
  The chiller start-up is carried out through a flow-switch in the water line of each chiller and an auxiliary contact-switch on each pump. Therefore each chiller automatically starts-up after its pump has been activated.

  The boilers start to operate when there is a heating demand in one of the zones. Again after the pump of the specific zone starts-up, it will be followed by the primary pump of the circuit and the main boiler itself. The auxiliary boiler will be automatically introduced into the heating action only if the temperature in the supply manifold, after a specific time interval, has not reached the desired level. In the same way the boilers will cut-off their operation, depending on heating demand, while the main circulation pump will stop running when the water temperature falls below 45°C.
- Ceiling fans:
  These will start automatically during the summer when the indoor temperature exceeds 29°C and will be turned-off when it drops below 26°C (with thermostat control), but also with confirmation by the presence detectors that there are people in the room. It's also possible to adjust speed of fan rotation.
- Forced ventilation system:
  The building demand ventilation system is controlled automatically for the specified air changes per hour (ACH), in order to maintain the indoor air quality to the desired levels together with the air conditioning plant and the natural ventilation (automatic windows) systems. The relative humidity, temperature and CO_2 concentration sensors in any space will increase or decrease (through the BEMS) the actual ACH in order to optimise the indoor conditions.
- Other building services:
  The BEMS controls not only the main services of lighting, shading, A/C and ventilation, but also supervises the operation of all the auxiliary E/M systems such as fire protection, security, sewage plant pumps, etc.

2.9.5.3 Slovene Ethnographic Museum

The total exhibition area of 2,884m^2 is divided into seven zones, the east wing of the ground floor, and east and west wings of the 1st, 2nd and 3rd floor, which are separately controlled by the BEMS.

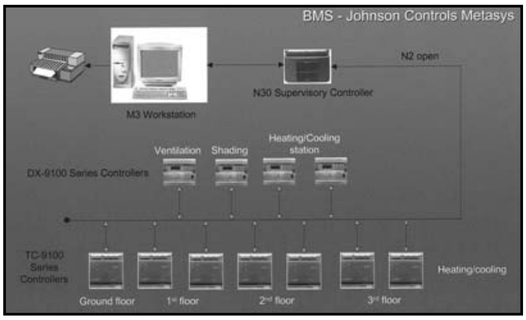


Diagram of the built-in BEMS in the Slovene Ethnographic Museum, Slovenia

- Heating:
  The heating wall system of the building is connected to the district heating system. It is divided into seven zones; the east part and west part of the building and each floor separately.

A temperature/time/season sensitive control system is designed to enable different set-point temperatures to be established during opening and non opening hours.

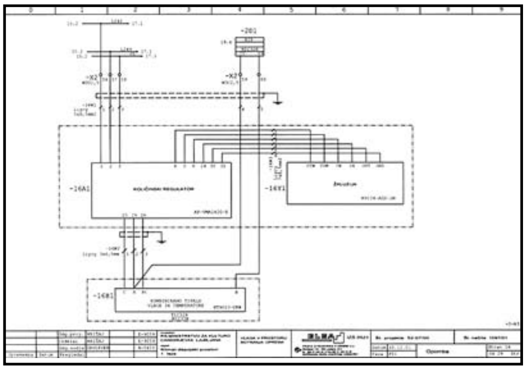
- Cooling:
  The wall cooling system is connected to a common cooling plant (McQuay AGF-XN 070.2, cooling power: 218 kW, electric 88 kW, 2 compressors, 4 steps (25, 50, 75, 100%)). Similar zones are used for cooling: the east and west of the building and each floor separately.

  A temperature sensitive control system is applied via ventilation and by the wall cooling system. The wall cooling system starts to work if outside conditions do not provide adequate ventilation. Both systems are linked and harmonised.

  The temperature/time/season sensitive control system is designed to enables different set-point temperatures to be used during opening and non-opening hours.

- Ventilation:
  Ventilation of 0.5-1.0 ACH during opening hours, and increased night ventilation during summer period are employed for cooling purposes.

  An occupancy/time sensitive system has been designed. It is linked and harmonised with night ventilation cooling.



Control within a narrow band

- Shading:
  This is organised in three separate, independent zones, depending on the orientation of the façade: south, west and east.

  An illumination sensitive control system is designed with manual regulation included.

- Data acquisition:
  The following data will be permanently collected by the BEMS: (in the following table)

Microclimate	
	Ambient air temperature
	Ambient air humidity
Energy Systems	
	Heating consumption (district heating each zone separately and total consumption)
	Cooling consumption (electricity)
	Lighting consumption (electricity)
	Total electricity consumption
Indoor Comfort	
	Indoor air temperature
	Indoor air humidity
	Lighting levels

2.9.5.4 Kristinehamn Museum of Contemporary Art, Sweden

The BEMS controls and monitors the operation of the heating, cooling, humidification, dehumidification, ventilation and energy use of the building. For indoor climate reasons the building is divided into two different zone: exhibition rooms and non-exhibition rooms. The BEMS is also used for detailed monitoring of the indoor climate and energy use.

The BEMS is a computerised building automation system. There are three direct digital controllers: one for the air handling unit for the exhibition rooms, one for the air handling unit for the non-exhibition rooms and one for the heating system. The controllers are connected to a central workstation. All the monitored data and the flow diagrams with instantaneous measured values, set points for temperatures, relative humidity, carbon dioxide, time schedules etc. can be accessed and downloaded via the Internet.

- Air handling unit:
  There are basically two different operational modes: stringent indoor climate requirements, when the indoor temperature and humidity has to be controlled and normal indoor climate requirements, when the only need is to maintain the temperature above a certain level.

  The set point for mechanical cooling was 21°C. The set point for preheating of the supply air is 16°C, unless cooling is required. Night cooling with ventilation is used to cool the building to 20°C.

  For indoor air quality the ventilation is demand-controlled using the CO_2 level. If the level exceeds 800ppm the ventilation rate is increased i.e. the amount of outdoor air is increased and the amount of return air is decreased.

The normal ventilation rate for the exhibition rooms is 1040 l/s, of which 200 l/s is outdoor air.

For normal indoor climate requirements there is no mechanical cooling, no humidification and no dehumidification. Night cooling with ventilation is used in the evening if the indoor temperature is higher than 23°C.

In both cases, the control system determines, when heating is required, and whether it makes sense or not to bring the outdoor air through the solar collector, for preheating purposes.

- Heating system:
  The set point for heating, with stringent indoor climate requirements, is 19°C. The temperature to the floor heating system is controlled as a function of the outdoor temperature, but adjustments are made to maintain the correct indoor temperature.

  For normal indoor climate requirements the set point for heating can be 21°C.
- Data acquisition:
  The following data are recorded and stored continuously:

Quantity
Outdoor environment
Solar radiation (global on horizontal plane)
Wind velocity and direction
Outdoor temperature
Indoor environment for representative rooms
Indoor temperatures
Relative humidity
Carbon dioxide
Energy use
Space heating
Space cooling (electricity)
Humidifier (electricity)
Hot water
Electricity for ventilation of the exhibition rooms
Electricity for ventilation of the non-exhibition rooms
Electricity for lighting
Electricity for pumps etc.
Total electricity
Contribution from solar collector
Efficiency of heat exchanger
Quantity
System operation
Air velocity and direction in passive stack
System temperatures
Floor heating
Radiator heating
Time schedules
Damper positions
Pressure drops
Rotational speed of fans

2.9.5.5 National Etruscan Museum ‘Pompeo Aria’, Marzabotto, Italy

The control strategy for this museum aims to regulate the indoor microclimate according to preventive conservation and human comfort requirements.

Indoor climate control is obtained by balancing the input of passive systems with active systems, optimising the building bioclimatic concept. This means that active systems have to be adjusted to allow as much as possible the energy contributions coming from solar radiation, (including daylighting and natural ventilation). The selected control systems are specific for each device according to actual needs.

- Heating system:
  The high efficiency condensing boiler has a dedicated control system based on climate control. Such control directly regulates the operation time and water temperature using modulating gas flame controls. Each climatic zone has a thermostat connected to electric (on-off) valves which control indoor temperature according to the set point.
- Ventilation:
  The new exhibition area and multimedia room have a dedicated system for ventilation. The system aims to guarantee indoor air quality and to perform some night ventilation and free cooling during intermediate seasons. Air quality is controlled by CO_2 sensors and a timer, while ventilation has different settings according to day and night and season.

  During the summer and intermediate seasons, free cooling and night ventilation depends on a temperature control system. Indoor and outdoor temperatures are measured and processed depending on the indoor set-point temperature. If indoor temperature is greater than outdoors and if the indoor temperature is greater than the set-point, the ventilation system starts. During visiting hours, ventilation is reduced in order to control air speed while ventilation is increased during the night.
- Artificial lighting:
  Lamps in the circulation spaces are controlled by illuminance sensors which turn on lights according to daylight availability. Infrared sensors inside the museum detect people and turn on the showcase lighting system. This

control both saves electricity and preserves the exhibits from light deterioration.

- Security sensors:
  For security control, fire alarm and smoke detection systems are installed in every exhibition room.

3.1 ARCHAEOLOGICAL MUSEUM OF DELPHI, GREECE

3.1.1 Project Background

Delphi was one of the most important places in ancient Greece, famous for its oracle. The Greeks considered Delphi to be the navel, “Omphalos”, of the earth.

Location of Delphi

The Archaeological Museum of Delphi, situated next to the archaeological site, is one of the most important museums of the country. Every year more than half a million visitors from all over the world visit the museum and over 2,500 visit on a peak day.

Due to the museum's significance its retrofitting is expected to have a great dissemination value.

The existing museum was built in phases:

- The original building in a classical style was designed in 1903 by the French architect Tournaire.
- A first modification was built in 1935 that introduced elements of the modern movement (deformation of symmetry, ribbon windows).
- A second modification extension was designed in 1958 by the Greek architect P. Karantinos. This introduced a complex section shape in order to admit daylight.
- A third modification-extension in 1985 was designed by A. N. Tombazis and Associates, construction of which was completed in 2000. It incorporates a new linear building in front of the existing one which houses the administration on the ground floor and the entrance lobby on the first floor. A new volume was added for the Statue of the Charioteer at the south end of the museum. Special attention was given to the daylighting strategy of the new hall: a central lantern roof-light and vertical slits at the side walls were constructed. At the north side, a new one-storey wing was added containing public amenities, storage and a laboratory. An elaborate system of ramps was created to better connect the museum to the archaeological site and enable easy access for a large number of visitors. The façade of the extension and the eastern parts of the existing building were clad in a light beige coloured sandstone.

New Charioteer Hall

External view of Delphi

- A fourth modification was constructed in 2003 in the framework of the current project, designed again by A. N. Tombazis and Associates. It included the retrofitting of the main exhibition space (1,150m^2). The museum today has a total area of 2,500m^2 on two levels.

3.1.2 The Building Before the Interventions

The conditions in the existing museum were studied extensively in two projects funded in part by the European Commission:

- the JOULE III project "Retrofitting of Museums for Antiquities in the Mediterranean Countries" (1995-1998) and
- the SAVE II project "Guidelines for the Design and Retrofitting of Energy Efficiency Museums for Antiquities in the Mediterranean Countries" (1998-1999).

The research and the documentation realised in the framework of the above projects showed that the building provided inadequate conditions for visitors and staff in terms of:

- air quality,
- thermal conditions (summer spot measurements of up to 32°C peak indoor air temperature),
- visual comfort (problems of glare and uneven distribution of light),

Hall VI before the retrofitting action

- acoustic comfort (peak background noise levels of the order of 70 dB and reverberation times between 5 and 7 seconds),
- heating and ventilation systems that were unable to follow the high fluctuations in the number of visitors,
- inefficient use of energy through outdated equipment (practically no control and bad maintenance) and
- inadequate spatial organisation for the high numbers of visitors (congestion and discomfort).

3.1.3 Architectural Interventions and Construction Materials

The retrofitting works that took place under the current project aimed to integrate bioclimatic and sustainable measures in the existing (old) exhibition halls. The good passive properties of the old building have been enhanced.

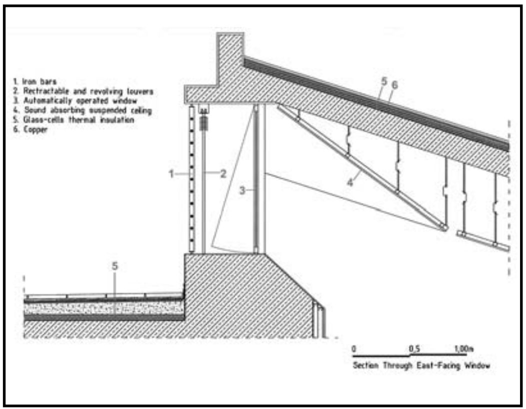
The massive stone, brick and concrete structure of the building has been insulated externally with 5cm of extruded polysteryn or glass foam boards in order to reduce thermal losses during winter and help avoid overheating during summer.

The original building had adequate openings for daylight and natural ventilation. However, in many cases their design and position was not appropriate causing serious glare and overheating problems. For this reason the openings were redesigned (see 'Daylighting' on following page).

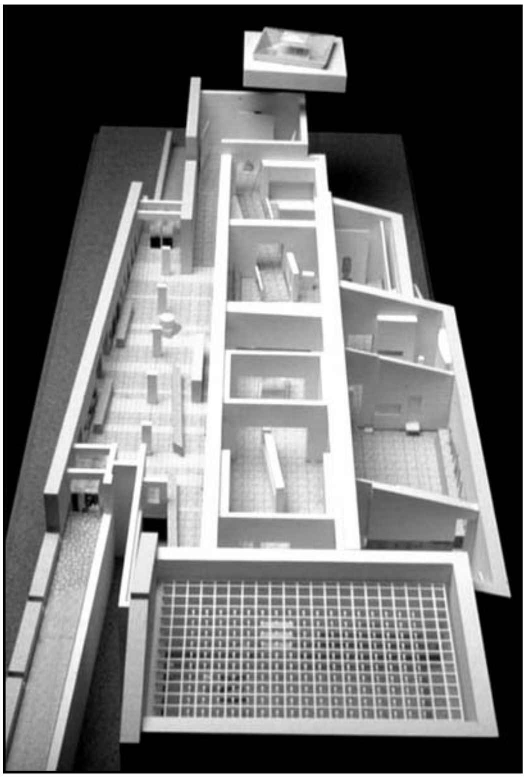
All windows have been replaced with new double glazed ones, about 50% of which are automatically operable (through BEMS control) for natural ventilation purposes. External shading was applied. A new roof was constructed for Hall V (Siphnians) with controlled penetration of daylight.

Hall V (Siphnians)

The existing tiles of the inclined roofs were replaced by a copper cladding to better blend visually with the adjacent landscape.



New openings between the halls have been constructed to facilitate the flow of visitors and to avoid congestion. In addition, a new exhibition layout has been developed which conforms with present-day exhibition requirements.



3.1.4 Elements of the Environmental Design and Innovations

In addition to the architectural interventions, a number of other measures have been applied to minimise energy consumption, and help improve comfort and exhibition quality in the museum.

3.1.4.1 Daylighting

Daylight analysis and simulations have been carried out in the framework of the JOULE III programme "Retrofitting of Museums for Antiquities in the Mediterranean Countries. Case study: The Archaeological Museum of Delphi". Problems were indicated and several suggestions were made. The building had adequate openings for daylighting and ventilation, however in many cases their design and position was not appropriate causing serious glare and overheating problems.

The final design of the windows, roof-lights and the shading system was executed within the MUSEUMS project.

Specific daylighting simulations were undertaken for three typical halls (XI, VI-VIII, V) and final design solutions were applied as follows:

Hall XI (Daochos)

Hall XI

- Blocking of existing low, east-facing windows.
- Opening of a new west-facing clerestory.
- Provision of external shading to the high, existing east-facing windows.
- Proposal for the replacement of part of the suspended ceilings with reflective ones to optimise the daylight distribution.

Hall VI (Apollo)

Halls X, VI, III, IX, VII, II

- Provision of external shading to the existing east-facing windows.

Hall VIII

- Opening of new west-facing clerestories.

Hall V

- Replacement of the shallow pitched glazed roof with a new glazed one with external louvers for shading. The louvers regulate the transmittance of direct radiation and allow only indirect light to enter the hall.
- An egg-crate structure was suspended from the ceiling acting as a diffusing device for incoming daylight and sound.

3.1.4.2 Artificial lighting

Replacement of all lighting and electrical installations.

Low energy fluorescent lamps are used for general illumination while for special daylighting solutions (simulating illumination from skylights), metal halide lamps have been used.

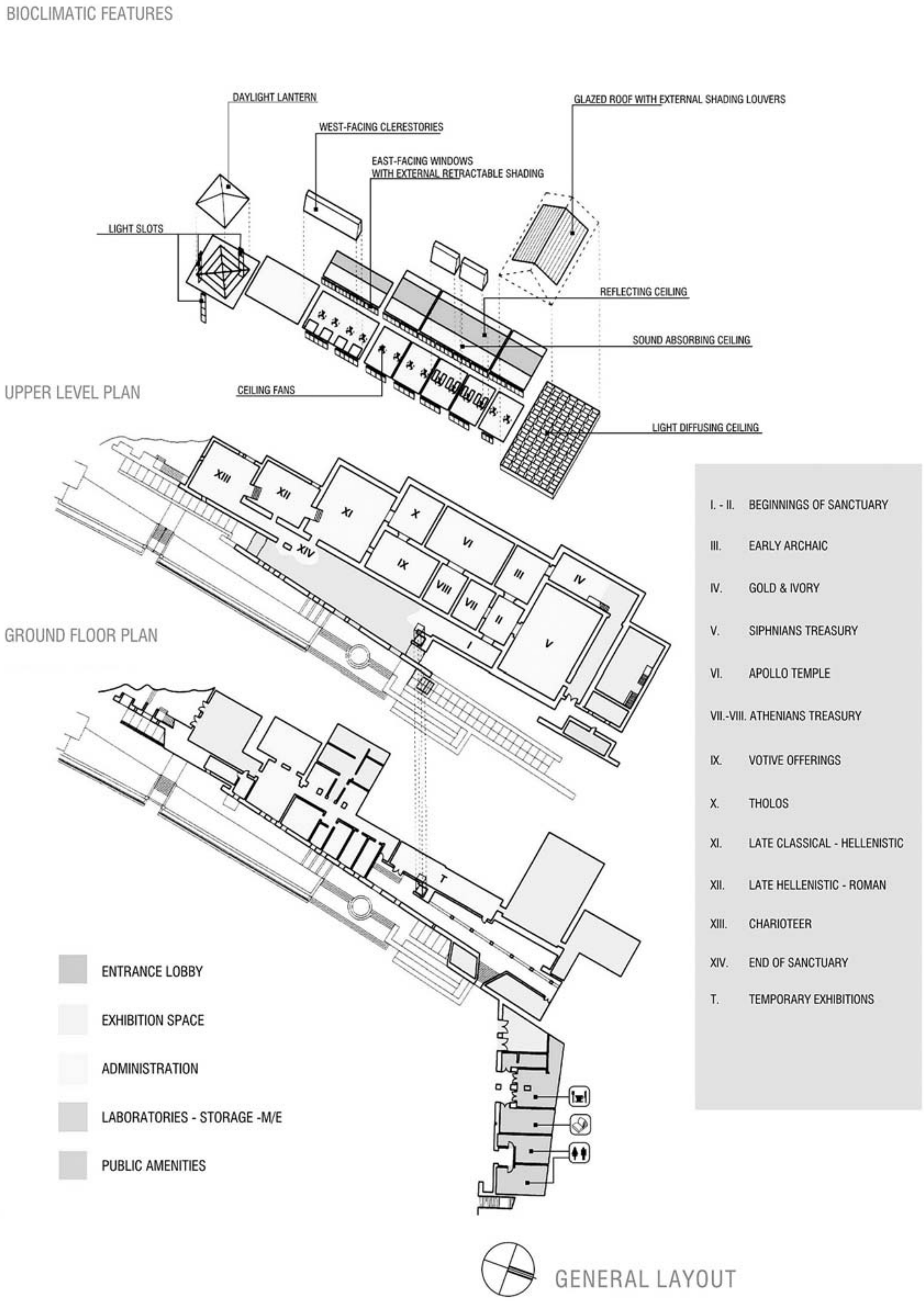
High efficiency luminaries (100 lumen/W) and high frequency (HF) ballasts have been installed. Daylight compensation and optimisation is achieved through BEMS control.

After the application of the following measures:

- use of high efficiency luminaries,
- HF ballasts,
- fluorescent metal halide lamps and
- daylighting techniques

the energy requirements for lighting were simulated and showed a reduced volume of 47.3 kWh/m^2 which results in energy savings in the range of 60%.

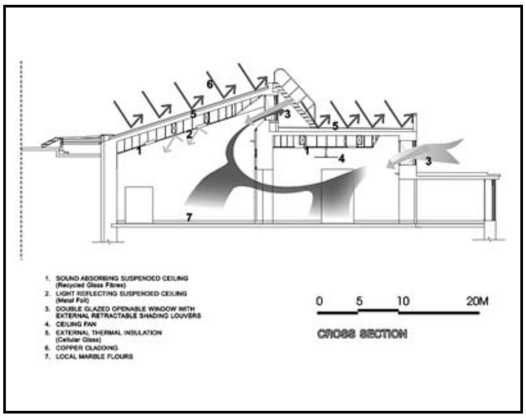
External View of Delphi


BIOCLIMATIC FEATURES
DAYLIGHT LANTERN
WEST-FACING CLERESTORIES
EAST-FACING WINDOWS WITH EXTERNAL RETRACTABLE SHADING
GLAZED ROOF WITH EXTERNAL SHADING LOUVERS
LIGHT SLOTS
REFLECTING CEILING
SOUND ABSORBING CEILING
CEILING FANS
LIGHT DIFFUSING CEILING
UPPER LEVEL PLAN
GROUND FLOOR PLAN
XIII
XII
XI
X
XIV
VI
IX
III
IV
VIII
VII
II
I
V
T
I. - II. BEGINNINGS OF SANCTUARY
III. EARLY ARCHAIC
IV. GOLD & IVORY
V. SIPHNIANS TREASURY
VI. APOLLO TEMPLE
VII.-VIII. ATHENIANS TREASURY
IX. VOTIVE OFFERINGS
X. THOLOS
XI. LATE CLASSICAL - HELLENISTIC
XII. LATE HELLENISTIC - ROMAN
XIII. CHARIOTEER
XIV. END OF SANCTUARY
T. TEMPORARY EXHIBITIONS
ENTRANCE LOBBY
EXHIBITION SPACE
ADMINISTRATION
LABORATORIES - STORAGE -M/E
PUBLIC AMENITIES
GENERAL LAYOUT

3.1.4.3 Acoustics

The existing suspended ceilings were replaced in all exhibition spaces by new ones made of recycled glass fibre, with the advantage of maintaining the required light reflectivity.

3.1.4.4 Thermal and air flow systems



The existing air-conditioning system has been removed and a new air-to-air HVAC system has been installed. The new system is equipped with heat recovery to minimise energy consumption.

A hybrid ventilation system has been installed consisting of automatically operable windows that are opened and closed according to the ventilation demand and the demand-controlled HVAC system that only operates when heating or cooling becomes necessary.

Automatically controlled ceiling fans have been installed to minimise the use of the HVAC system. By using ceiling fans, the summer cooling set point of the HVAC system is increased from 26°C to 29°C resulting in considerable energy savings.

Night ventilation techniques through automatic openable windows have been applied to cool down the building's thermal mass.

All systems are controlled by an advanced Building Energy Management System that controls air-conditioning, heat recovery, demand control ventilation, night ventilation, ceiling fans, lighting levels, shading devices, fire protection and security.

3.1.5 Exhibits

All the exhibits in the Archaeological museum of Delphi are objects from the adjacent archeological site. The majority of the objects are marble statues, metopes and pediments etc. The most famous exhibit of the museum is the Charioteer, which was part of a bronze group.

There are also bronze, gold, ivory and silver objects from offerings to the Delphi Sanctuary.

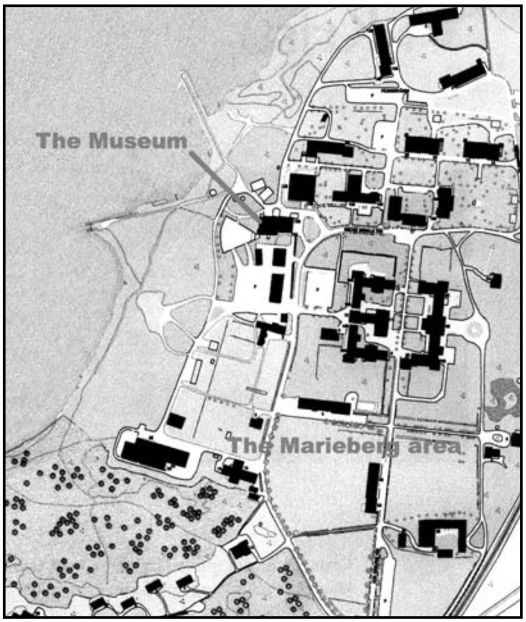
3.2 KRISTINEHAMN MUSEUM OF CONTEMPORARY ART, SWEDEN

3.2.1 Project Background

Kristinehamn is a city of 25,000 inhabitants, located in Sweden on the shores of the Lake Vanern at latitude 58°.

The city is, among other things, famous for hosting one of the largest statues of Pablo Picasso, which overlooks the lake.

Marieberg, north of Kristinehamn was once a large hospital with more than one thousand employees. The magnificent 18th Century brick buildings, located in beautiful parks, now stand empty as a result of a major reorganisation of Swedish health care system during the 1980s. The area is now being converted to a modern centre for arts, culture and business.



The Marieberg district showing the location of the museum

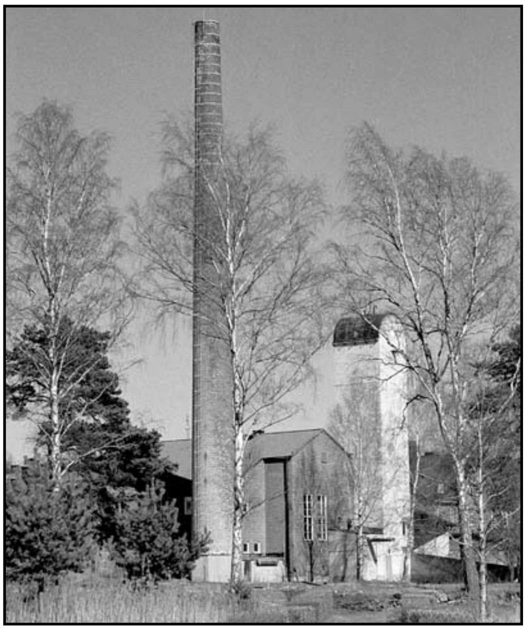
The old hospital buildings in Marieberg

3.2.2 The Building Before the Interventions

The Museum building was once an old charcoal plant which was used to heat the hospital. It was closed when Marieberg was connected to the city's district heating system and has now been converted to a museum of contemporary art.

Before renovation

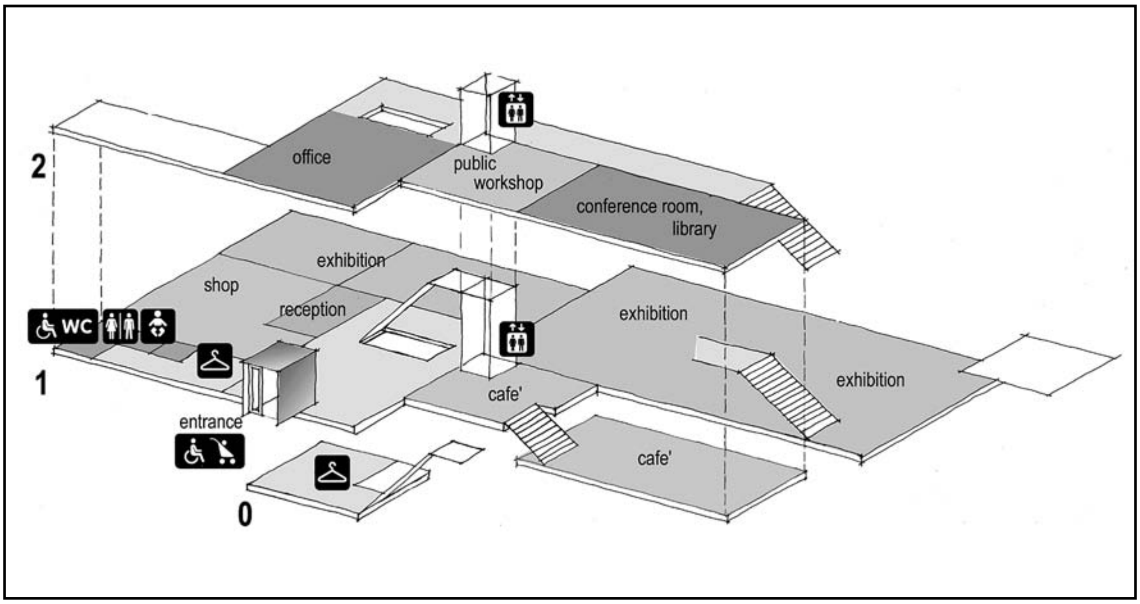
Before the renovation, the building was in a very poor condition but the building form of the former boiler halls was very well suited for conversion to an exhibition space.



The charcoal tower seen from the pier in Lake Vanern

3.2.3 Architectural Interventions, Design and Construction Materials

The former heating plant has been renovated for museum purposes and holds three exhibition rooms, coffee and museum shops, reception, creative workshop, library, conference room and office and staff spaces.



Layout of the building

Exhibition hall

Stairs

The floor and ceiling, as well as certain outside walls of the building, have been insulated. The inside pane of glass of the existing and old windows has been replaced with a heat reflecting energy-efficient one. An advanced control system has been installed to help optimise the heat and ventilation system.

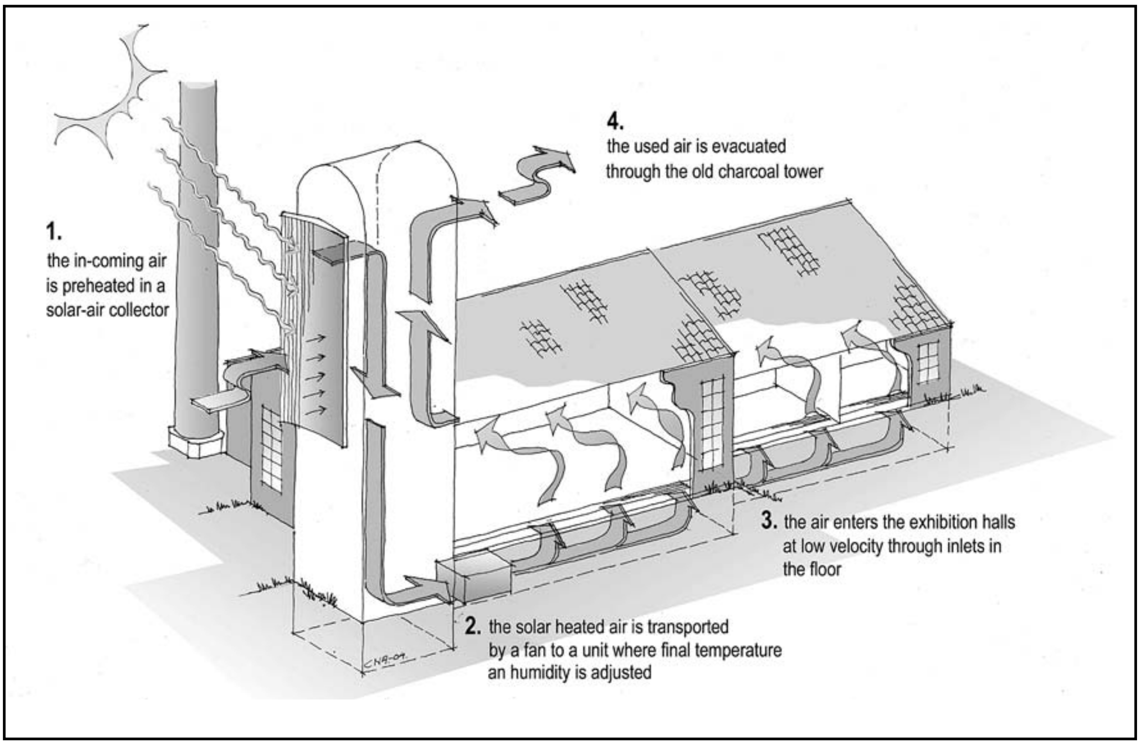
Reception

Natural and local material such as wood are used for construction and floor finishes in the exhibition halls. The entrance area and the museum shop floors are finished in Swedish polished stone.

Shop

View of the lake from the museum café

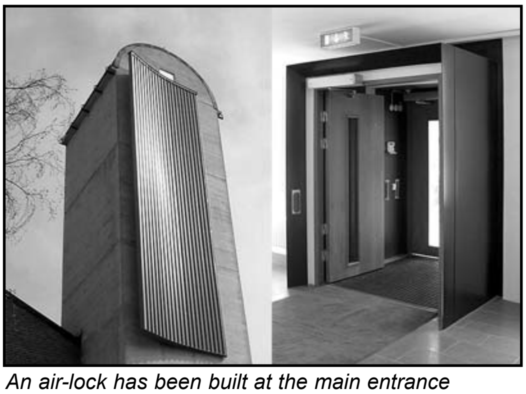
3.2.4 Elements of the Environmental Design and Innovations



Heating and cooling strategies

3.2.4.1 Air solar heating and hybrid ventilation

The fresh air for the exhibition rooms is preheated by an air solar collector placed on the south façade of old charcoal tower. The solar collector is unglazed and of a so-called ‘free flowing’ design where the fresh air passes through small holes in the absorber plate. This gives high heat transfer and efficiency. The solar heated air is supplied by fans to the exhibition rooms via valves in the floor and is finally evacuated naturally through the old charcoal tower. Thus the exhibition rooms have hybrid ventilation which is demand controlled (CO_2). Other spaces have been equipped with mechanical ventilation with modern, efficient heat recovery.



An air-lock has been built at the main entrance

Daylight control

3.2.4.2 Optimisation of daylighting

A new solar shading system in combination with UV-filtering window glass has been installed to utilise as much daylight as possible and at the same time protect the objects of art against UV-radiation.

3.2.5 Exhibits

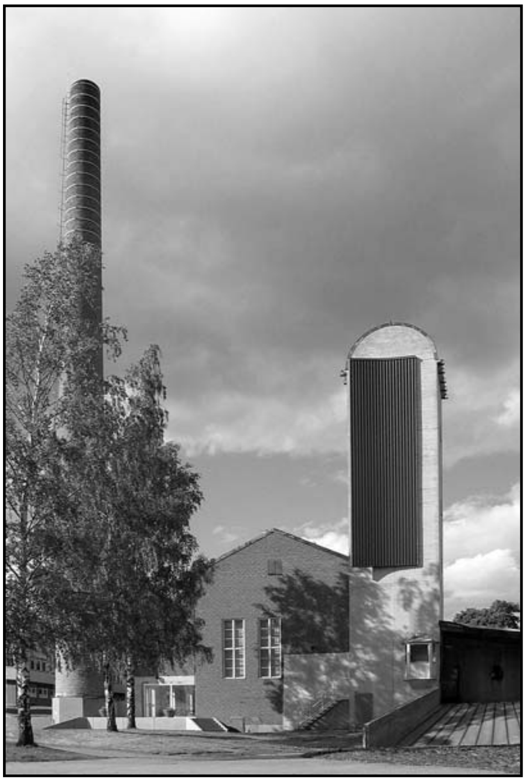
The building is a museum of contemporary art and is mostly used for temporary exhibitions including paintings, sculptures and other installations. The building was inaugurated in April 2003 with the exhibition “Picasso and the Public Space”.

Picasso exhibition

3.2.5.1 Security and indoor climate

The building meets the highest security requirements which gives unlimited possibilities to host valuable exhibitions. The indoor climate can meet all the demands of modern exhibitions with regards to daylight, temperature and humidity control.

For the most stringent requirements e.g. 19-21°C and 43-47% RH, there is a back-up mechanical system for cooling, humidifying and dehumidifying. These requirements are rarely applicable.



The completed museum

3.3 HERZOG-ANTON-ULRICH MUSEUM, BRAUNSCHWEIG, GERMANY

3.3.1 Project Background

Location map of Braunschweig

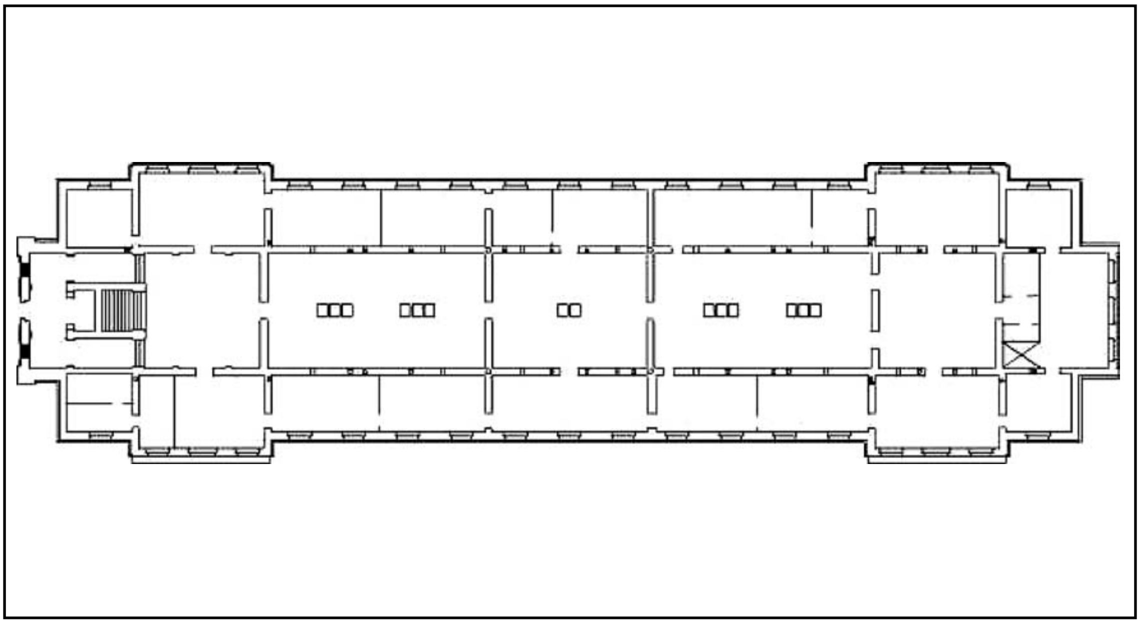
The Herzog-Anton-Ulrich Museum in Braunschweig is among the great German art museums and probably the most important in Northern Germany. The Building construction began in 1887 to the plans of architect Oskar Sommer (1840 - 1894). It accommodates one of the largest and oldest art collections in Germany consisting mainly of paintings from the 15th to the 19th Centuries. It is as representative of a set of typological gallery buildings, as they were built in many European cities at the end of the 19th Century. Hardly damaged in the Second World War, the first renovation of the technical equipment took place in 1950. Within this renovation, the historical ventilation system among other things was shut down. In 1975 the equipment of the museum was adapted again to provide a state of the art museum at that time. However, the solid structure has remained unchanged. An extension is planned, but the commencement of construction has not yet been specified, for financial reasons.

3.3.2 The Building Before the Interventions

The three storey sandstone building accommodates sculptures and paintings. The net floor area amounts to 6,300m^2. As well as the exhibition spaces, rooms for administration, workshops and stock rooms are included. The approx. 100m long and 25m wide structure consists of up to 1.4m thick walls made of natural stone and brick. The timber beam floors and steel roof structure are original.

In the dialogue between the architect and the director of the museum Hermann Riegel (1834-1900) during the design and construction phase, a particular concept was developed. The incidence of natural light from the northern side, the avoidance of direct sunlight on the pictures in the gallery halls and the absence of reflections from other buildings indicates the knowledge about museum buildings that the design team had. The basement served mainly as a store and for technical purposes, while on the ground floor suitable lighting conditions permitted its use for administration and parts of the exhibition. The two upper floors contain the main exhibition areas of

Aerial view of the Museum. Source: Prof. Gockell



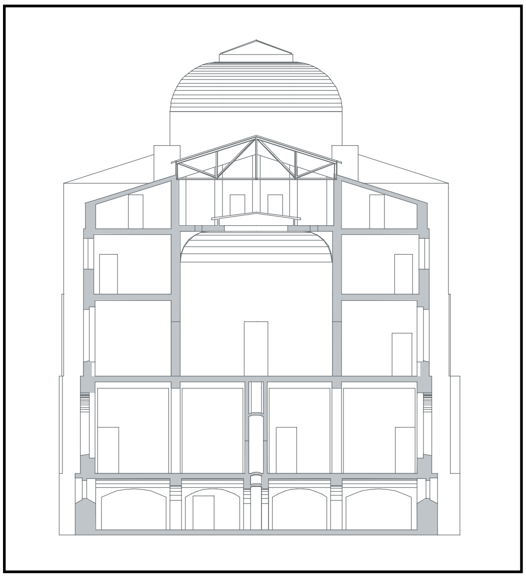
Floor plan of the Herzog Anton Ulrich Museum (1st Floor)

the museum. Four large skylight halls are surrounded by two cabinet floors. Box windows on the south side, an integrated ventilation system, and the thermal inertia of the construction provided a constant indoor climate, which was suitable for the keeping of the exhibits.

3.3.3 Architectural Interventions and Construction Materials

Nearly 30 years after the last significant retrofit, a comprehensive renovation of the building was proposed to meet today's needs. Mindful of today's climate of energy-efficiency and the development of sustainable solutions, it is proposed that the energy consumption of the building be lowered while comfort and an optimal interior climate is maintained. The German government proposes the adherence to threshold U-values for existing buildings in the case of renovations in the "Energieinsparverordnung". Because it concerns a historical monument, these requirements must be balanced with the preservation of the buildings, the improvements of thermal and visual comfort and reduced energy consumption. In order to reduce transmission losses, insulated plaster was applied to the inner surface of the outside walls, following interstitial condensation analysis. New glazing (solar protection glazing, energy transmission rate g = 0.34, light transmission factor t = 0.66) with an U-value of 1.1W/m²K, and new internal window frames with improved thermal protection replace parts of the old box windows. This also helps improve the air tightness of the building envelope and therefore, the integration of a mechanical ventilation system is necessary.

During the analysis of the building, the presence of existing ventilation shafts and channels were detected. It was proposed to reuse these for a modern ventilation system instead of installing new ducting into the building. The possible air change rate, the mean air 'age' and thermal comfort were examined by modelling the operation of the existing ventilation shafts and channels with CFD Simulation. The simulation confirmed the potential of the existing shafts and channels.



Cross section of the Herzog-Anton-Ulrich Museum (IGS)

3.3.4 Elements of the Environmental Design and Innovation

A new shading system was mounted within the box windows to improve the visual comfort, which provides better daylight in the exhibition rooms and reduces heat gains and cooling loads. Furthermore, the paintings are protected from irradiation especially within the UV-spectrum. The Hueppe system selected is similar to the existing louvre blinds in the museum and consists of concave louvres. It differs in being divided into upper and lower sections. The louvres in the upper section are mirrored on the upper side while the lower section louvres are painted grey on both sides. The two sections are linked together so that the upper section is always more open and can not be totally closed like the lower part. The bottom part of the blind is generally closed, while the top part reflects light onto the ceiling.

In addition, the installation of a new artificial lighting system will lead to a reduction in the electrical demand for lighting. The operation times will be determined by daylight availability to minimise electrical consumption and artificial light irradiation on the paintings as much as possible. Furthermore an improvement in the illumination of the paintings on the wall will be achieved by reducing glare.

3.3.5 Exhibits

The collection of the Herzog Anton Ulrich Museum is the oldest publicly accessible art collection in Germany and one of the oldest in the world. The quality and richness of the exhibits is traced back to the collections of the Dukes of Braunschweig. Sculptures and arts-and-crafts of the Renaissance and Baroque periods are presented beside smaller works of antiquity and non-European art. The extensive gallery exhibits works of less well known masters beside better known artists such as Cranach, Holbein, Rubens or Vermeer. Worthy of mention are the collections of French enamelled painting and the considerable collection of East Asian lacquered works.

The collection is rather heterogeneous, from a conservational view consisting of oil paintings on wood and canvas, copperplate engravings and lithographs and porcelain art as well as sculptures of stone, bronze and ivory. Each material has its own conservational requirements, although a


Dust roof


Skylight hall


North cabinet


Foyer

uniform climate is applied throughout the entire exhibition, which also takes account of the thermal comfort of visitors.

New artificial lighting system

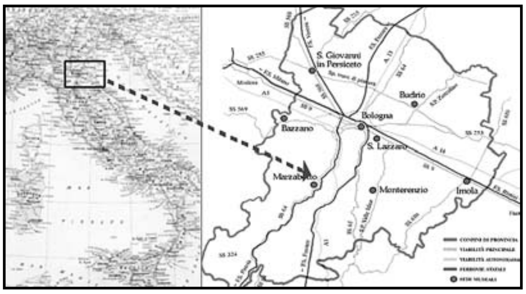
External view to the testrooms

3.4 NATIONAL ETRUSCAN MUSEUM 'POMPEO ARIA', MARZABOTTO, ITALY

3.4.1 Project Background

Italian museums are frequently located in ancient buildings of monumental and architectural importance. The introduction of mechanical and artificial systems to control the indoor micro-climate is often undertaken in museums that do not have satisfactory indoor climate control, especially from the exhibit conservation point of view. Heating and cooling systems do not normally optimise the potential of passive building measures, which can contribute significantly to internal and external climate control. Ignoring this important aspect in sizing and defining the "operational model" for artificial systems can result in high energy consumption and poor indoor environmental quality. The National Etruscan Museum 'Pompeo Aria' in Marzabotto is representative of this recurrent situation.

The museum is located beside an Etruscan settlement of the 6th Century B.C., close to Marzabotto (Bologna). It belongs in the small/medium sized museum category (850m^2) which is very typical for Italy. Such museums are usually publicly owned and generally host exhibits from archaeological sites. In many cases their indoor environmental quality and the energy performance are poor.



Location of Marzabotto, Italy

3.4.2 The Building Before the Interventions

The museum complex can be divided into three different sections that are partially connected.

The first building is a two story square building constructed at the end of the 19th Century that has its main entrance and an exhibition space on the ground floor with a caretaker's flat above. Close to this building is a long and narrow one (an extension of 1958) which is oriented north-south with an arcade on its western façade that is used to exhibit some archaeological pieces. To the South is another long building (an extension of 1979) that, at the beginning of the project, housed toilets, a boiler room and small warehouse. During renovation, this building was demolished and a new exhibition space was constructed. Close by is a small building housing a cafeteria, while some offices and new storages are located in an old, adjacent rehabilitated barn.

View of the museum during the construction of the new exhibition hall

The analysis that was performed has underlined the need for a complete reorganisation of the museum and for a major reduction in energy consumption. This will be considered in the extension of the exhibition area together with the thermal, daylighting and acoustic design of the retrofit. The extension of the museum carried out in 1950s has no insulation in its walls and roof and has a very low thermal inertia by comparison with the older part of the museum.

The heating system comprises radiators with no specific design for microclimate control, and therefore does not satisfy exhibit conservation requirements. In fact, some radiators are located directly under the showcases causing great damage to the exhibits due to thermal stress and uneven temperature distribution.

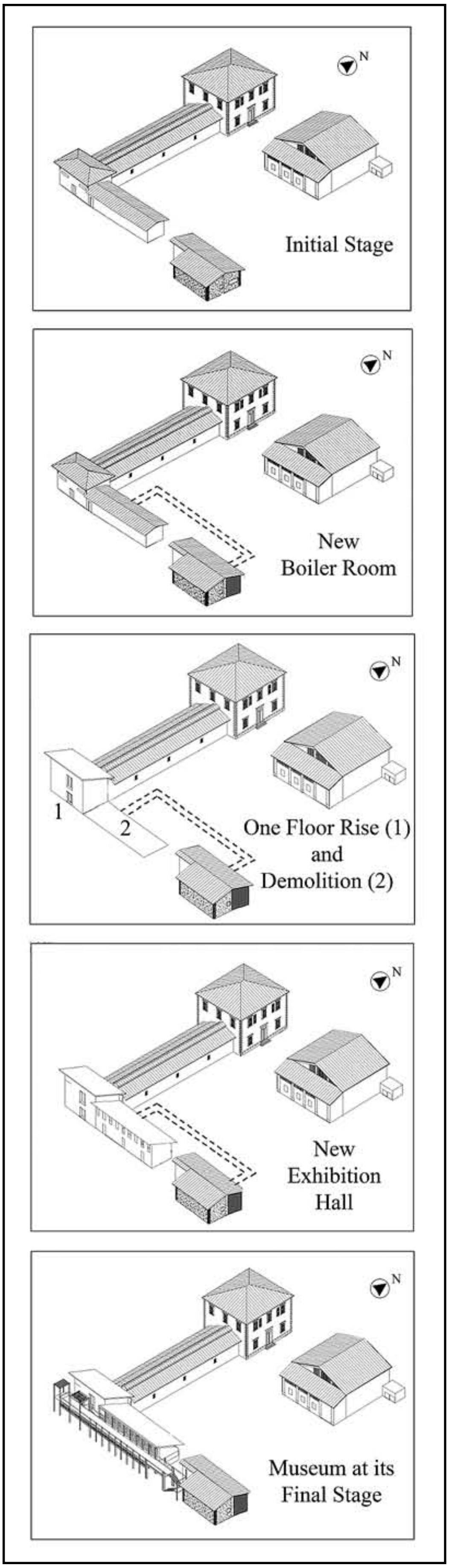
The lack of solar shading devices on the skylight in the exhibition spaces increases internal gains in summer and adds to the cooling load.

The monitoring that was performed shows the problems related to indoor climate.

Indoor view of the existing exhibition of the National Etruscan Museum 'Pompeo Aria' in Marzabotto

3.4.3 Interventions and Construction Materials

A sustainable approach has been applied to the extension and retrofit project for the museum based on common-sense and responsible use of energy resources and environmental conservation. The solutions proposed for the project have been investigated during the implementation of two other projects carried out in the framework of EC Programmes on energy savings: "Retrofitting of Museums for Antiquities in the Mediterranean Countries" - JOULE III Project (ct. JOR3-CT95-0013) and "Guidelines for the design and Retrofitting of Energy Efficient Museums for Antiquities in the Mediterranean Countries"-SAVE II Project (ct. XVII/4.1031/Z/97-086) in which the museum itself was a case study. This project focuses on balancing bio-climatic and passive solar techniques with the operation of active systems, to create adequate climate and environmental conditions for preventive conservation and to offer a good indoor climate to visitors and workers saving energy.



Original state and construction phases

From a functional point of view, the target is to combine the three distinct buildings into one single museum in which it is possible to both visit the interior halls and view the archaeological site. For this reason, the link with the outside is designed to provide a good view of the archaeological area while at the same time providing outdoor exhibition spaces. The walkway brings visitors from the inside to the outside so that they can experience the ancient village after admiring the Etruscan masterpieces that were found in it. The totally rebuilt exhibition hall faces south. The southern façade is protected over its length by a timber balcony which has specific solar control functions. The balcony also provides an excellent viewing area for visitors who wants to have an overall view of the area, while moving towards the multifunction room located at the upper level of the corner building. The new exhibition hall is divided into three northern exhibition spaces by heavy mass walls and show cases. A south facing circulation area links them. The exhibition and circulation spaces have different requirements. While the exhibition rooms need a stable and controlled climate with uniform, reduced daylight levels, the corridor allows more variation in daylighting to create a visual and link with the outside through the view.

The selection of technologies and materials has considered the environmental consequences associated with the acquisition, transportation and manufacture of materials prior to construction and the health effects for inhabitants in the form of emissions of noxious substances from building materials. The final selection also reviewed locally produced materials to reduce transportation energy use and environmental impact, and those materials that could be re-used or re-cycled at the end of their use.

Retrofitting design hypotheses were verified with simulation tools to compare different strategies and perform cost benefit analysis.

3.4.4 Elements of the Environmental Design and Innovations

3.4.4.1 Thermal control

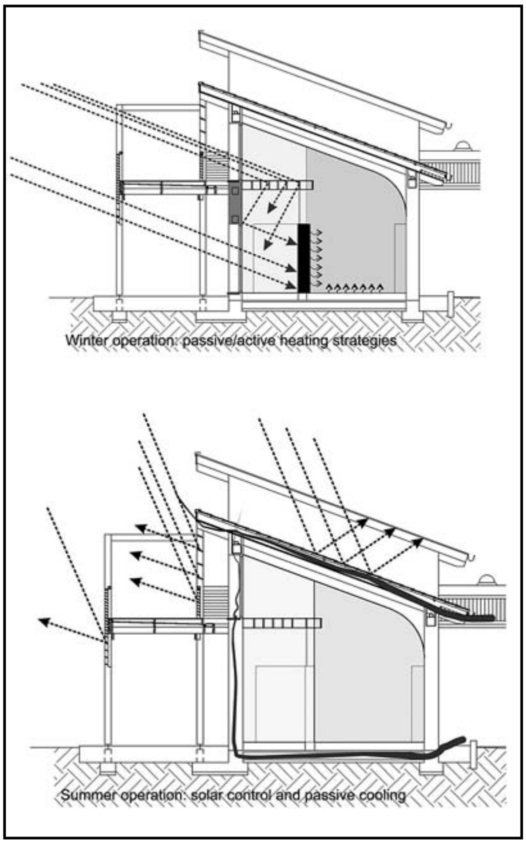
Passive techniques have been applied in this bio-climatic design enhancing both solar access and reducing heat losses through the envelope during winter and controlling solar gain in summer.

In the new exhibition hall and the multifunction room, this strategy is applied by the correct placement, sizing, and orientation of the glazed surfaces together with fixed external shading placed outside the openings and connected to the wooden balcony. This horizontal shading controls the solar radiation throughout the year according to indoor micro-climate and energy savings requirements. To avoid summer over-heating, the roof slope faces to the north. The walls have high thermal mass and insulation. The incoming air provides good cross ventilation, and openings in the roof provide stack-effect ventilation.

Air extractors equipped with fans and a specific control system supply night ventilation during the summer, free cooling during intermediate seasons and air changes as required.

The provision of solar radiation control, high thermal mass, a ventilated roof and night ventilation avoid the necessity for an air conditioning system.

The heating system consists of underfloor radiant panels, with low temperature water supplied by a high efficiency condensation boiler.



Solar control in the new exhibition hall

3.4.4.2 Daylight

On the south-facing façade, the external shading device regulates interior daylight. The device is combined with internal blinds in order to diffuse sunlight.

The solar shading device protects the glazing from summer radiation. In winter, the system admits solar gain and allows natural light control. The walkway has higher illuminance levels because of openings towards the archaeological site and has daylight redirecting systems in the space.

Internal walls control daylight, reduce glare and help provide a comfortable visual environment.

The artificial lighting system responds to daylighting levels and the presence of visitors.

3.4.4.3 Control systems

Indoor climate control is obtained by balancing passive strategies with active systems, emphasising the bioclimatic concept. Active systems are adjusted in order to take as much advantage as possible of the passive energy contributions including solar radiation, daylighting and natural ventilation.

Each climatic zone has a thermostatically controlled indoor temperature according to its set point.

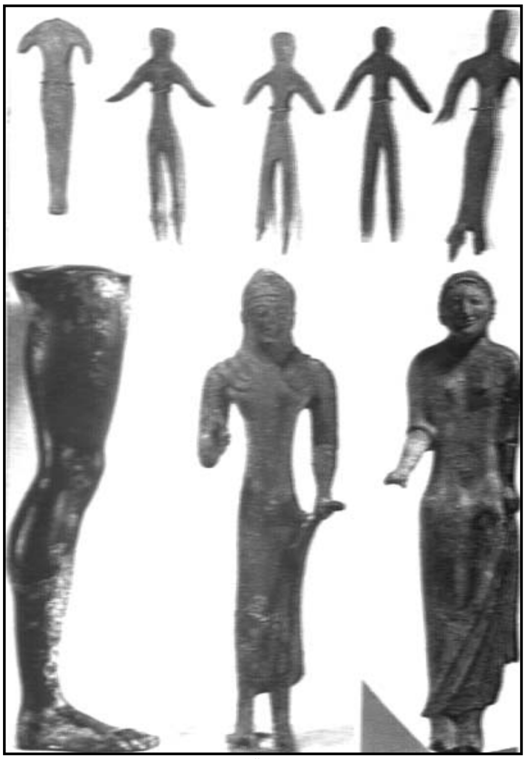
The ventilation system is controlled both by CO_2 sensors for air quality and by indoor / outdoor temperature sensors. Sensor control, together with an air change timer control, allow free cooling when appropriate and night ventilation is used during the summer.

Illuminance sensors control the lights In the circulation spaces according to daylight availability.

Infrared sensors inside the museum detect the presence of people and turn on the showcase lighting.

3.4.5 Exhibits

The artifacts exhibited in the museum come from the adjacent archaeological site. Exhibits are of natural stone, marble, travertine, sandstone, amber, alabaster and terracotta. Metal exhibits are of bronze, iron, lead, silver and gold. The museum also hosts some exhibits of organic origin (mainly bones). Exhibits and archaeological finds are very important because they provide a lot of information on the industrial activities of the Etruscan civilisation. Exhibits do not have any strict climate requirements from a conservation point of view.



Bronzes on display in the “Pompeo Aria'” Museum

New exhibition hall

3.5 THEpUBLIC ARTS CENTRE, WEST BROMWICH, UNITED KINGDOM

3.5.1 Project Background

THEpUBLIC Arts Centre is a ground breaking concept in community arts, education, entertainment and urban regeneration in the centre of West Bromwich, Sandwell.

Site plan of THEpUBLIC Arts Centre, West Bromwich

Map of the country with the indication of the area

The building will be a stunning, modern, flagship building containing six stories (11,000m^2) of exhibitions, digital art, hands-on displays, creative studios, multimedia and technology production facilities, education and training resources and performance space. There will also be bars, a café and restaurant, a range of specialist shops, facilities for 400,000 visitors per year and office space for businesses operating in the creative sector.

THEpUBLIC Arts Centre is designed bioclimactically. The bioclimatic area is intended to be a space that feels more like an avenue than an enclosed artificial environment. It will offer a changing environmental experience that has different characteristics night to day and season-to-season. The conditions within the bioclimatic enclosure will reflect the external conditions. It is, in effect, a moderated outdoor space and therefore the occupants are expected to wear outdoor clothing.

3.5.2 The Building Before the Interventions

The Sandwell area of West Bromwich, had few entertainment centres and no cinemas, and will benefit from a hub that the local community can visit for entertainment, art and lifelong learning. The site before the interventions was a bus garage. THEpUBLIC Arts Centre will regenerate West Bromwich and provide the long-awaited focal centre for the local community. Not only will THEpUBLIC Arts Centre rejuvenate a run-down area, it will also give the existing site a face-lift. It will demonstrate how an arts project can meet the highest environmental requirements and lowest energy consumption effectively.

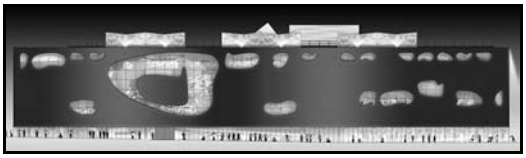
THEpUBLIC Arts Centre (under construction)

3.5.3 Architectural Interventions and Construction Materials

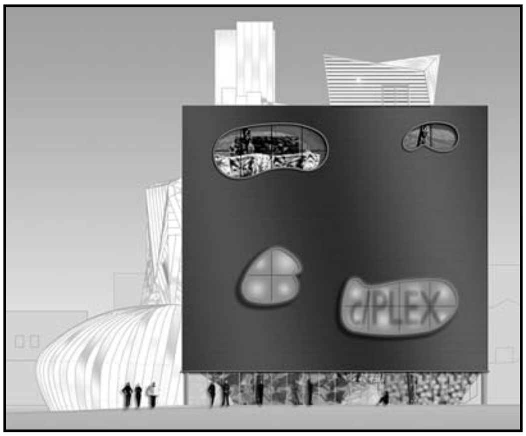
The new design wraps a simple, rigorous, rational skin around an inventive structure. It is a powerful, uncompromising enclosure and form. Holding up the external skin is an innovative, visually striking structure from which the key horizontal and vertical elements span dividing the vast space into its three principal functions:

1. Commercially related managed workspace and events spaces (south west end);
2. Access, management and entry to galleries (Upper levels north east bays);
3. A vertical maze, celebrating a journey through a range of different spaces and internal enclosures (Lower levels north east bays).

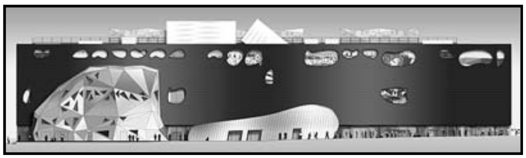
Inside is a rich series of multiple organic forms juxtaposed at different heights and levels.



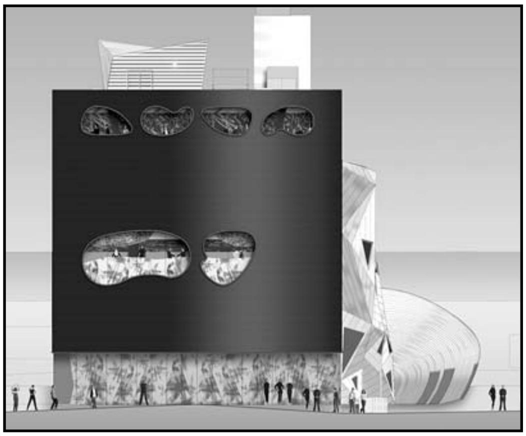
North-west elevation



North-east elevation



South-east elevation

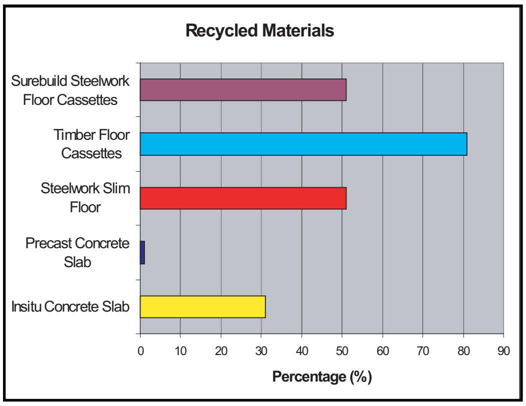


South-west elevation

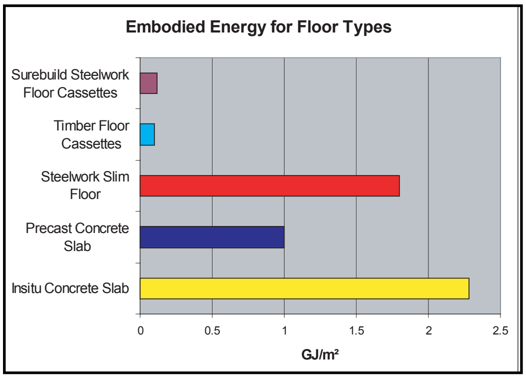
The selection of construction materials is guided by the following:

- Recycled control
- Embodied energy
- Recyclable materials at the end of their life
- Life cycle costing
- Environmental impact

The building is designed with minimal unnecessary use of materials, thus reducing material wastage as well as the total volume of material that will have to be disposed of when the building is eventually demolished.



Recycled materials



Embodied energy for floor types

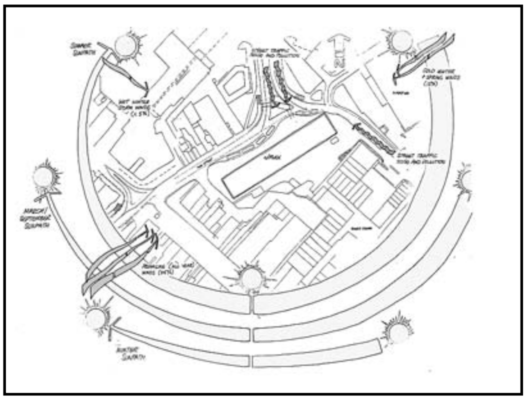
Elements are prefabricated off-site to avoid producing waste on-site during the construction period. Materials are specified in the following order of priority:

1. Re-usable and secondary or recycled materials are specified over virgin products (e.g. sustainably grown timber)
2. Materials with recycled content

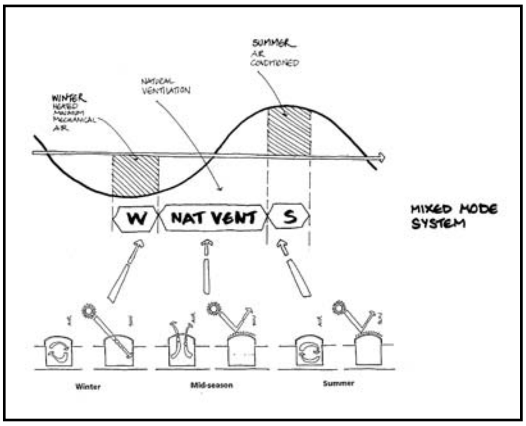
3.5.4 Elements of the Environmental Design and Innovations

The site analysis together with environmental design strategies show that THEpUBLIC Arts Centre will benefit from the following technologies:

- Substantially naturally daylit internal space;
- Mixed-mode ventilation system to provide comfortable conditions throughout the year whilst allowing all occupants to open windows;
- Creation of an intelligent façade system that incorporates external shading, natural ventilation and night-time cooling systems;
- Low energy and maintenance cost systems;
- Photovoltaic solar energy collection;
- Borehole water system for cooling and water supply.



Analysis of the site



Schematic of mixed mode system

The targets for THEpUBLIC Arts Centre are as follows:

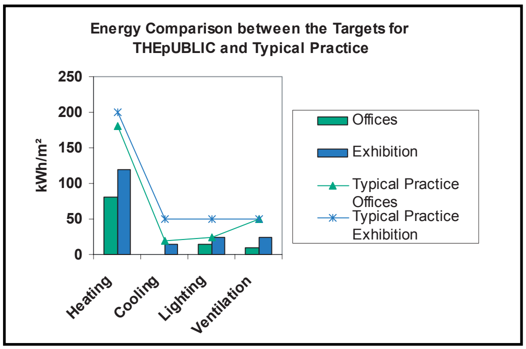
- 40% reduction in energy consumption with a target of 130kWh/m^2;
- 40% reduction in maintenance;
- Significant reduction in embodied energy materials.

	Heating (kWh/m^2)	Cooling (kWh/m^2)	Fans and Pumps (kWh/m^2)	Lighting (kWh/m^2)
Actual	60.4	0	9.4	17.6
Target	80	0	0	15

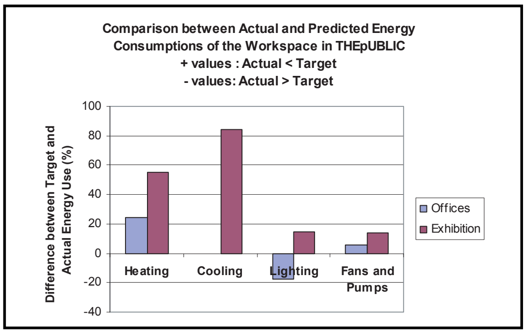
Workspace

	Heating (kWh/m^2)	Cooling (kWh/m^2)	Fans and Pumps (kWh/m^2)	Lighting (kWh/m^2)
Actual	54	2.4	21.5	21.4
Target	120	15	25	25

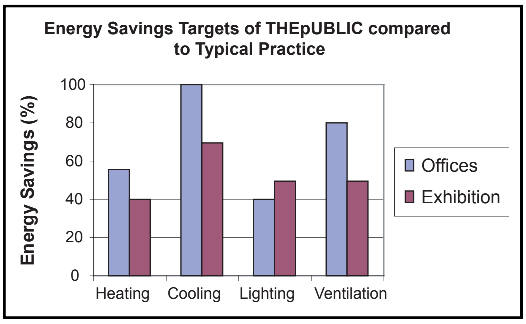
Exhibition



Energy comparison



Actual and predicted energy consumption



Energy savings

3.5.4.1 Lighting

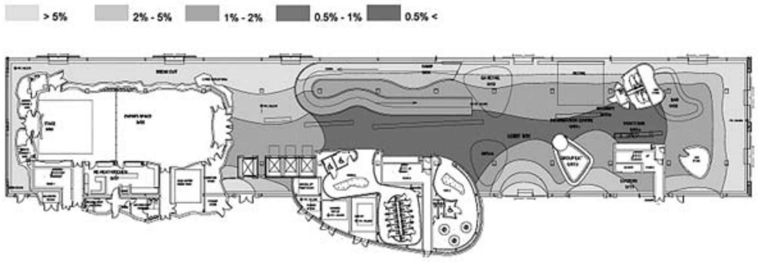
Daylight studies were performed using a combination of artificial sky studies, radiance calculations and manual calculations. The objective of the analysis is to examine the daylight availability in the spaces that require adequate daylight illumination, principally the managed workspaces (levels 1, 2 and 4), and the main crèche areas (levels 1 and 2) as well as those spaces that would benefit from some daylight penetration - the restaurant, public entrance lobby and circulation ramp. Artificial lighting design components such as improved efficiency luminaries and efficient high frequency ballasts, lamps and fluorescent TS will be used. The daylight factors achieved are outlined below for each floor.

Ground floor

The façade at this level uses 100% clear low E double-glazed units (transmission factor 0.69) and consequently the principal spaces have very good daylight availability.

	Entrance Lobby	Elevator Lobby	Bar
Av DF	2%	3.5%	5.3%
Uniformity	0.7	0.43	0.18
Appearance	Daylit	Daylit	Daylit
Electric Light Use	No	No	Some

Ground floor



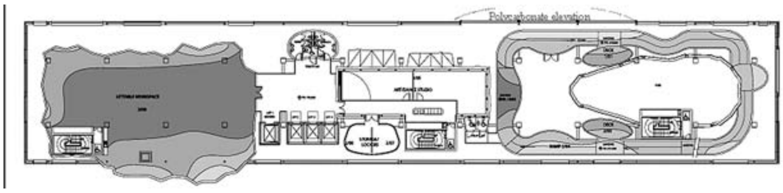
Ground floor daylight contours

Second floor

The managed workspace has an uneven daylight distribution with brightly daylit areas at the periphery and a darker core. On average the space will have a daylit appearance but some electric lighting is needed. Daylight-linked controls can help minimise the load of the artificial lighting system by taking advantage of the adequately daylit peripheral zone.

	Workspaces	Creche
Av DF	0.8%	1.7%
Uniformity	0.35	0.55
Appearance	Partly daylit	Artificially lit
Electric Light Use	Yes	Yes

Second floor



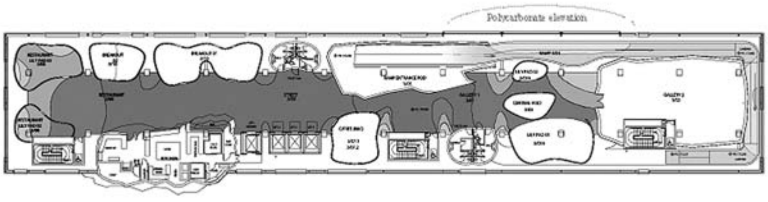
Ground floor daylight contours

Third floor

The high floor to ceiling height helps distribute the daylight efficiently in the restaurant area. The adjacent façades have similar glazing ratios to the workspaces on the first and second floors. The main central area and the "breakout" spaces are poorly daylit and would need to use some electric lighting.

	Restaurant Main	Breakouts
Av DF	1.2%	0.6%
Uniformity	0.41	0.57
Appearance	Partly Daylit	Daylit
Electric Light Use	Yes	Yes

Third floor



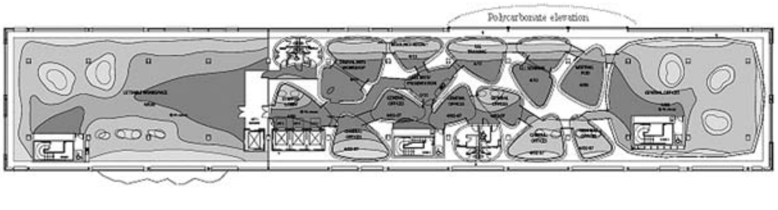
Third floor daylight contours

Fourth floor

The two main managed workspaces (at the SW and NE sides of the building) have excellent daylight levels and can avoid the use of artificial lighting throughout most of the day. The glazing ratio on all facades is 40% and there are also several skylights (5% of roof area).

	Main Workspaces
Av DF	3.1%
Uniformity	0.48
Appearance	Daylit
Electric Light Use	No

Fourth floor

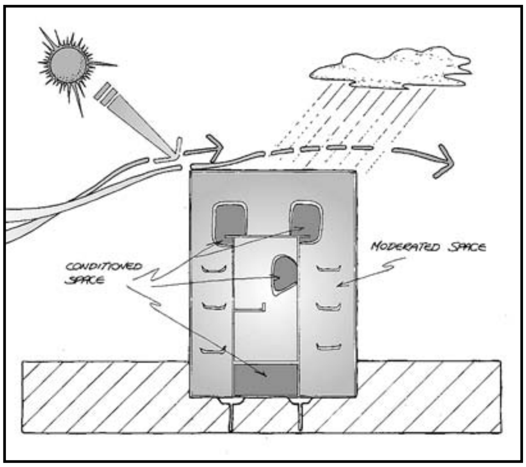


Fourth floor daylight contours

3.5.4.2 Electromechanical design

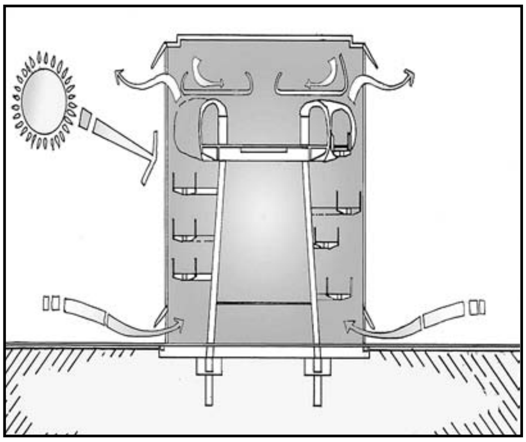
THEpUBLIC Arts Centre is made up of many different spaces, which vary in function and occupancy. Due to the diverse nature of the spaces, a number of distinct comfort requirements exist:

- Areas requiring close control (exhibition type spaces, denoted close control zones);
- Areas with less stringent comfort requirements where natural ventilation and heating is proposed (office and circulation spaces, denoted natural ventilation zones);
- The bioclimatic area (general public areas and some exhibition spaces, denoted bioclimatic zones), that closely follows outside conditions, where minimal heating is proposed.

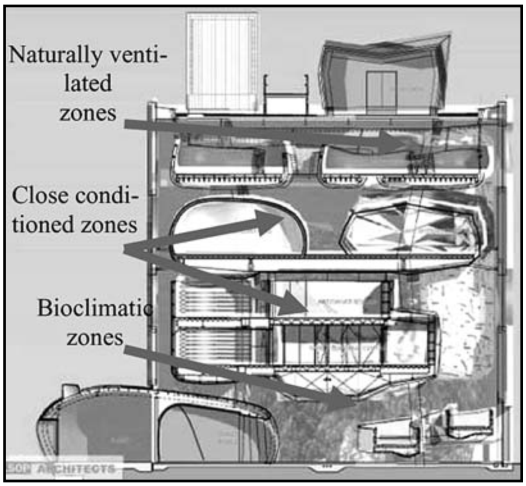


Use of the building skin as environmental modifier

The bioclimatic area is intended to be a space that feels more like an avenue than an enclosed artificial environment, it will be a changing environmental experience that has different day and night characteristics which vary seasonally. The bioclimatic skin is therefore an environmental modifier which tempers the effects of the outdoor environment and provide occupant comfort. The bioclimatic areas are located within the "bioclimatic enclosure" which takes the form of an intelligent building skin.



Use of the building skin to provide a bioclimatic enclosure



Zone arrangement

The internal climate control systems uses an ultra low energy approach to ensure minimal CO_2 emissions throughout the usable life of the building. The aim is also to minimise costs both in terms of initial capital and operational maintenance costs. This is achieved by the following heating, cooling and ventilation strategies:

- Use of heat recovery system
- Heat exhaust from pods
- Passive solar heating
- Passive cooling
- Demand-controlled ventilation
- Natural ventilation
- Boreholes
- Night-time ventilation
- Exposed thermal mass

The prevailing climate encourages the use of natural ventilation and for many of the spaces the relaxed comfort brief permits a wide range of thermal conditions. The bioclimatic zones are primarily heated by passive solar heating and by capturing the heat loss from the close conditioned spaces, however perimeter heating and warm air is provided to the ground areas for peak winter situations. Generally the close conditioned zones can be considered as isolated volumes that do not experience the outside ambient conditions but lie within the tempered climate of bioclimatic enclosure.

The integration of intelligent components and computers ensures that the stringent environmental requirements are met in the museum building. These devices are self-regulating and require minimal interventions for heating, cooling or daylighting control. Automatic intelligent controls are used to optimise the building performance, and thus improve the overall energy use and the indoor microclimate.

The BEMS controls:

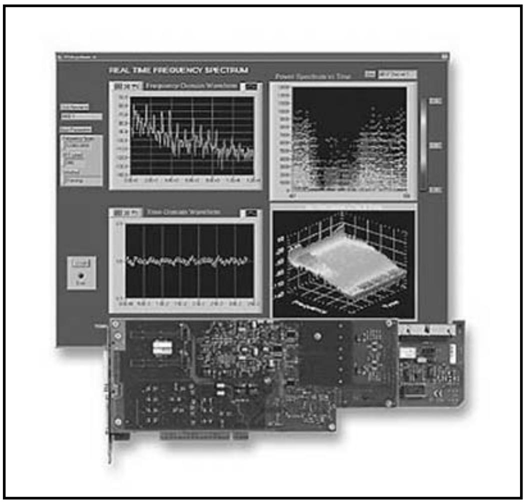
- Heating
- Ventilation
- Cooling

A separate system controls:

- Lighting
- Lifts
- Access Control
- Burglary Protection
- Fire Protection

Monitoring

The efficiency of the integrated environmental strategies for day-to-day operations of THEpUBLIC Arts Centre will be assessed by monitoring data recorded on an hourly and monthly basis for both internal and external conditions.



Monitoring system

Monitoring of external conditions

- Temperature (hourly)
- Global solar radiation (hourly)
- Humidity (hourly)

Monitoring of internal conditions

- Energy in Office and Visitors zones (monthly):
    - Heating energy consumption
    - Cooling energy consumption
    - Lighting energy consumption
    - Small power loads
- Specific systems (hourly):
    - Ground Water Cooling Flow rate
    - Flow and Return temperatures

Furthermore, air temperature will be monitored at each floor level; humidity will be recorded at the top and bottom of each zone; and radiant temperature will be measured at two locations.

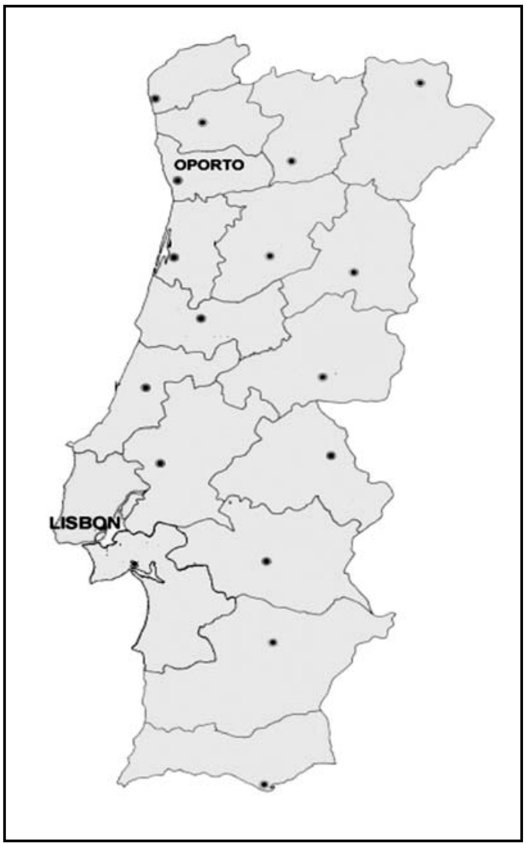
This rigorous computerised monitoring system will provide the necessary data to determine the effectiveness of the low-energy strategies, energy efficiency, as well as ensuring that all building systems are operating smoothly.

3.5.5 Exhibits

Innovative exhibitions and performances, which communicate a variety of issues relating to health, regeneration, education, art, science and technology, will be on display to a wide range of visitors. The exhibits will be delivered in the form of digital art, hands-on displays, creative studios, paintings, textile and paper sculptures, interactive multimedia and technology production, education and performances.

3.6 NATIONAL ARCHAEOLOGICAL MUSEUM, LISBON, PORTUGAL

3.6.1 Project Background



Location map of Lisbon

The National Archaeological Museum (Lisbon, Portugal) is located in the Monastery of Jerónimos, near the river Tejo, in one of the historical zones of the city. This monastery is one of the most important ancient monuments in Portugal. It was ordered to be built by King D. Manuel I in 1501, to celebrate the Portuguese Maritime Discoveries. In 1907 it was designated a National Monument and a “World Heritage Site” by UNESCO in 1984.

General view of the Monastery where the museum is housed

The museum has been housed there since 1903 in the south wing of the Monastery of Jerónimos (the other spaces are occupied by the Navy Museum and Library). At present, the museum uses the two floors of the south wing. The reception and exhibition spaces are on the ground floor. The first floor houses the administrative and technical offices, laboratories, storerooms and a library.

General view of the Monastery (Main façade)

This museum exhibits stone, clay, metal and ceramic archaeological pieces and is in need of further exhibition space. It has an area of 5,834m^2 and it is to be upgraded and extended with an additional 5,503m^2. In order to increase exhibition space in the existing building, laboratories and offices are to be housed in a new underground extension and two vacant towers are to be retrofitted to accommodate some support services, e.g., a reading room, a bar and the museum store.

3.6.2 The Context of the Intervention

The need for further exhibition space has been the main motivation for an upgrade and a retrofit of the museum. The difficulties of dealing with such an ancient monument are obvious, due to legal regulations and restrictions. The main façade of the monastery, for example, in any way, including the existing single-glazed windows and their wooden frames cannot be changed. The new extension building has fewer restrictions as such, but its architecture must integrate itself harmoniously with the existing building.

The existing building also has some excellent characteristics that must be preserved. It has a high thermal inertia because most of the building envelope is made of thick limestone. Walls are typically 1 metre thick. The thickness of the walls guarantees good shading levels in summer. In the downstairs exhibition galleries, the air change due to infiltration is sufficient, and not excessive, to fulfil the fresh air needs of the occupants and visitors. Measurements have shown that, in summer, the downstairs gallery has a very stable temperature that no HVAC system could improve upon.

The architectural design aims to combine, aesthetically, the old and the new building through the Museums Programme, promoting sustainable architecture and energy efficiency, and to deal with the indoor climate, lighting and acoustic requirements.

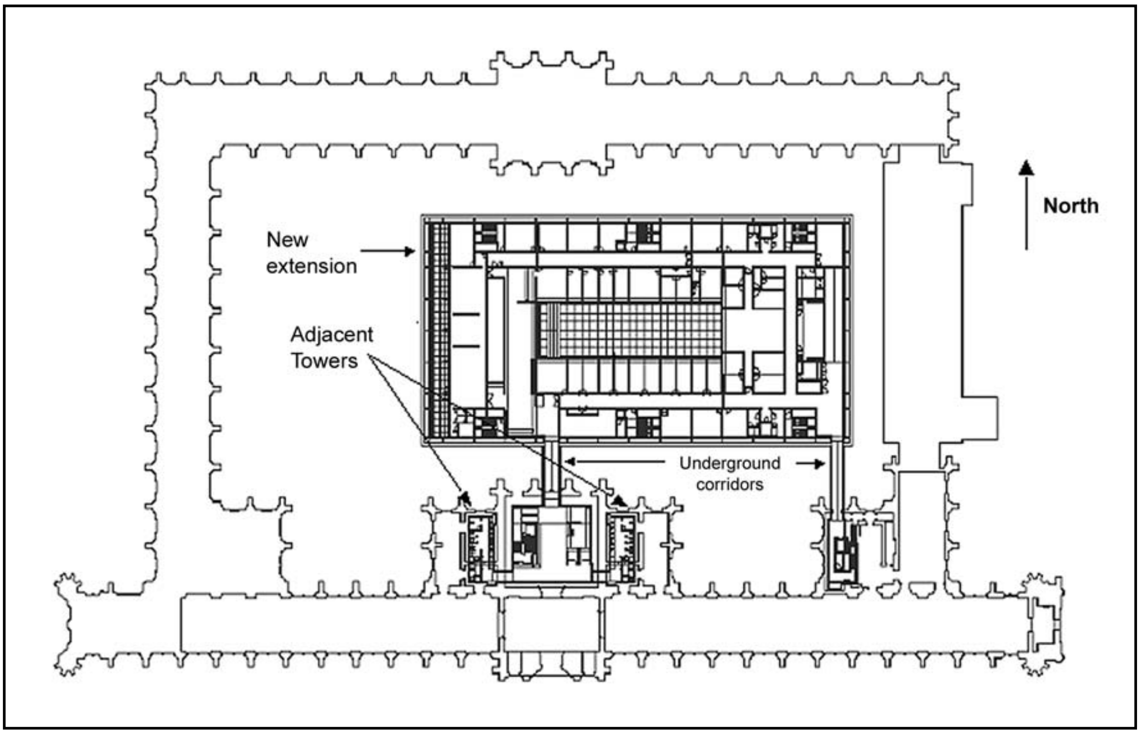
3.6.3 Architectural Intervention

The museum is to be upgraded and extended to about twice its present useful area. The main objective is to double the exhibition area, also using the whole first floor of the existing monastery for this purpose. Storerooms, technical and administrative offices, laboratories, and all the necessary rooms to prepare the exhibitions will be moved to a proposed addition to be constructed underground, in the courtyard of the monastery. The exhibition areas in the existing building will be connected with the addition through two underground corridors. Two small towers adjacent to the existing building will be retrofitted to offer support services to the visitors, including, a reading room, an auditorium, a coffee house, a shop, etc.

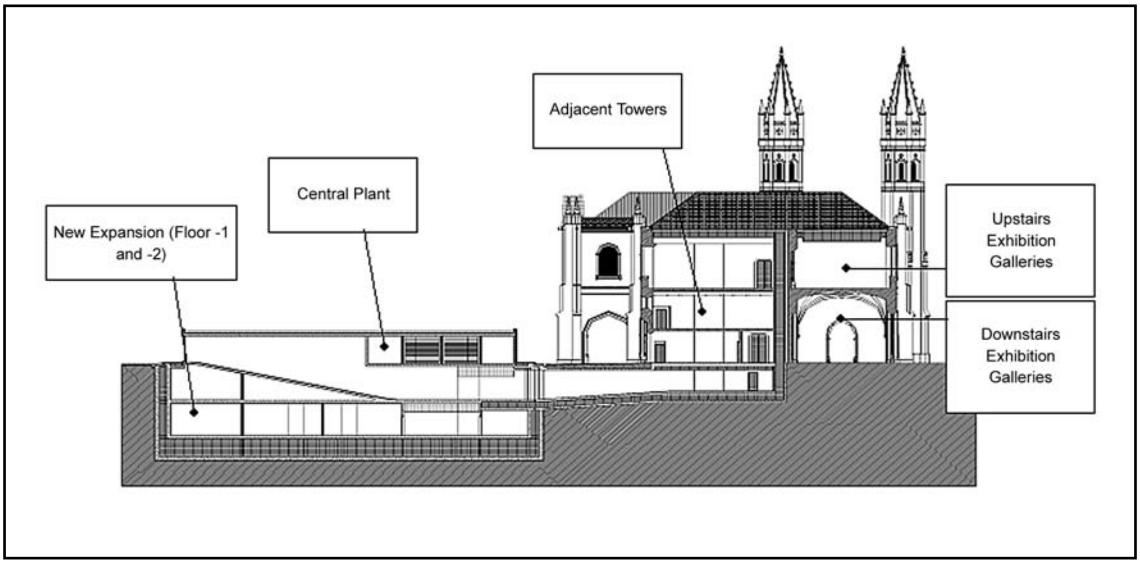
Despite the limitations in making any interventions in the existing building, the roof of the upstairs exhibitions galleries and the building envelope with the poorest thermal efficiency can be improved because there will be no visible changes to the outside or inside of the building. At present, the roof has no insulation, as shown in the following photograph (there is only a wooden structure that supports directly the clay tiles). After a sensitive study of investment cost versus energy savings in the mild winter climate in Lisbon, it was decided to fit 5cm of insulation in the roof. This is twice the thickness required by national building regulations.

Roof of the upstairs exhibition galleries

No changes can be made to the ceiling of the ground floor, one of the most striking architectural features of the existing building.



Simplified plan view of the future museum



Cross-section view of the future museum

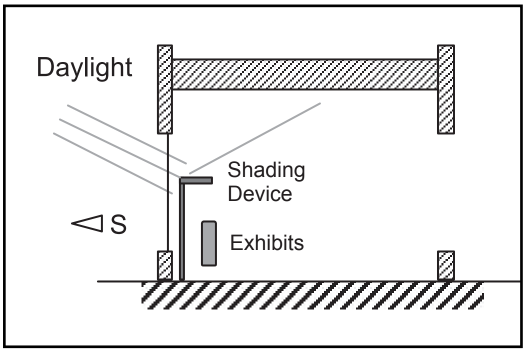
3.6.4 Elements of the Environmental Design and Innovations

3.6.4.1 Lighting and acoustic design

As there can be no visible changes to the exterior façades of the existing building, the intervention is limited to measures inside the galleries. The windows are protected on the inside with fixed dark metal screen shades that block most daylight from the interior of the downstairs galleries. Upstairs, windows have movable internal wooden panels.

Ground floor view

Detailed simulations and measurements were carried out to find a solution that can provide improved daylighting in the downstairs galleries while still avoiding sharp light contrasts in the viewing of the exhibits. These new shading devices will also have acoustic absorbing materials to improve the high reverberation that is present in the existing building, due to the highly reflective limestone ceiling and floor that cannot be altered.



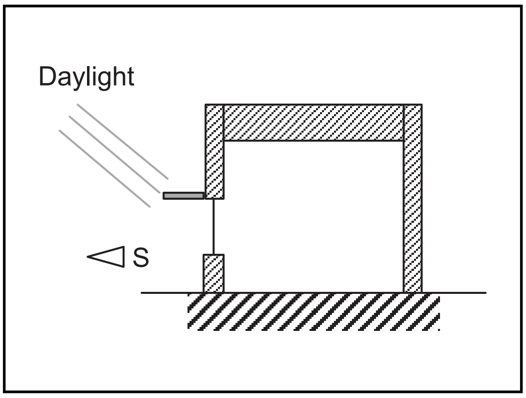
Exhibition galleries - shading devices

Daylighting conditions are already adequate in the upstairs galleries as the movable window panels can be opened whenever desired. Wooden ceilings and floors also provide good acoustic environments so they do not require special, corrective measures.

Type of space	**External background levels**	**Reverb. times(s) (@500Hz)**	
		Existing	**Proposed**
Naturally ventilated rooms (small)	Neg	2.4	0.7
Naturally ventilated rooms (medium)	Neg	3.1	1.2
Naturally ventilated rooms (large)	Neg	3.9	1.5
Mechanically vent. rooms (small)	-	-	0.7
Mechanically vent. rooms (medium)	-	-	1.2
Mechanically vent. rooms (large)	-	-	1.5

Measured and proposed reverberation times

In the new extension, all the offices have windows that open to an internal courtyard. These spaces will be fitted with interior shading devices (blinds), and fixed exterior shading devices when placed in the south façade, as shown schematically in the following diagram. Light pipes shall also be placed in the offices to provide daylighting in the core space further away from the courtyard windows, significantly reducing artificial lighting needs.



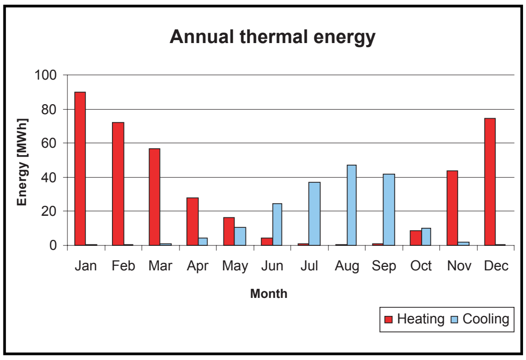
New extension - shading devices

The electric lighting system of the building shall be replaced by more efficient modern systems. The electric power installed for artificial lighting shall, on average, be 8 W/m^2 throughout the building. The downstairs galleries in the existing monastery building will have low-level general lighting system with indirect lighting towards the high ceiling, together with special lighting directed to the exhibits.

3.6.4.2 Heating, cooling and ventilation

At present, the museum has no heating or air-conditioning. The temperature is very stable in the exhibition areas downstairs, due to the high thermal inertia of the construction, and AC is not needed in summer. The temperature can be a little low in winter (14°C, but no heating is available). Upstairs, the staff use small electric heaters during the coldest periods.

The new museum will be equipped with different HVAC solutions for the various types of spaces, according to the desired thermal and air quality parameters to be maintained in each space. The exhibition galleries on the ground floor well have a heated floor to bring indoor temperatures to comfort levels. No humidity control is needed as natural ventilation is sufficient. The exhibition galleries upstairs will have an all-air system. Several air-handling units will be placed in the attic space. Ventilation, temperature and humidity control will be available for conservation of exhibits and visitor comfort. Fan-coil units will be installed in the adjacent towers and the new underground extension. A separate fresh air ventilation system will supply air at close to room temperature to each space, as needed. The following diagram shows the calculated annual thermal energy for the entire building and the next table presents the calculated heating and cooling peak loads for the main groups of spaces considered.



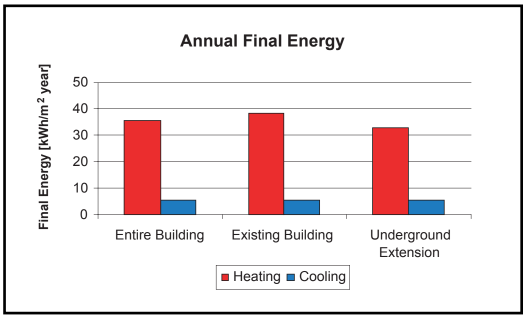
Annual heating and cooling energy

SPACE PEAK LOADS

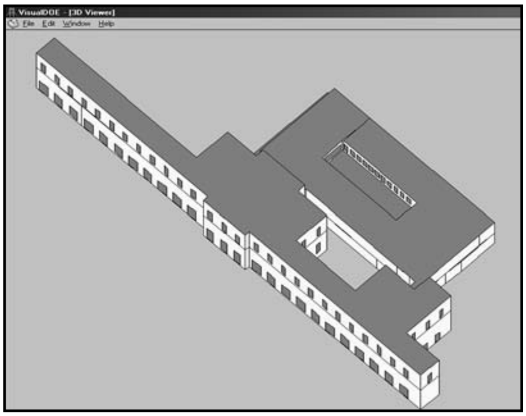
Space	Heating	Cooling
	kW	kW
Upstairs Gallery - West	55	45
Upstairs Gallery - Atrium	14	12
Upstairs Gallery - East	63	57
Downstairs Gallery - West	17	0
Downstairs Gallery - Atrium	7	0
Downstairs Gallery - East	30	0
Adjacent Towers	101	64
Tech. Offices - New Expans.	160	141
Corridors – New Expans.	162	99
Others, e.g., storerooms, etc	102	56
Entire building	**609**	**453**

Peak space loads for heating and cooling

The energy design strategy was achieved with dynamic simulation of the building that tested several solutions and carried out sensitivity studies, namely, different strategies for the air conditioning of the spaces and in terms of energy sources. Several scenarios for the power plant have been studied in detail, including conventional and renewable sources. Despite the interest in a geothermal solution, it had to be discarded because of high cost and relatively long payback periods. The solution adopted uses two high efficiency condensing gas boilers and two air-cooled chillers. The following diagram shows the calculated annual energy needs.



Annual heating and cooling energy



3D View of the museum model

3.6.5 Exhibits

The museum exhibits metal objects (silver, gold, copper, bronze, iron, steel, etc.), ceramic objects (mosaic earthenware, terracotta, majolica, china, etc.), and mineral objects (limestone, marble, volcanic materials, etc.), few of which special environmental requirements. Special, climate-controlled exhibit cases will be used for sensitive pieces.

3.7 BARDINI MUSEUM OF FLORENCE, ITALY

3.7.1 Project Background

The building is located in the centre of Florence, Italy, near the Old Bridge. The general area is a densely built residential region. The building is open on all sides, except on the east and its only entrance is from the west. This building represents one of the most important buildings of the Eclectic period. It was adapted from an old church with a monastery in 1883 by the Italian architect Bardini to house and display his art collection.

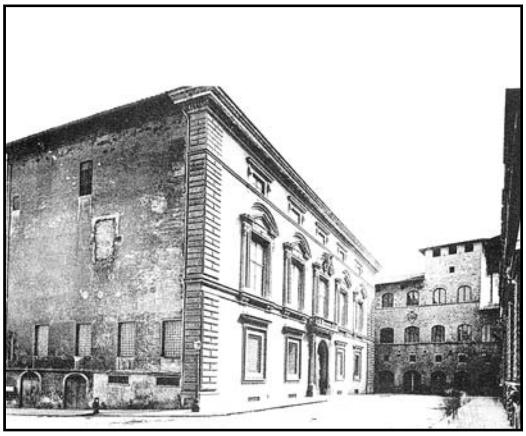
Aerial plan of Bardini Museum area

3.7.2 The Building Before the Interventions

This historical museum is a representative paradigm of Italian museum building and is one of the most important buildings of the Italian Renaissance. Therefore, the retrofitting has taken account of these architectural and artistic values.

The exhibition space is 3,200m^2 with a 6m ceiling height and a total volume of 15,000m^3. All the storeys are occupied with works of art with visiting hours between 09.30am - 19.00pm on a daily basis, except for the summer period.

With the exception of the administration area, there is no heating, cooling, mechanical ventilation or environmental control system there are no surveys for thermo-hygrometric, CO_2 and illumination evaluation. The building is naturally ventilated and has no air conditioning system installed. It has massive stone walls. The long axis of the building is north-south oriented.



An old photo of the Bardini Museum

The building presented some notable structural and functional problems:

- out modified environmental conditions for visitors and staff in relation to air quality, and thermal and visual environment
- no environmental monitoring or control; i.e. no controlled ventilation: unfavourable and changeable conditions for objects and occupants
- excessive energy consumption: (lighting represents 70% of the total energy consumption due to insufficient and obsolete devices in the exhibition spaces), no presence detectors, no daylighting compensation system
- efficient use of energy due to poor building maintenance and obsolete equipment
- damaged windows and windows frames
- high air infiltration rates
- inadequate exhibit handling and display
- inadequate spatial organisation of the exhibition space.

3.7.3 Architectural Interventions and Construction Materials

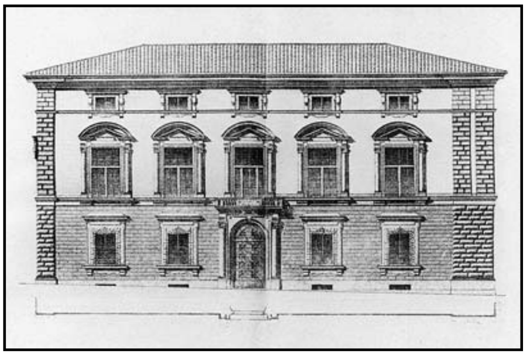
The strategy for the retrofitting consists mainly in four types of actions:

Building Improvements
Improved U-value of windows
Reduced infiltration: weather stripping of windows and doors
Replacement of windows frames in poor condition
Ventilated roof and roof insulation
Additional shading devices for the third floor
Use of passive cooling techniques
Modulation of heat gains. Night ventilation
Electric lighting improvement
Change the type of lamps and luminaires to improve their efficiency
Replacement of existing skylights
HVAC system improvements
Installation of a new energy-efficient heating system

Retrofitting actions

It is important to notice that existing façades cannot be altered, in particular the main façade.

Losses through the envelope are mainly caused by infiltration due to the poor condition of windows. Increased levels of insulation, reglazing and the reduction of air leakage were necessary to achieve savings in convective and radiation losses.



Existing façade

The retrofitting actions proposed to reduce heat losses include the upgrading of all windows in poor condition (to assure air tightness as well as double-glazing for all openings), and increased insulation levels in the roof.

CONSTRUCTION MATERIALS			
	Type of material	Thick-ness	U-value (W/m^{2}K)
Interior partitions	Brick partition	30 cm	n/a
Roof	Clay tiles	40 cm	---
Roof insulation	Granulated cork	10 cm	0,36 W/m^2°C
Ground floor	Baked tile	---	---
Ground floor insulation	Ground floor loose stone foundation	---	---
Intermediate floor	---	---	---
Window glazing	Double-Glazing	0.02 cm	2.80
Window frames	Wood/steel	---	N/a

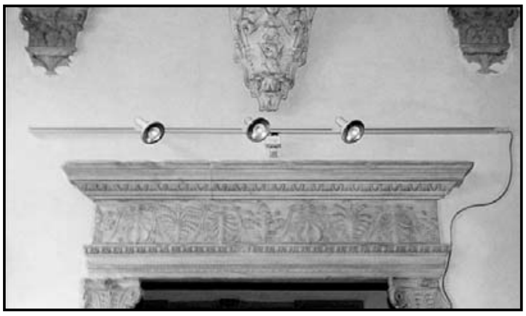
Construction materials used

3.7.4 Elements of the Environmental Design and Innovation

3.7.4.1 Daylight and artificial lighting

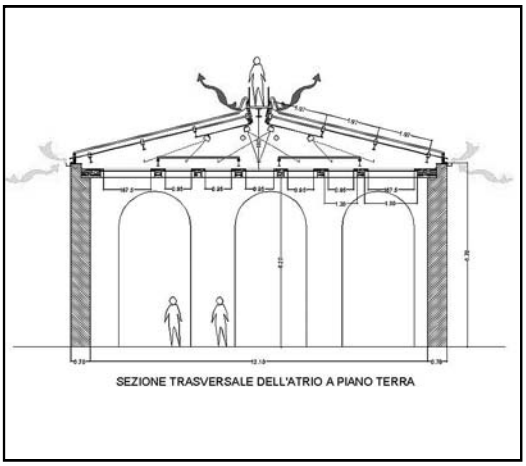
The energy consumption for lighting the Bardini Museum is high because it has unnecessarily high lighting efficiency levels with poor control and low efficiency system. Priority has been given to actions aimed to reduce the installed power and improve the lighting efficiency, avoiding high heat gains that occurred in the old lighting system. In fact, good lighting design means not only lower energy consumption but also, as recent research has shown, improved exhibition conditions and user comfort.

The improvement of the luminaries (those without efficient reflectors) is a very important measure because the luminaries need to be more effective so that more light is directed onto the exhibition space. The use of efficient luminaries with a special reflector can reduce glare and increase illumination levels. This retrofitting measure has provided the required lighting levels with half the number of fixtures, has reduced glare, and has increased illumination levels.



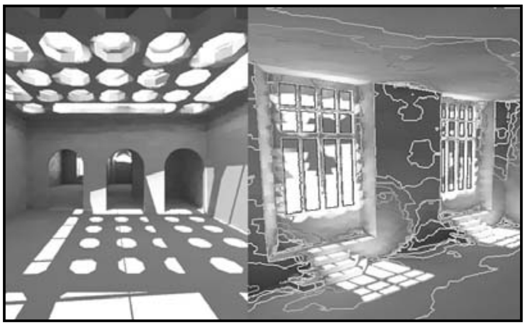
New luminaries installed

The daylighting level has been optimised by replacing the existing skylights with new ones. The first step was to change the skylight roofing structure in the main room near the entrance.



Section showing the skylight

Simulations with 'RADIANCE' have shown a significant reduction of transmittance using high diffusion components in place of the existing glass.

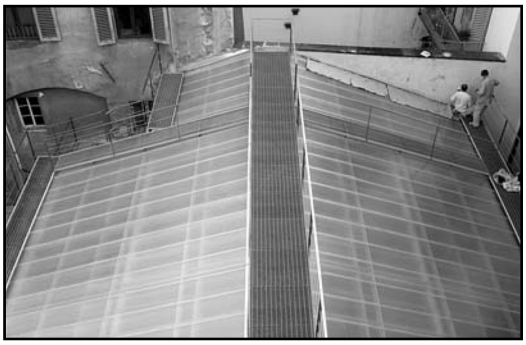


Radiance simulation

Luminaries have been installed in place of the heavy glazed roofing, that have a transparent 30mm twin-wall polycarbonate panel with a special reflector that reduce glare and increase illumination levels.

The existing skylight: external view

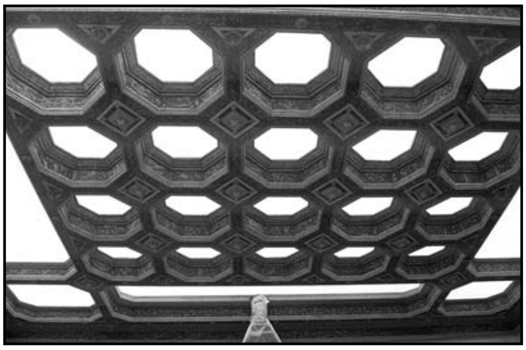
Light transmittance of skylight roof structure	τ = 80%
Light transmittance of high transmittance diffuser for false ceiling	τ = 70%



The new skylight: external view

In the existing wooden false ceiling all the bulletproof glass will be replaced with special, high transmittance diffusing components made of a high-grade flexible plastic positioned to assure a uniform luminance distribution from the ceiling in the room.

The existing skylight: internal view



The diffuser panels installed on the old wood ceiling

The new skylight, internal view

3.7.4.2 BEMS

It is difficult to preserve constant indoor conditions in a museum without the use of additional artificial systems. So, in order to have an indoor climate without variations, artificial systems are supported by advanced control systems. Controls systems for optimised building energy management are address essentially three issues:

- thermal control systems
- artificial lighting control systems and solar radiation control systems
- ventilation and air quality control systems, including integrated building automation control systems for lighting, ventilation, overall energy consumption, etc. or special components, such as the Intelligent Windows

Moreover, there are, today, sophisticated, intelligent systems, such as Building Energy Management Systems, that integrate a larger number of sensors for fire alarms, smoke ventilation, security control and HVAC according to the internal requirement, etc.

The basic element of an intelligent control system is one or more sensors to measure the parameters required for the implementation of any required control strategy. Once a controller has processed this information, appropriate commands can be sent to the actuators. The controller will instruct the actuators based on programmed algorithms and in response to the measurements from the sensors.

A BEMS for the regulation of thermo-hygrometric conditions and daylighting control will be used in the Bardini Museum of Florence.

The control system for optimised indoor climate for preventive exhibit conservation and user comfort will include:

- Temperature and Humidity sensors:
  Which combine previous operational responses and current conditions to determine the optimum time for turning on the heating system in order to reach the desired indoor temperature at a specific time
- A ventilation control system which can be used for controlling passive measures to promote natural ventilation, including the opening and closing of lourves installed under windows
- Occupancy sensor:
  Which can be used to turn lights off when the space is unoccupied or periodically occupied. The use of the most efficient ones, which turn lights off when room is unoccupied and leave the occupant to turn the lights on if required, eliminates the possibility of the lights coming on by small movements such as wind
- Lighting sensors which makes it possible to maintain the level of illumination in the room at the design level as daylight varies. They also permit a considerable saving of electricity, longer life for lighting equipment and simple management of reserve lights.

3.7.5 Exhibits

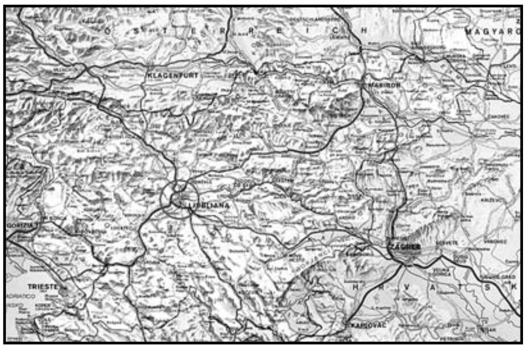
Ancient historical buildings, converted into museums, provide an opportunity to show collections in an impressive context. But this offers limited possibilities for intervention because the ancient buildings were not originally conceived for exhibition purposes and many compromises may need to be made in the design process. The installation of HVAC system may not be compatible with the architectural characteristics of the building. In fact, from a exhibit point of view, the Bardini art collection does not require extensive control of indoor conditions because the works of art exhibited are mainly metals (weapons, armours, pendulum clocks, silver, copper, bronze, brass, lead, coins) and minerals (terracotta, majolica, stones, marble) that do not need particular care regarding light and temperature / humidity parameters.

On the first floor, where more delicate objects, such as paintings (watercolour, drawings, pastel, oil paint, tempera), and tapestries are housed, strategies are adopted to avoid deterioration due to direct lighting: double glazed windows have been installed, and equipped with internal shading systems to reduce light penetration. Temperature and humidity are set and controlled by the HVAC system.

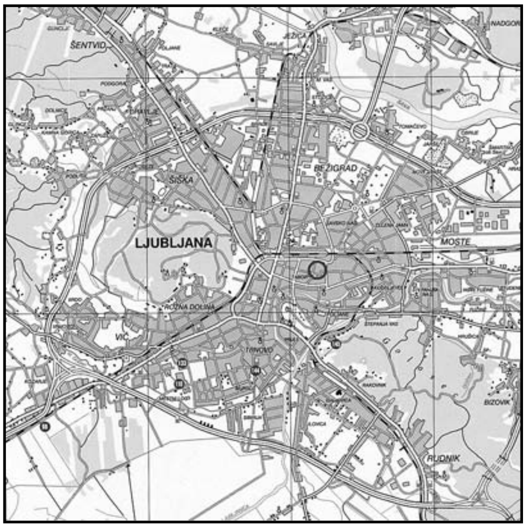
3.8 SLOVENE ETHNOGRAPHIC MUSEUM, LJUBLJANA, SLOVENIA

3.8.1 Project Background

The Slovene Ethnographic Museum (SEM), is situated in a 19th Century building in the centre of Ljubljana. The beginnings of the Ethnographic Museum were the ethnographic and folklore collections of The Carniolian Provincial Museum in Ljubljana, founded in 1821. In 1923 permission was obtained for the Royal Ethnographic Museum. After the Second World War the museum changed its name to the Ethnographic Museum, and “Slovene” was added in 1964. During all these years the museum was part of the National Museum and has had ongoing spatial problems. These lasted until the 1990s when Slovenia achieved independence. In 1994 the Government of Slovenia decided to allocate the southern part of the complex of the former Yugoslav military buildings in Metelkova street to the cultural institutions, and among the two buildings were assigned to SEM.



Map of Slovenia



Map of Ljubljana with microlocation of SEM

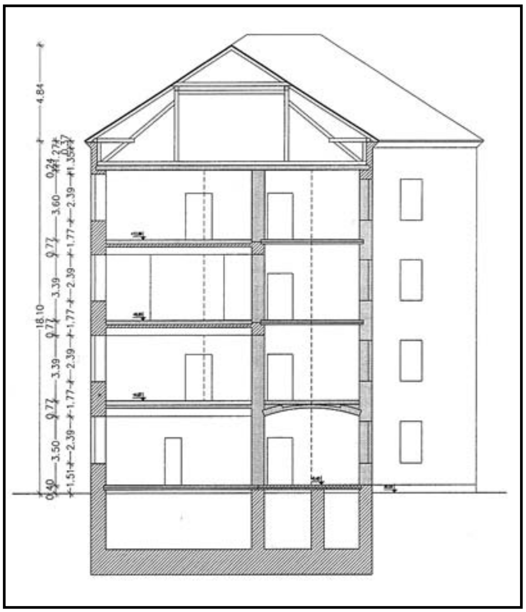
3.8.2 The Building Before the Interventions

The majority of museums in Slovenia are in historical buildings such as castles, palaces, historic public buildings of other uses, which have been adapted to their new function. Practically no interventions have been made in SEM with regard to energy savings and illumination upgrading. Daylighting is poor, installations are old and obsolete. Heating costs are high, and there are problems with moisture in the rooms. There is no common doctrine for reconstructions. Because the majority of museums are in old buildings, classed as part of the cultural heritage, the façades and roofs must be preserved. Collaboration with the responsible heritage protection agency is practically impossible and based on the principle of negative intervention.

Building of SEM before reconstruction, south-east view

The SEM building envelope is composed of walls of brick and stone masonry with plaster on both sides. Floor to floor height is 3.5 to 4m. The floors originally had a brick arch structure which was partly replaced with reinforced concrete slabs. The walls, floors, roof and basement were not thermally insulated. The windows were double-glazed in box type and wooden frames. Space heating was provided by radiators. Electrical boilers were used for water heating. There was no mechanical ventilation in use.

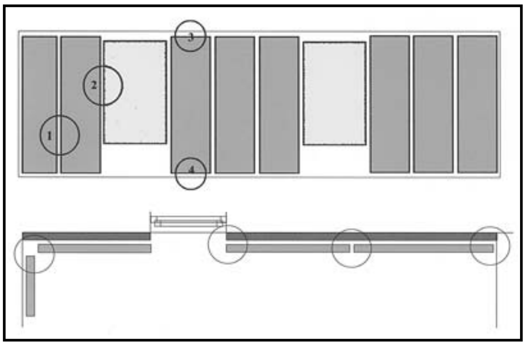
The most important positive characteristic of the building are its basic architectural concept with big spaces which can be optionally connected to the administrative building of SEM. Other advantages are that SEM is part of larger area that hosts planned cultural activities, and is close to the city centre and railway and bus station of Ljubljana.



Cross-section of building before reconstruction

3.8.3 Architectural Interventions and Construction Materials

The building has exhibition spaces on the ground and three upper floors, a basement for storage and an attic for additional storage and offices. The building is on an east-west axis, with its long façades facing south and north. Outer walls remain unchanged from the outside. Inside, some reinforced concrete vertical plates and slabs were introduced. All horizontal parts of the loadbearing construction were removed, with the exception of some selected parts of brick vaults, and replaced with reinforced concrete slabs / plates. There is a new timber roof construction.

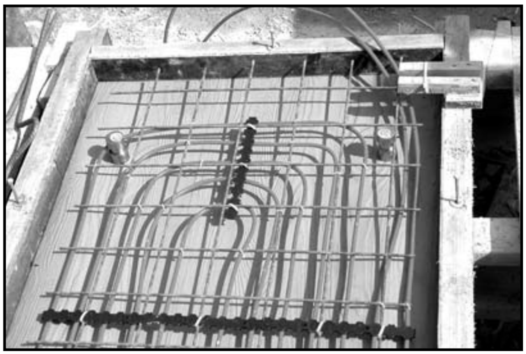


Identification of problem areas in the system of heating/ cooling panels

In the framework of this project, the priorities for both objects and visitors are optimal daylight and rational use of energy without prejudice to the quality of the environment provided for the exhibit. The objectives are to assure: optimal conditions for exhibitions and for storage of museum objects in accordance with international standards; an appropriate environment for visitors from the visual and thermal point of view, optimal bioclimatic conditions (internal climate) for exhibits and visitors, balancing the use of daylight in exhibition spaces and rational use of energy for heating and cooling with the intention of reducing operational costs.

Preliminary testing and monitoring, reference room, 2nd floor

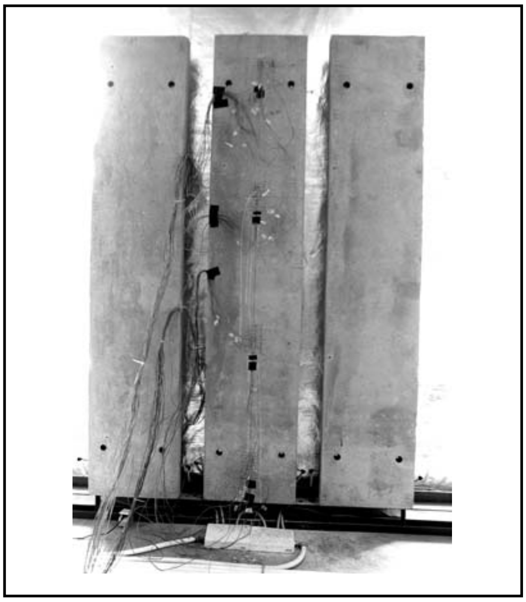
Preliminary testing and monitoring, model room, 1st floor



Production of heating-cooling panels

The issues focused upon in the framework of MUSEUMS SEM project were thermal energy (heating and cooling), ventilation, daylight and control systems. These issues were largely solved in the redesign of the building envelope (wall, roof and basement) by upgraded thermal insulation and in the external walls with the design of a system optimising the relationship between indoor air temperature and indoor surface temperature.

The existing window frames were copied and new upgraded glazing was introduced.



Preliminary testing and monitoring, measurement of temperature distribution inside heating-cooling panels

There were two interventions for the improvement of daylight: roller blinds to prevent glare and provide shading, and the management of daylight and artificial light.

Total floor area is 3,914m^2, with an exhibition area of 2,885m^2. Each floor area is 1,056m^2. Average floor to ceiling height is 3.8m.

3.8.4 Elements of the Environmental Design and Innovations

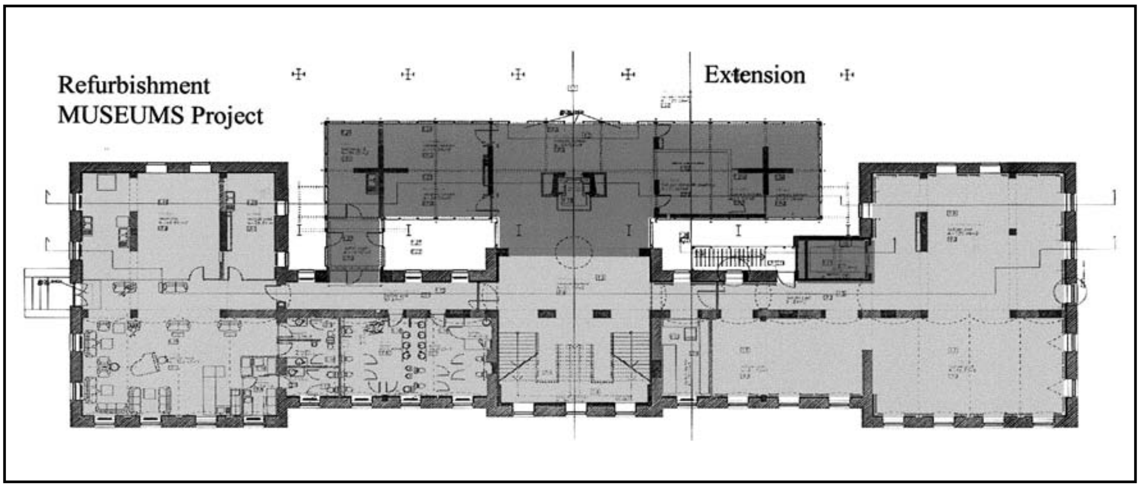
The exhibition area is divided into seven zones: the east wing of the ground floor, two zones east and west on the 1st, 2nd and 3rd floor, which are separately controlled by a BEMS.

- Heating:
  The wall heating system of the building is connected to the district heating system. A temperature / time / season sensitive control system is installed which enables different set-point temperatures to be established.
- Cooling:
  The wall cooling system is connected to a common cooling plant (McQuay AGF-XN 070.2, cooling power: 218kW, electric 88kW, 2 compressors, 4 steps (25, 50, 75, 100%)). The space zones for heating are also those for cooling temperature sensitive control is ensured by ventilation and by the wall cooling system. Both systems are linked and harmonised.
- Ventilation:
  A window-integrated BEMS controlled ventilation system with small tangential fans is used for ventilation during opening hours and for increased night ventilation during the summer period for cooling purposes. An occupancy/time sensitive system has been installed.

Solar shading is separated into three independent zones depending on the orientation: south, west and east. An illumination sensitive control system has been designed, with the option of manual regulation.

The following data will be collected by the BEMS:

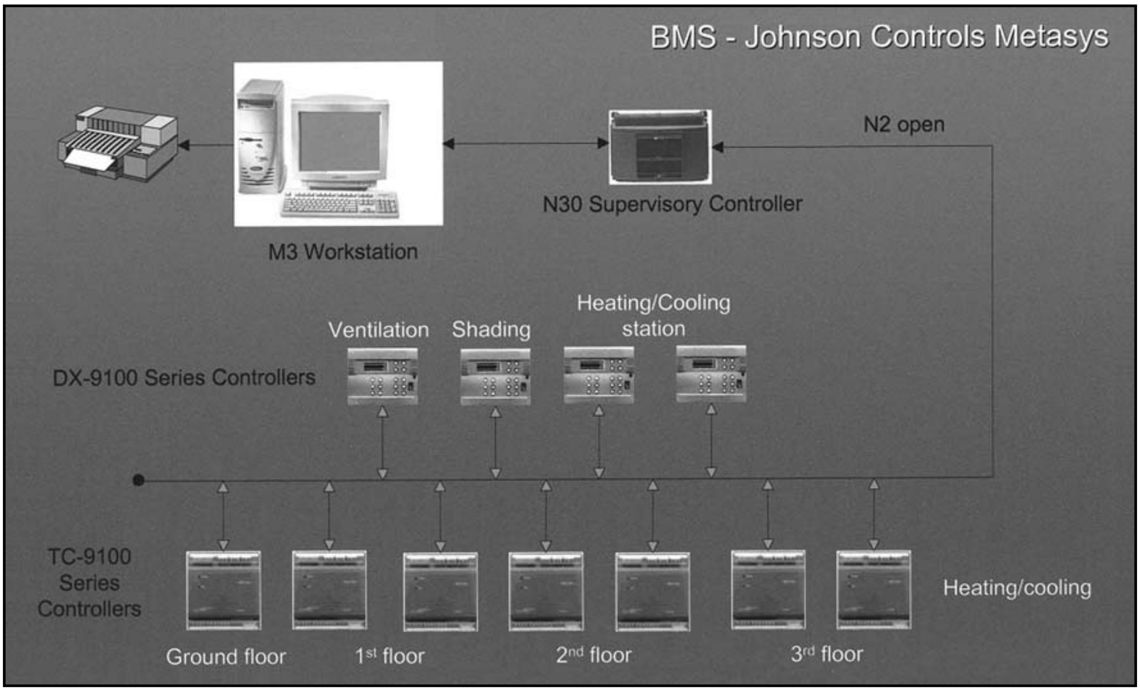
1. Microclimate:
   Ambient air temperature, ambient air humidity
2. Energy Systems:
   Heating consumption (district heating for each zone separately and total consumption), cooling consumption (electricity), lighting consumption (electricity), total electricity consumption.



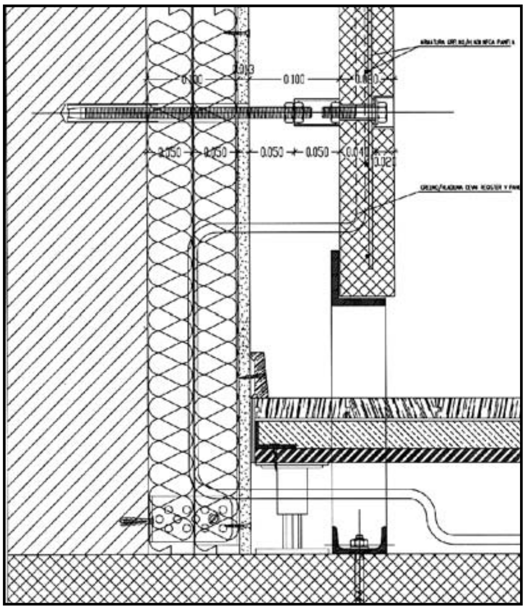
Typical floor with marked refurbished part (light grey) and new extension (dark grey)

3. Indoor Comfort:
   Indoor air temperature, indoor air humidity, and lighting levels

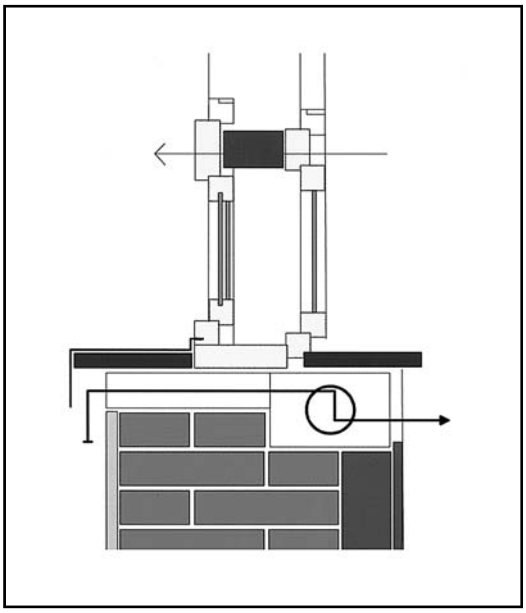
Protocols for the control system have been developed to provide permanent, on-line monitoring during the operation of the building. This system will enable the following information to be available:



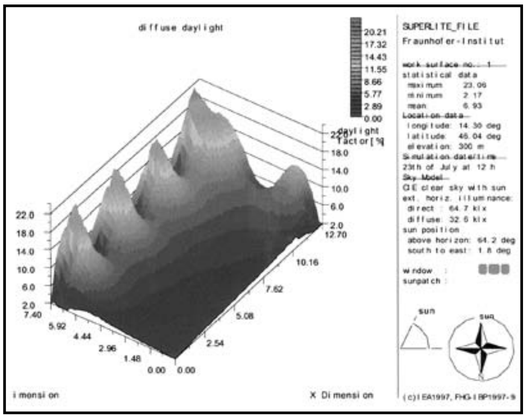
Scheme of build in BEMS



Heating-cooling panel in the cross-section outer wall – floor: construction detail



Scheme of ventilation system



An example of 3D daylight factor distribution

Refurbished interior view with heating-cooling panels and example of sun patches study

Refurbished part of the building after the renovation

3.8.5 Exhibits

In the SEM the majority of exhibits in the exhibition area are not problematic from thermal, visual, air quality or acoustic view point compared to normal human comfort parameters. Among the exhibits, a whole range of materials are represented: paper, textiles, paintings, wood and objects of vegetable and animal origin, metals, photographs, glass and ceramics.

4 EVALUATION & MONITORING

4.1 Evaluation Objectives

A large variety of technical innovations regarding the energy design and control systems were implemented in the retrofitting, conversion or new erection of the museum buildings involved in this project.

The evaluation strategy, with energy simulations and full monitoring aimed to achieve the following:

- To assist designers in the final selection of the various renovating / retrofitting features to be applied by analysing the performance and effect of each system.
- To optimise the design of the energy systems by carrying out sensitivity studies investigating the specific impact of a parameter, component, system or any combination of these in each building and to help adapt their design accordingly.
- To predict / estimate the potential energy savings achieved by comparing initial and final simulation results.
- To assess qualitatively the environmental and energy performance with respect to energy conservation, thermal and visual comfort and indoor air quality.
- To monitor the energy performance of the various systems selected over a period of 12 months (winter – summer) by analysing the recorded data.
- To investigate and assess the real performance of the energy strategies and features implemented by comparing the simulation results with the monitored energy consumption figures; and to evaluate the specific / global energy and environmental efficiency of the final building designs.
- Finally, to compare actual results with initial targets or existing consumption data and to rate/ classify each of the museum buildings according to a rating scheme based on the applied energy norms and performance standards.

The homogeneity of the calculation methods / results that were used to evaluate and predict the impact of the interventions on each building's performance was ensured, as it would be possible to make comparisons of the efficiency of specific measures under various design approaches and environmental conditions, because monitoring would follow through the appropriate protocol and mechanisms.

The evaluation methodology would allow designers to normalise the specific as well as the global energy consumption of the museums, and then compare them to a common reference, traditional museum building. Each energy conservation scenario or package of measures considered could be rated on the same basis, thus direct comparisons were possible. The method allowed for the consideration of not only energy and environmental quality parameters, but also cost and other financial aspects that were taken into account.

4.2 Monitoring Methodology

Monitoring activities were necessary to evaluate in practice the specific and the global energy and environmental qualities of the buildings. Thus, monitoring protocols and strategies were defined and planned in order to get the necessary information to be compared with the theoretical results obtained during the evaluation simulation phase.

MUSEUMS PROJECT - CONTRACT NNE5-1999-20
HORIZONTAL ACTIVITIES GROUPS
Detailed Common Monitoring Protocol

January 2003
37/03

The monitoring phase in each museum was planned to start after its successful commissioning, so as to allow for settled occupation and optimisation of the museum building operation. It lasted 12 months with continuous measurements of the outdoor environment, indoor environment, systems operation and energy use, e.g. space heating & cooling, electricity for ventilation & lighting, contribution from renewable energy sources, etc.

Monitoring aimed to verify the project progress, as well as to report the final results. Being a standard task, this encouraged further exchange of information among the project partners and ensured scientific appropriateness and comparative analogy to the simulations previously performed.

Finally, the various measurements had to be complemented with the distribution of an indoor climate questionnaire to find out how the visitors perceive the indoor air quality and what is the occupancy profile of each building.

4.2.1 Monitoring plan

The monitoring was to be undertaken during all seasons: autumn, winter, spring and summer, in order to test the global efficiency throughout the year. The actions shown below were followed:

- Documentation and selection of the measuring equipment and data loggers.
- Proper set-up of monitoring strategy and installations, running the monitoring with frequent intermediate checks and final analysis and evaluation of the data obtained from the monitoring and the surveys.
- Re-calibration, checking of the data acquisition system.
- Data acquisition, analysis and evaluation of the measurements.
- Determination of the energy codes for the building, comparison of the actual codes with aspirational standards. Reports from the measurement equipment and the recorded data. Comparison of simulated and measured data.
- Conclusions as to what worked as predicted and suggestions for improvements. The first conclusions were drawn after the once-off tests and the final conclusions after the actual monitoring phase.

4.2.2 Description of work

Monitoring comprised a long period of twelve months for the main energy characteristics, but short time / spot measurements were also taken in winter and summer to estimate the thermal energy performance of the museum buildings in accordance with the protocol developed by the project experts.

Measurements include the distribution of air temperatures in the building zones, the specific energy consumption, the wall and roof surface temperatures (interior and exterior), the solar radiation plus all of the relevant meteorological parameters. Thus, the specific performance and contribution of each of the five sub-systems could be assessed under different operating conditions.

Monitoring began with commissioning tests to verify that the installed heating, cooling and ventilation systems were functioning as designed and to determine certain values (air-tightness of building envelope, air flows in ventilation system, etc.).

All the necessary inputs to characterise the thermal performance of the buildings became available, after the application of the retrofit measures. All data were submitted to quality control and data sets were prepared.

To characterise the indoor climate the following parameters had to be monitored during the short time, preliminary tests: thermal comfort within the occupied zone, lighting and visual comfort, etc. As far as the indoor air quality is concerned, the full protocol defined through the IAQ research project of the Commission was adopted. This is mainly based on a walk through approach and very specific measurements are performed only when problems are fully identified.

On some occasions, even the improved microclimate around the museum buildings could be assessed by appropriate monitoring of the specific changes prior to and following the interventions, such as the distribution of the outdoor temperature around the building as well as that of the surrounding surface elements.

To evaluate the performance of the buildings shell regarding natural ventilation phenomena, tracer gas techniques had to be used. A measuring protocol was defined according to the definitions of the Air Infiltration and Ventilation Centre (AIVC), of the International Energy Agency (IEA). In all cases where tracing gas equipment was not available, PFT techniques had to be used. These techniques are very simple and the user has just to collect some samples of indoor air and then send them to a specialised laboratory that evaluates the air flow rates for each considered space.

Data logging equipment

The thermal performance of the opaque and transparent elements of the building's shell could be evaluated by using infrared cameras, when available, or a set of heat flux sensors in the opaque elements. As previously, a monitoring protocol according to the one defined by PASSLINK outdoor testing facilities network has been produced.

Energy consumption of the HVAC and Heat Recovery systems were measured in detail. The specific energy consumption for heating, cooling and ventilation could be measured separately.

Whenever possible, the monitoring system should be linked to the BEMS. For this purpose, additional fuel consumption meters and electricity meters had to be installed, otherwise conventional measuring techniques could only be used. The possible benefits gained from a BEMS system can be evaluated by defining a detailed protocol involving operation of the building with and without the building management system. Such a protocol has been defined through the BUILTECH and GENESYS research projects. Wireless sensing equipment may be used to avoid problems with the occupancy or operation of the buildings.

To facilitate all of the above a complete operational manual was prepared for this task, based on the experience gained through the PASCOOL and OFFICE research programs of the European Commission DG - Research.

Finally, in order to compare the measured efficiencies of the specific systems and techniques, as well as that of the global system, with the corresponding simulation results, a normalisation protocol was necessary. Such protocols permit comparison under the same climatic and operational conditions of the experimental and theoretical results.

A monitoring plan was prepared for each museum building according to the specific alternative systems and techniques coupled with the conventional systems in each building.

4.3 Example of Monitoring Plan- *Summary of Delphi Museum*

Various energy saving interventions were applied to the Delphi Museum in Greece to improve the overall energy performance, the indoor thermal comfort and air quality for visitors & exhibits, to minimise the need for heating & mechanical cooling (air-conditioning), and to improve daylighting, thus reducing fuel and electricity consumption. The changes in the building fabric / envelope, had been designed and were constructed to higher than Building Regulation standards in Greece. Further improvement of the building thermal efficiency and optimisation of the energy systems use, were achieved through the installation of an advanced BEMS system.

A detailed monitoring programme was in progress for a period of 12 to 14 months to assess the performance of specific energy retrofit systems in this building.

The general aims were:

- To assess the overall energy use and thermal performance of the building fabric.
- To assess the energy performance of the HVAC and energy systems.
- To assess to what degree of indoor comfort (thermal, visual, etc.) was being achieved.
- To obtain visitors' and operators' views on comfort and systems usage.
- To produce guidance for staff on the best use of the BEMS and to optimise the performance of the various systems.

The way in which the BEMS system performs will affect greatly the indoor comfort and energy consumption achieved and thus part of the monitoring was to carry out trials on different usage patterns (combined effects).

Opening or closing of windows and shading devices, demand ventilation air flow rates, use of night ventilation, ceiling fans and artificial lighting, were the main systems to be controlled by the BEMS.

There were other environmental factors that can not be controlled such as wind speed and direction, external temperature and humidity levels, some of which were recorded and assessed separately.

The first stage of the monitoring was virtually a "commissioning" stage, to carry out short term and on the spot measurements (plus adjustments) to optimise the system and to propose the best use of the system. The second stage was a long term (twelve month) period of recording of energy, comfort and system usage.

4.3.1 Stage One - Preliminary monitoring

Commissioning and adjustments recommendations: It was proposed to spend between a few weeks and a couple of months (one in winter and one in summer including non-visiting hours) taking measurements in the building and trying out different operating patterns / uses by adjusting the BEMS controls.

These included the following:

- Installation and testing of all monitoring sensors / equipment (including those installed during construction).
- Use of the air inlet / outlet temperatures, time of day, and fresh air fan / damper control
- Testing of the demand control ventilation patterns for heating / cooling at different volume rates (CO_2 concentrations)
- Setting of summer night cooling options (forced or natural ventilation)
- Effects of various shading devices and automatic opening windows on indoor comfort, (thermal, daylighting and noise levels).
- Effect of internal gains (different numbers of visitors, etc.) in each zone

4.3.2 Stage Two - Long term monitoring

A. Monitoring of energy use

Methodology: A great advantage offered by BEMS control is the continuous monitoring of all the building zones of the Delphi museum as well as of each energy system individually.

The overall electricity use and fuel consumption were monitored over a whole year. Automatic meter readings were taken hourly and the data were stored in the Control Room computer (Excel database) to allow for further analysis.

Similarly, the electricity used by the auxiliaries (fans, pumps, etc.), the HVAC units and other systems (lighting, ceiling fans, etc.) were also sub-metered and data-logged at regular intervals (by software settings). The sub-meters were fitted to the units during installation and the output "pulsed" data, could be logged to provide both times of use and energy consumed.

The main objectives of the analysis were to:

- Determine the energy use for heating, cooling, ventilation, lighting, etc. i.e. the energy consumption of the systems and the times and hours run.
- Compare the actual total energy use in the selected building or zones with that of other conventional museum buildings in Greece.
- Check on any additional energy demand or adjustments over the monitoring period.

Although it was not intended to monitor energy use outside the twelve month period, the BEMS would offer the capability of continuous monitoring and total dynamic control of all the energy systems over the whole lifetime of the installation.

B. Monitoring of indoor comfort

The maim aim is to preserve the exhibits in top condition, while maintaining adequate thermal, visual and acoustic comfort levels both for the visitors and staff.

Methodology: In this part of monitoring the internal and external conditions and systems usage were recorded over the whole monitoring period, while visitors' perception of comfort was also assessed (see next paragraph).

The following variables have been monitored for the different building zones on an hourly basis during the heating and cooling seasons:

- External temperature
- External relative humidity
- Exhibition Hall temperatures
- Exhibition Halls Relative humidity
- Illumination levels
- Air change rates & air movement in the halls
- Number of Visitors / usage patterns
- CO_2 concentration levels

In addition to from the BEMS sensors (temperature, humidity, CO_2, lux, etc.) permanently installed in each zone, Tiny-talk loggers were also used to collect the temperature and humidity data in particular areas / positions. Air change rates (ACH) have been determined from the flow inside the ducts of the HVAC system and the use of tracer gas techniques, bearing in mind the effects of automatically opening windows. Illumination and noise levels at specific positions was obtained by spot metering.

C. Monitoring of the energy systems

The performance of the each system must be determined to assess the individual degree of success and its contribution to the overall energy saved. The following are the key issues:

- The fuel or electricity consumed by each system
- The volume of air delivered (ACH)
- The air temperature and relative humidity in the supply ducts and return ducts
- Solar radiation and weather data

Methodology: All of these systems (demand ventilation, night ventilation, auto-shading, etc.) were monitored and controlled by the BEMS. Performance monitoring has been achieved with systems included in the BEMS control software package, through specially installed sensors and actuators. Readings from these instruments were programmed and recorded as necessary.

Similarly, sensors to measure the temperature and relative humidity of the inlet and outlet air were included into the HVAC plant, as well as air flow meters and electricity consumption counters.

Solar radiation and wind weather data were been obtained from the nearest station in the area.

D. Visitors / Operators Surveys

It is important that the visitors are comfortable in the building and that staff can operate the various systems and controls easily. A survey was carried out to assess the following issues:

- Thermal, optical and acoustic comfort
- System use patterns, window opening, demand ventilation, daylighting, etc.
- Problems of overheating, over cooling, draughts, noise, smells, etc.
- Ease of use of BEMS controls (cooling, heating, ventilation, lighting, etc.)
- Opinions about energy and maintenance costs

Methodology: All of the museum building zones subjected to detailed monitoring were included in the survey that took place during and after the planned data acquisition. The issues mentioned above were discussed and analysed.

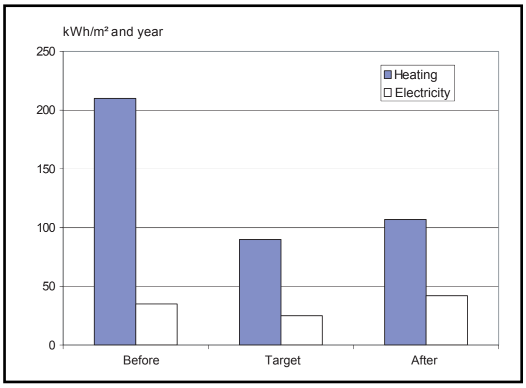
Staff working patterns which are strongly related to the above were assessed from observations, actual use of the museum building and from the operators' questionnaires. Visitor comfort / satisfaction was determined via the visitor survey forms.

4.4 Museum Buildings Monitoring

A summary of monitoring results for the building in the MUSEUM project follows. A monitoring plan had been prepared for each museum building. The monitoring phase of the project started at a later stage, since this was scheduled to occur after retrofitting.

4.4.1 KRISTINEHAMN MUSEUM OF CONTEMPORARY ART, SWEDEN

Computer simulations were performed and have been completed successfully. The initial target was to reduce loads for heating by 60% from 210 kWh/m^2 and for electricity / lighting by 30% from 35 kWh/m^2.

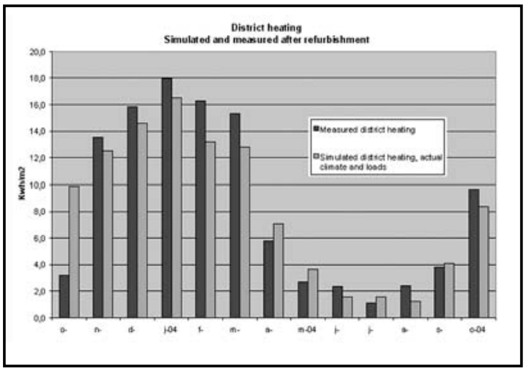


Simulation results gave final annual energy demands of 90 and 25 kWh/m^2 respectively, whereas actual monitoring figures came close to 107 and 42 kWh/m^2, leading to an overall energy saving of around 40%. The solar collector for preheating outdoor air contributed 7 kWh/m^2 (m^2 of floor area) or 250 kWh/(m^2 of solar collector area). Full monitoring started in summer 2003 (after opening in April) and continued until the end of the year 2004.

The monitoring period began with on-the-spot metering tests to discover if the installed heating and ventilation system was functioning as designed and to determine certain values. The indoor climate was also monitored in detail during these tests.

A follow-up of the energy use during the period November 2003 - October 2004 gave an actual energy use 20% higher than the target value. In order to normalise the measured energy use, dynamic energy simulations have been performed with reference climate data and actual loads including excess ventilation to investigate the reasons why the energy use was higher than the target.

The actual monitoring phase included continuous detailed measurement of the outdoor environment, the indoor environment, energy use and system operation. The result is presented in the following diagram:



District heating energy use

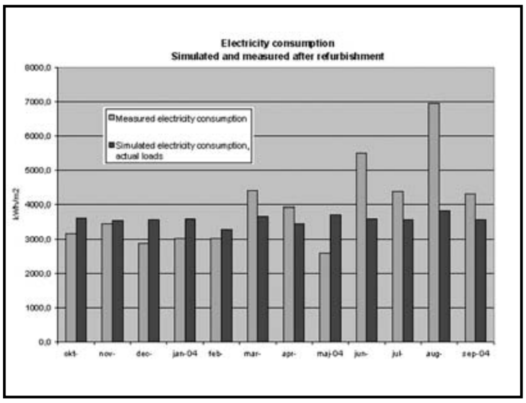
The whole monitoring phase lasted 18 months, and the system was integrated with the building energy management system (BEMS). The measure-ments were evaluated and compared with the specific performance specifications.

In order to normalise the continuously measured energy use and indoor climate, the energy and indoor climate simulations were repeated using existing materials, installations, loads and reference climate data. This was done to enable a comparison with the predictions and so that the results for a normal climate year could be presented.

The measured use of electricity was 70% higher than the target value. However, additional equipment such as computers and alternative ventilation were not included in the target value.

In the following diagram, the measured use of electricity is compared with a simulation using actual loads.

Cooling was not included in the simulations. The cooling system was turned on during parts of the summer period in July and August, which explains the higher energy use in these months.



Electricity consumption

4.4.2 HERZOG-ANTON-ULRICH MUSEUM, BRAUNSCHWEIG

The investigations included values of the indoor and outdoor climate as well as criteria for visual comfort for the retrofitting of the Herzog-Anton-Ulrich Museum .

Detailed measurements were made for the windows and the thermal insulation of the external walls to evaluate different design concepts.

The thermal behaviour and the energy consumption were measured and compared with the results anticipated from simulations. In addition, the monitoring data were used to identify the simulation parameters.

To cover both scenarios (before and after retrofitting), the designed changes were constructed in two reference rooms, which were then compared with their neighbouring rooms. Instrumentation was installed and some monitoring work had already started in 2003.

Exhibition space

Each room was equipped with the same sensors in similar positions. Several surface temperatures were also recorded as air temperatures to give meaningful values for the indoor climate as was the relative humidity close to the paintings. In addition, the vertical illuminance was measured to identify the loads by radiation.

Investigations with an infrared camera were carried out to evaluate the thermal quality of the building envelope of the building. This allowed the exact determination of surface temperatures.

Further analysis of different structural elements, such as radiator niches and window / wall junctions helped identify thermal bridges. The thermal insulation on the inside of the building had to be improved at these places and the junctions had to be sealed.

Heating is supplied by a district heating network. A single month's consumption was measured to verify the accounts of the utility supply company. The energy consumption was recorded with an ultrasonic heat meter in the heating room. The comparison of the measured data with the account of the energy supply company showed a good correlation, so their data could be used further in the project.

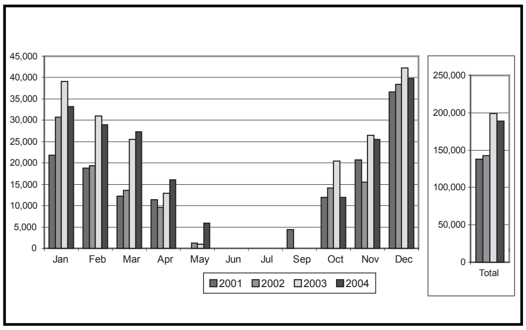
Monitoring showed a base load of nearly 10 kW caused by decentralised air conditioning, circulation pumps etc. The opening of the museum around 08h00 led to a rise in the electric power consumption of nearly 30 kW. The visiting hours after 10h00 am showed a high load 40 to 60 KW due to the lighting.

Energy monitor

Analytical thermal and lighting simulations were completed with ESP. A 3D model was also used to analyse the heating and ventilation systems as the main objective was to control relative humidity.

4.4.3 NATIONAL ETRUSCAN MUSEUM 'POMPEO ARIA', MARZABOTTO

Simulations were completed by using ESP-r. Final annual energy demand results show 74 kWh/m^2 for heating, 1 kWh/m^2 for ventilation/cooling (only passive cooling) and 8 kWh/m^2 for electricity, compared to the initial values of 219, 14 and 34 kWh/m^2, and give an overall energy reduction greater than 60%.



Monthly monitored energy consumption

Results show a benefit due to the greater global efficiency of the new heating system and to improvements in the envelope insulation in some parts of the museum.

Such benefits as evaluated are limited because they include consumption for a large museum zone for which no interventions were planned or executed while at the same time they exclude the newer parts (new exhibition space and multi-function room), which are completed but not yet heated.

Exhibition space

Once the new exhibition space and multifunction room are used, specific performance, evaluated on a square meter basis, will be higher. These new spaces are highly insulated, they benefit from passive solar gains and they are provided with a very efficient low temperature heating system integrated within the floor Pre-existing rooms are heated with conventional radiators.

Full monitoring started in September 2003 and continued until the end of 2004. Monitoring data were combined with simulation results for the exhibition and multifunction spaces to allow consistent estimation of future global energy consumption.

Simulated annual energy demand for heating on a square metre basis for the whole museum, and specifically for the new exhibition and multi-function room was as shown below:

Space	Proposed Project	Reference building (standard project)	% of savings
Whole museum	74	219	66%
New exhibition room	37	92	60%
Multifunction room	20	71	72%

Values are expressed in kWh/(m^2 year)

Estimated global annual energy demand (monitoring + simulations):

Space	Proposed project	Reference building (standard project)	% of savings
Whole museum	105	219	52%

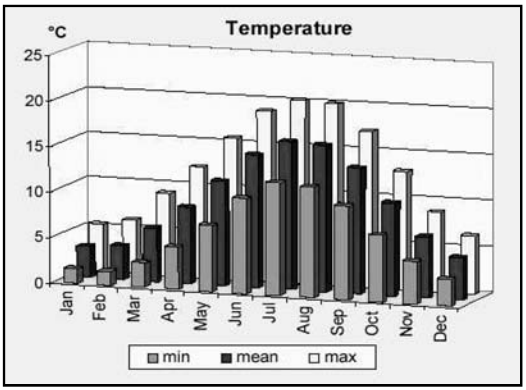
Values are expressed in kWh/(m^2 year)

Simulated annual energy demand

The monitoring results following interventions showed an improvement of overall thermal conditions. Although the requirements were not fully verified (in particular during the summer season), there is still strong will to take corrective actions, i.e. boosting natural ventilation. Thermal variations after interventions were more stable than before thanks to the better thermal insulation and inertia obtained by increasing the thermal mass of the walls.

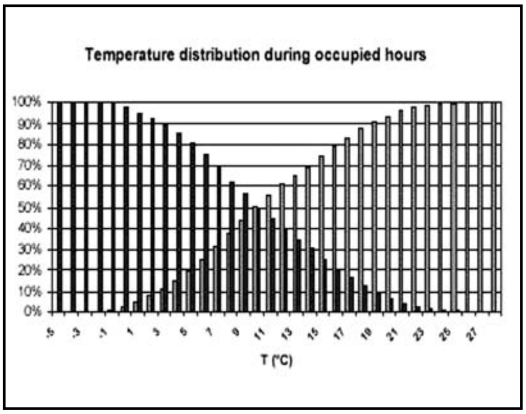
A severe climate control only by means of passive strategies proved to be a very difficult task. The results showed that even if the requirements are not fully satisfied, this is not really critical either for the exhibits and / or visitors. Moreover, since only passive strategies are applied, this represents an appreciable result. When necessary a larger use of active systems may assure the complete fulfilment of the requirements especially R.H. control and air temperature during the hottest summer days.

4.4.4 THEpUBLIC ARTS CENTRE, WEST BROMWICH



Monthly temperatures

Final simulations were completed in 2003 by TAS. Energy demand was expected to be 120 kWh/m^2 for heating, 15 kWh/m^2 for cooling and 25 kWh/m^2 for lighting. A saving of 46% is achieved when compared to the annual total of 300 kWh/m^2 shown by normal practice. A detailed natural ventilation simulation study has also been completed (using tools such as COMIS, etc.).

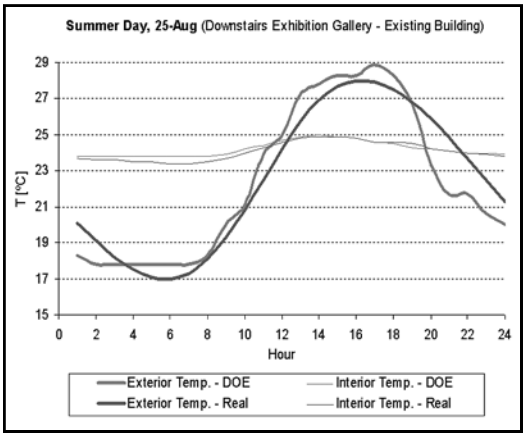


Temperature distribution during occupied hours

4.4.5 NATIONAL ARCHAEOLOGICAL MUSEUM, LISBON

The new MNA Museum described in chapter 3 was still not built by the end of 2004 and thus no monitoring of the indoor environmental conditions in the refurbished museum have been possible. However, the conditions inside the existing museum have been monitored to evaluate any need for HVAC systems in the existing spaces, which will continue to be used as the main exhibition space.

The results clearly showed the need for heating in the existing building, as well as a slight overheating tendency in the upstairs galleries that may increase with the higher loads that will result from their use as exhibition spaces. In summer, downstairs, the temperature is so stable that no HVAC is needed. The typical indoor relative humidity level is fairly constant and within the desired range for both occupant comfort and exhibit conservation.



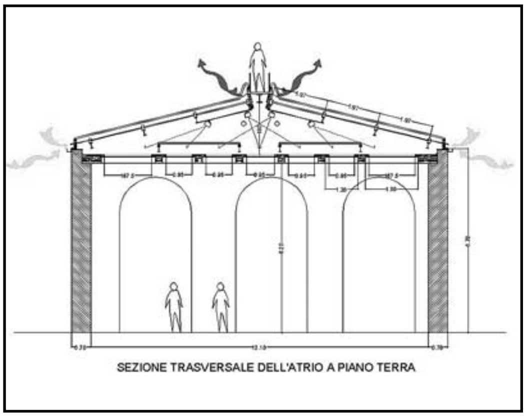
Summer day temperature swings

These results were the justification for designing a floor heating system in the downstairs galleries and a full HVAC system for the upstairs galleries. Simulations were completed using the DOE-2 tool. A detailed model was also developed for more precise analysis of the building performance.

The upgraded energy consumption was predicted to be 53.9 kWh/m^2 (35.2 kWh/m^2 for heating and 18.7 kWh/m^2 for cooling) giving a payback period of 2.1 years for the best (chosen) solution condensing gas boilers and two air cooled chillers).

4.4.6 BARDINI MUSEUM OF FLORENCE, ITALY

The monitoring phase and analytical thermal lighting simulations in the Bardini Museum building have been completed in order to assess the performance of the specific energy retrofitting systems. A large quantity of data was collected and analysed following 12 months of continuous measurements of the outdoor and indoor environment, systems operation and energy use of space heating and cooling, together with contribution from renewable energy sources. In particular, the monitoring focused on the third floor of the museum during all of the representative seasons where the new energy and lighting systems were fitted in order to test their global efficiency throughout the year.

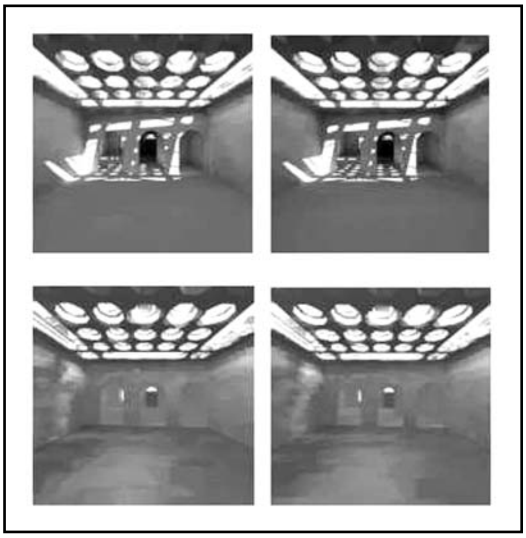


Cross section of the building showing ventilated roof

The performance of the systems had been determined through thermal, daylighting and comfort simulations, in order to assess the degree of success and their contribution to their overall energy saved:

A 3D model was used for analysing the heating and ventilation systems as the main objective was to control Temperature and RH. The simulation results showed that the thermal loads decreased from 133.4 kWh/m^2 to 69 kWh/m^2 for heating, with an energy saving of 48% annually, while increasing the internal comfort for occupants; the cooling loads decreased from 61.2 kWh/m^2 to 31.6 kWh/m^2 due the installation of a natural ventilation system below the window frames which improved thermal comfort during the summer season.

For daylighting evaluation, a simulation was performed with the RADIANCE tool that allowed daylighting levels in the interior spaces to be predicted and helped to analyse possible glare problems caused by the retrofitting measures.



RADIANCE images of ceiling

The reflectance of the wall stone coloured finish was carefully analysed because investigation work have revealed its original blue painting and the designers decided to restore the original colour. The natural stone finish had a reflectance of about 60%, while the blue finish reflectance was 35%. The measured wall illuminance under the brighter sky conditions had therefore, changed from 42.5 cd/m^2 (stone) to 25.6 cd/m^2 (blue) and under the darker lighting conditions from approximately 25 cd/m^2 (stone) to 16 cd/m^2 (blue).

Finally, some accurate calculations were carried out to evaluate the Indoor Air Quality with regard to the concentration of indoor pollutants and to estimate the real air-flow, and the contribution of fresh air introduced into the space by the natural ventilation system which integrated in the replaced windows. A thermal comfort analysis was also performed using PMV and PPD indices. The analysis showed that no pollution problems occur due the changes and that comfort conditions were satisfied.

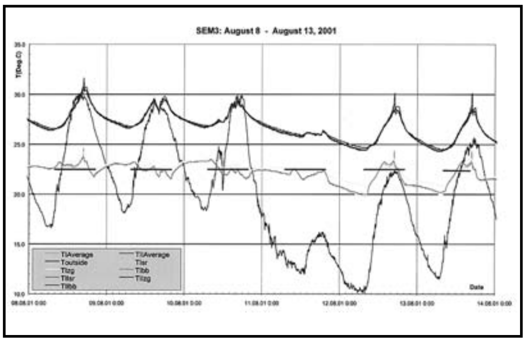
4.4.7 SLOVENE ETHNOGRAPHIC MUSEUM

Simulations were completed by using the TRNSYS software programme. Studies were also performed by using various tools such as SUMMER (thermal), ADELINE (illumination) and ASHRAE guide (HVAC).

The original target was to reduce energy needs by more than 40%. Final results of monitoring show 50.4 kWh/m^2.yr for heating, (reduction for 67%), for cooling 11.2 kWh/m^2.yr, for lighting 28.2 kWh/m^2.yr (reduction for 40%).

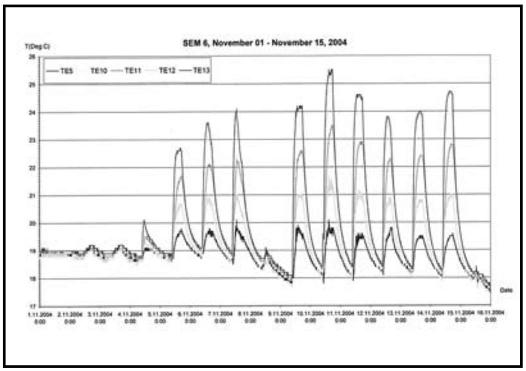
- First phase of measurements:
  Measurements started when the building was closed. Daylight and temperature in free run mode (two rooms: 3rd floor, SE and SW corner) was observed and analysed.
- Second phase of measurements:
  Two rooms were renovated on the 1st and 2nd floor, SW corner; with new thermal insulation on the outside walls, low-e, argon filled glazing and an electric heating system between autumn 2000 and March 2001.
- Third phase of measurements:
  Heating-cooling panels, with cooling aggregate and heating system, ventilation and control were placed on the 1st floor. Second phase

renovations were carried out on the 2nd floor between March 2001 to July 2002).



A 6 day period in summer (August) in intermittent cooling mode, August 2001

- Fourth phase of measurements:
  The whole building was monitored during 2004 in periods: winter-spring testing of the heating system, summer testing of the cooling system and autumn-winter testing of the heating system and additional measurements of illumination levels.



Vertical heating-cooling panel surface temperature distribution profile: 15 day period, November 2004

- Fifth phase of measurements:
  The integration of a permanent BEM system represented the results of the preliminary measurements. The BEMS controls and monitors defined parts of the building, constructional performance (heating-cooling wall panels, ventilation, illumination) and energy use (thermal and electric). This enables the control of selected fields of energy use performance in order to control internal environmental conditions in different rooms, and to reduce energy use without impacting on exhibits and visitors.

  The results of the second phase of measurements resulted in the decision to use the heating-cooling wall panels system on 2,884.6m^2 of exhibition area in the building, which is part of the Museums project, and the basis for the rejection of the original design to control of the internal environment.

4.4.7.1 Experiments of heating-cooling panels performance

Panel temperatures - plane distribution and average inside air temperatures

Panel temperatures were measured in 35 different places at four heights. Measurements took place between March 2001 and July 2002. The measuring period included all four seasons which enabled the testing of system in heating as well as cooling modes.

4.4.7.2 Measurements in refurbished building

The building was monitored between 1st January 2004 and the 31st December 2004, at one minute intervals.

4.4.7.3 Measured quantities

- Microclimate:
  Ambient air temperature, ambient air humidity, global solar radiation on horizontal level.
- Energy Systems:
  Heating consumption, cooling consumption, lighting consumption.
- Indoor Comfort:
  Indoor air temperature, indoor air humidity, lighting levels and CO_2.

4.4.7.4 Data acquisition and monitoring strategy

- Microclimate:
  Sensors for ambient air temperature and ambient air humidity are mounted on the north elevation of the building. Global solar radiation data was assessed from the Environmental Agency of the Republic of Slovenia, Ljubljana.

Energy Systems

The 2,575m^2 Exhibition area in the east wing of the ground floor and on the 1st, 2nd and 3rd floor (east and west) is divided into seven zones, which are separately controlled by the BEMS.

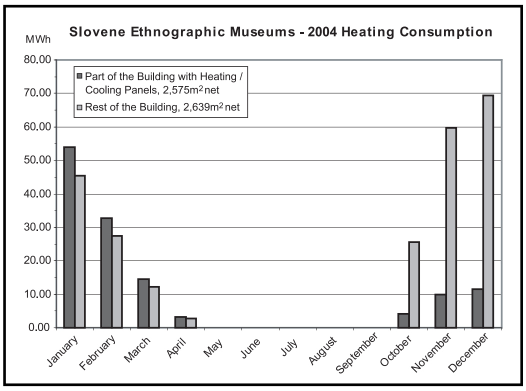
Measurements of temperatures and illumination levels

- Heating:
  The building is connected to the district heating system and supplied with several heat meters connected to the BEMS which enable the separate metering of heat consumption of the whole building the area with the wall heating system.
- Cooling:
  The zoning also allowed the cooling consumption to be measured.
- Electricity:
  Two meters connected to the BEMS enable metering of electricity consumption for ventilation and lighting for one floor with an exhibition area.

Indoor Comfort

For each zone indoor air temperature and indoor air humidity were measured.

There are two different energy use patterns in heating season: at the beginning and at the end of the year. In the earlier part energy consumption was higher in the part of the museum with wall panel heating by approximately 8.6%. During this period the controller maintained a constant temperature for 24 hours per day for the whole building.



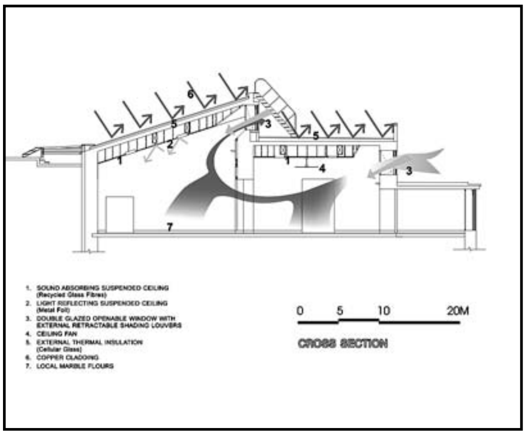
Heating consumption in 2004

In the second part of the heating season the HVAC system in the new extension and storage areas was fully functional for one period during and the other the results of tuning of the BEMS (intermittent heating, ventilation) become evident in an 80% reduction in energy consumption in December 2004 when compared with January 2004.

4.4.8 ARCHELOGICAL MUSEUM OF DELPHI, GREECE

Preliminary and final thermal simulations had been completed with the use of TRNSYS. Predicted energy demands were 55.2 kWh/m^2 for heating, 14.4 kWh/m^2 for cooling and 47.3 kWh/m^2 for lighting with an annual total of 116.9 kWh/m^2.

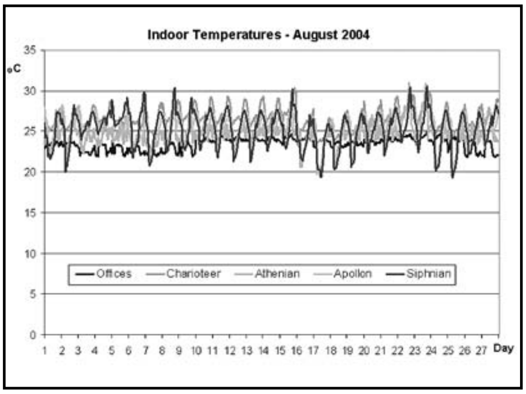
Pre-monitoring (free-float) started at the beginning of 2003, while full monitoring began towards the end of 2003 (after the renovation was almost complete) and continued until the end of 2004. The monitoring period was divided into Phases I and II.



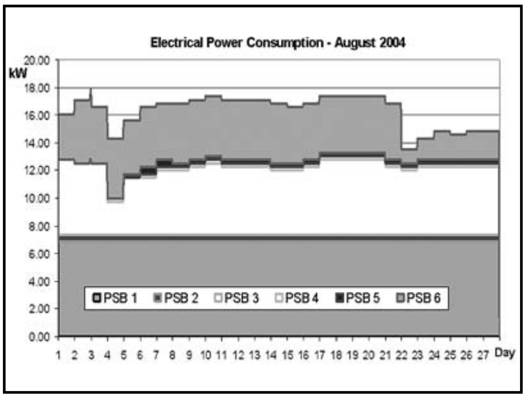
Thermal and air flow system

This was because, due to on-going operations and adjustments to the museum's Electro-Mechanical Systems, the BEMS control did not functioning fully initially, and for that reason extra recording instruments had to be used in parallel for data logging and comparison purposes. In addition, it was the year of the 2004 Summer Olympic Games, and therefore many changes in the normal operation of the museum took place as there was an increased number of visitors.

The BEMS controls and systems continued their full time data logging of temperatures, humidity, electricity consumption, etc. until the end of the year (Phase II).

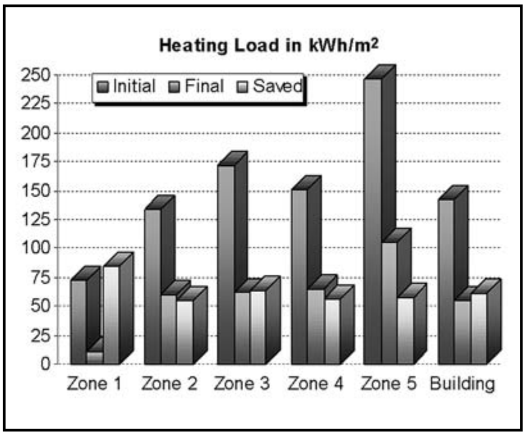


Indoor temperatures - August 2004



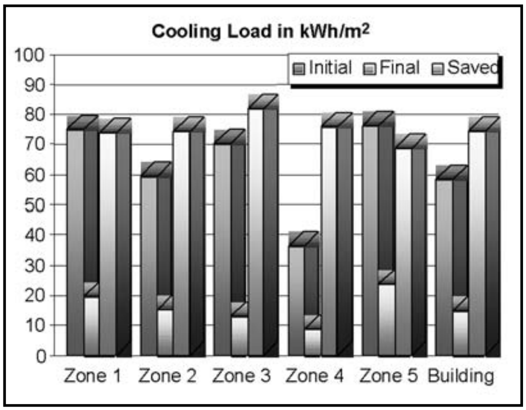
Electrical power consumption - August 2004

The project target was to achieve a reduction of 60% in the heating load, 70% in cooling load and 60% in electricity (60% in total for energy and CO_2).

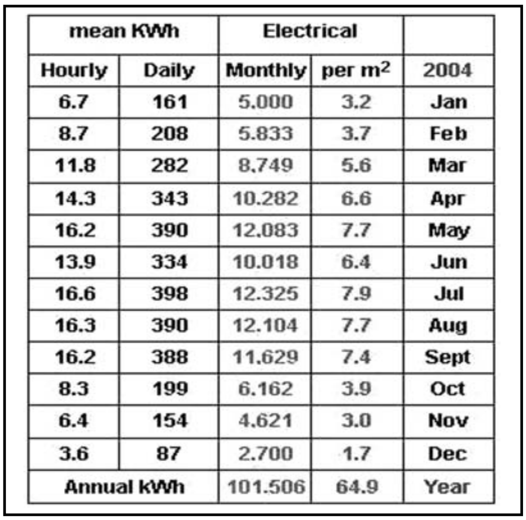


Heating load in kWh/m²

During the monitoring of this start-up winter period, the fuel consumption for heating was negligible - although heating loads existed, This was because of the mild winter ambient temperatures in 2004 and also due to the high internal gains from lighting equipment and the large number of visitors. Therefore, there was little need for heating. Furthermore, the above heating loads in Winter include the Charioteer's hall, which was not included in the retrofitted part of the Delphi Museum and is heated by an independent heating unit.

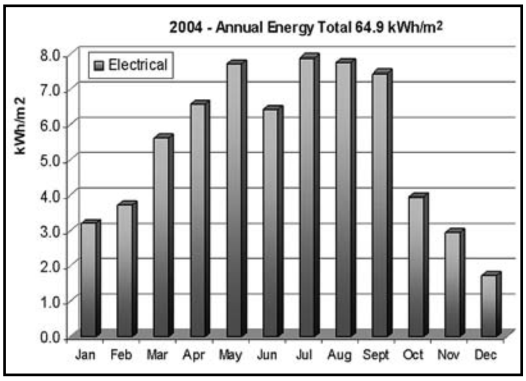


Cooling load in kWh/m²



mean KWh		Electrical		
Hourly	Daily	Monthly	per m2	2004
6.7	161	5.000	3.2	Jan
8.7	208	5.833	3.7	Feb
11.8	282	8.749	5.6	Mar
14.3	343	10.282	6.6	Apr
16.2	390	12.083	7.7	May
13.9	334	10.018	6.4	Jun
16.6	398	12.325	7.9	Jul
16.3	390	12.104	7.7	Aug
16.2	388	11.629	7.4	Sept
8.3	199	6.162	3.9	Oct
6.4	154	4.621	3.0	Nov
3.6	87	2.700	1.7	Dec
Annual kWh		101.506	64.9	Year

Monthly energy consumption



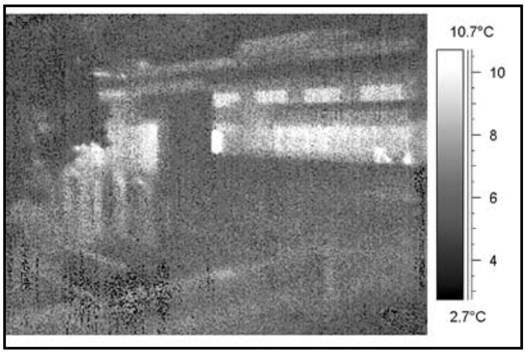
Total annual energy electrical consumption 2004

The electrical consumption presented above, includes all of the electricity consuming devices, i.e. the lighting equipment, the summer cooling A/C chiller and the auxiliaries (ventilation fans, pumps, motors, etc.).

Finally, an energy audit was performed to check thermal and visual comfort, indoor air quality, etc.

On the spot measurements of surface and air temperature in the interior of the building were also performed. To evaluate the energy and environmental behaviour and performance of the building.

Normal view of part of museum exterior



Same view using infra-red thermographic camera

Infra-Red thermography was also used to assess the homogeneity of the internal surface temperatures of the building shell. Temperature and relative humidity in the interior and exterior were also measured.

As far as indoor air quality is concerned, extensive measurements were performed in all exhibition areas for the detection and evaluation of internal pollutants. carbon dioxide, carbon monoxide and total volatile organic compounds (TVOCs) were measured. The tracer gas method was employed for the evaluation of the air change rate.

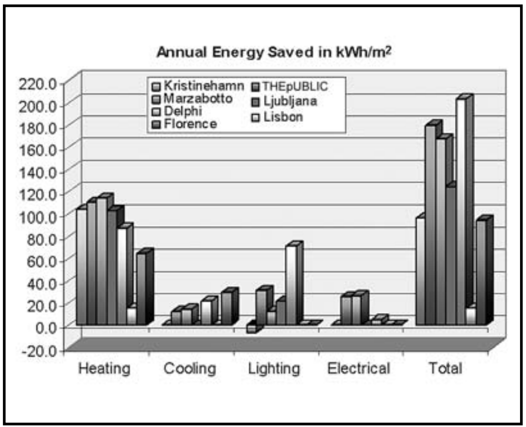
Indoor air quality was found to be excellent as carbon monoxide and carbon dioxide is concerned. Maximum concentrations for CO_2 and CO were 604 ppm and 0.40 ppm respectively. The concentration of TVOCs was slightly increased in some cases, but remained within acceptable limits.

The Air Change Rate (ACH) was calculated at 1.59 air changes per Hour. This value is representative for most of the museum areas and was considered to be a good compromise between energy efficiency and indoor air quality.

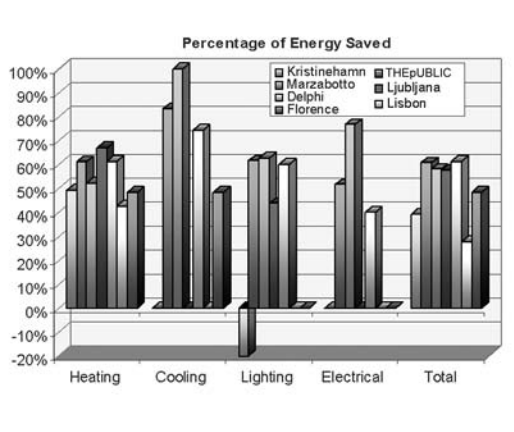
5. 'MUSEUMS' - PROJECT ACHIEVED RESULTS

The project was completed with partial success due to unexpected delays and unforeseen problems five of the nine museums in the initial proposal, only 5 to complete all of the work phases. One museum dropped out from the start, one reached the design evaluation stage within the time limits of the project and two more completed part of the construction works. Five sites progressed according to plan to complete construction and monitoring stages.

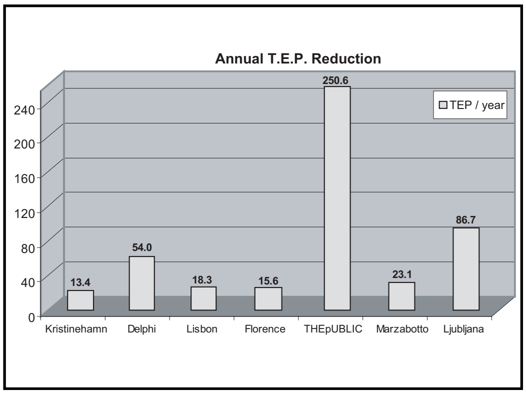
A brief summary and comparison of the simulation and / or monitoring results (energy savings, TEP reduction, CO_2 reduction and payback period) obtained for the museum buildings participating in this EU - RTD museums project is presented in graphical form below:



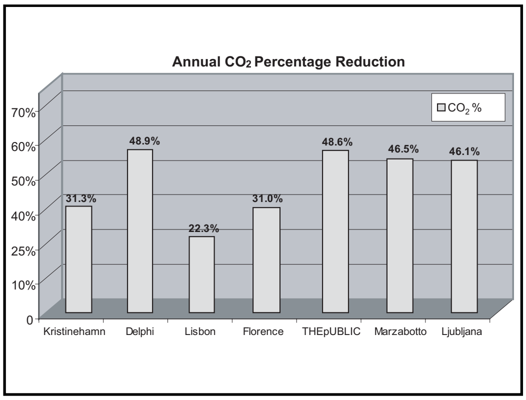
Annual energy saved in kWh/m²



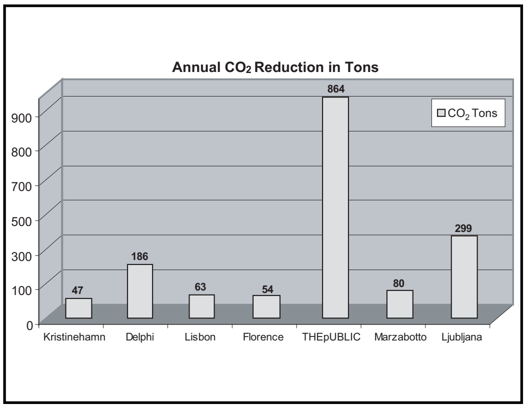
Percentage of energy saved



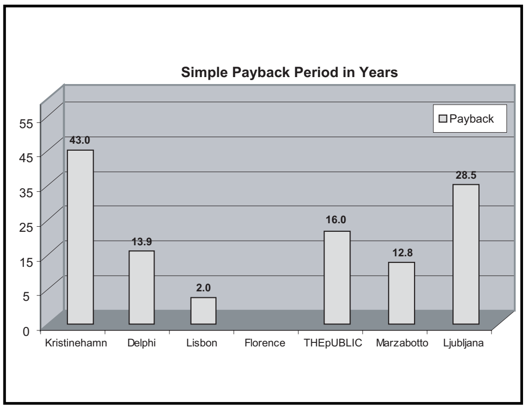
Annual TEP reduction



Annual CO_2 percentage reduction



Annual CO_2 reduction in tons



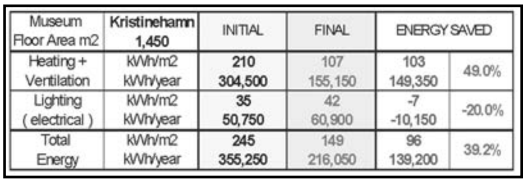
Simple payback period in years

5.1 Kristinehamn Museum of Contemporary Art, Sweden

The aim was to convert a large former local district heating plant into an energy-efficient art museum while preserving the character of the building. Before the renovation, the building had virtually no thermal insulation, poor windows and uncontrolled natural ventilation, thus being expensive to heat during the winter. New, cost effective and innovative methods for heating were necessary to use the building comfortably in wintertime. The following innovative features were implemented: a major increase in thermal insulation in the attic and in the basement, upgrading of windows, solar collectors for preheating of supply air, demand controlled hybrid ventilation, advanced climate control and BEMS, energy efficient lighting and improved daylighting.

The project has been implemented according to the project description and so far without any major problems in operation.

The total investment cost (materials and installation) for the features improving the indoor climate and reducing the energy use is €604,770, of which €538,401 are eligible costs. The eligible costs related directly to reduced space heating and use of electricity are €355,862. There are however further possibilities to reduce costs in the next project. The simple payback time is 43 years. The expected service life of the improved mechanical and lighting system is longer than 25 years and for the building technology improvements, this is 40 years.



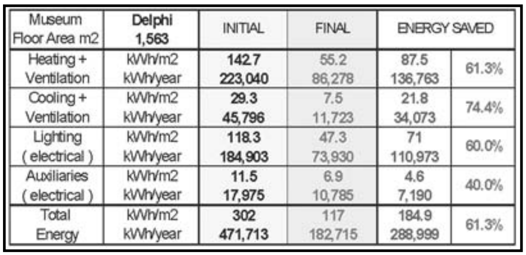
Museum Floor Area m2	Kristinehamn 1,450	INITIAL	FINAL	ENERGY SAVED	
Heating + Ventilation	kWh/m2 kWh/year	210 304,500	107 155,150	103 149,350	49.0%
Lighting (electrical)	kWh/m2 kWh/year	35 50,750	42 60,900	-7 -10,150	-20.0%
Total Energy	kWh/m2 kWh/year	245 355,250	149 216,050	96 139,200	39.2%

Energy savings for Kristinehamn Museum of Contemporary Art, Sweden

The annual energy use for space heating was reduced by 50 % from 210 kWh/m^2 to 107 kWh/m^2 and this could easily be further reduced to the target 90 kWh/m^2/year. The annual use of electricity was increased due to additional equipment. Without these additions, electricity would have been lower than before (35 kWh/m^2) and closer to the target (25 kWh/m^2), even though the artificial lighting and ventilation were improved. The refurbished museum building is heated by district heating generated by a biomass (wood chip) heating plant. If the refurbished building had had an oil based heating system, then the reduction in CO_2 emissions would have been 48 tons per year for the heating energy savings obtained.

In Sweden many old building (mainly hospitals, factories and army buildings) are being converted into museums, offices etc. However, they seldom result in an energy efficient, healthy and sustainable building. This project has clearly demonstrated how these aims can be achieved.

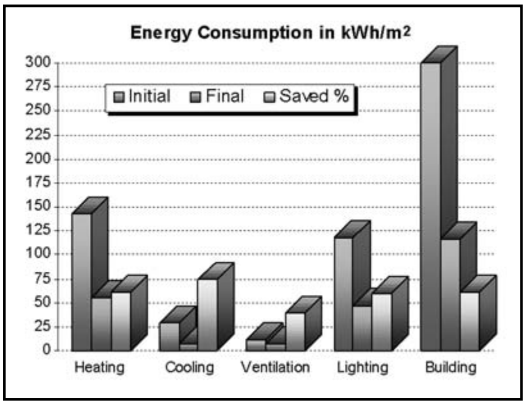
5.2 Archaeological Museum of Delphi, Greece



Museum Floor Area m2	Delphi 1,563	INITIAL	FINAL	ENERGY SAVED	
Heating + Ventilation	kWh/m2 kWh/year	142.7 223,040	55.2 86,278	87.5 136,763	61.3%
Cooling + Ventilation	kWh/m2 kWh/year	29.3 45,796	7.5 11,723	21.8 34,073	74.4%
Lighting (electrical)	kWh/m2 kWh/year	118.3 184,903	47.3 73,930	71 110,973	60.0%
Auxiliaries (electrical)	kWh/m2 kWh/year	11.5 17,975	6.9 10,785	4.6 7,190	40.0%
Total Energy	kWh/m2 kWh/year	302 471,713	117 182,715	184.9 288,999	61.3%

Energy savings for the Archaeological Museum of Delphi, Greece

As shown by the monitored results, the total annual energy requirement of the retrofitted section of the building - for heating / cooling purposes, lighting and electrical for auxiliaries, will be substantial lower from the initial values during the whole year.



Cooling (electrical) consumption is approximately half the cooling load

By considering the differences between the total initial (301.8 kWh/m^2) and final (116.9 kWh/m^2) energy consumption results, it is obvious that there is a large energy saving from the implementation of the various features included in the design (e.g. demand ventilation, ceiling fans, BEMS controls, automatic operation of roof windows, daylighting, etc.), specifically energy savings were 61% in the heating load, 74% in the cooling load and 60% in lighting.

The detailed analysis of the museum building throughout the monitoring stages, (following the application / retrofitting of the energy measures) has verified that the main objectives were achieved, and helped to optimise energy behaviour, leading to a reduction in overall energy requirements and consumption by approximately 61%.

It was confirmed by the energy audit that was performed that indoor thermal, visual and acoustic comfort, as well as indoor air quality targets were fully achieved.

5.3 Herzog-Anton-Ulrich Museum, Braunschweig

In contrast to the original plan the whole building was not retrofitted within this project (decision July 2003). So, a representative number of five exhibition rooms were monitored in detail. Two test rooms were retrofitted, one to the North and one to the South. Each was compared with an existing neighbouring room which was measured in the same way. As a fifth exhibition room, the skylight hall was audited to investigate the indirect influence of the measures to the sky-lit hall and to assess the existing indoor climate.

The results showed quite a good indoor climate in the examined rooms. Although the total number of hours above 24°C permitted was exceeded, the highest temperature was not above 28°C, as it was specified. A similar statement can be made for the relative humidity in the museum spaces.

The effects of the different retrofitting measures on the indoor climate could not be finally assessed, because the monitoring program was still running at the end of this project. First comparisons of the retrofitted rooms with unmodified ones, showed a slower change of indoor climate caused by improved shading. Even after a number of hot days there was no increase in room temperature in the south area.

5.4 National Etruscan Museum 'Pompeo Aria', Marzabotto

Museum Floor Area m2	Marzabotto 890	INITIAL	FINAL	ENERGY SAVED	
Heating + Ventilation	kWh/m2 kWh/year	219 194,910	105 93,450	114 101,460	52.1%
Cooling + Ventilation	kWh/m2 kWh/year	14.0 12,460	0 0	14 12,460	100.0%
Lighting (electrical)	kWh/m2 kWh/year	20.0 17,800	7.5 6,675	12.5 11,125	62.5%
Auxiliaries (electrical)	kWh/m2 kWh/year	34.5 30,705	8.0 7,120	26.5 23,585	76.8%
Total Energy	kWh/m2 kWh/year	288 255,875	121 107,245	167 148,630	58.1%

Energy savings for the National Etruscan Museum 'Pompeo Aria', Marzabotto

The predicted interventions have been achieved both to create an optimal indoor environment for exhibits conservation and to improve human comfort, providing better working conditions for staff and increasing visitors' satisfaction. The retrofitting demonstration project for the National Etruscan Museum 'Pompeo Aria' in Marzabotto, offers a high potential for passive microclimate control to reduce energy consumption, relying on the artificial system only as a back up.

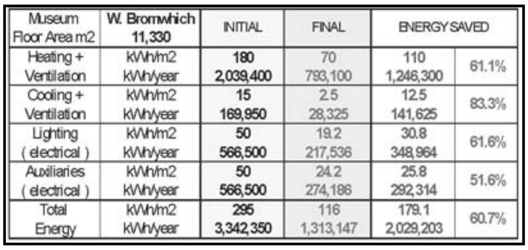
The solution adopted which employs passive means is very uncommon for Italian situations. For this reason, the interventions carried out in the museum of Marzabotto will be of great interest to visitors and the building itself will become an exhibit or exemplar for replication by many other similar Italian and European museums in the future.

5.5 THEpUBLIC Arts Centre, West Bromwich

The required heating energy consumption budget has been calculated based upon the thermal modelling results for the naturally ventilated and bioclimatic zones. Clearly for these zones, there was no energy consumption associated with cooling.

The close conditioned zones have been separated into those zones serviced by air-handling units, and those serviced with fan coil units. For these systems, the energy consumption in terms of heating, cooling, fans and pumps has been determined using appropriate methods.

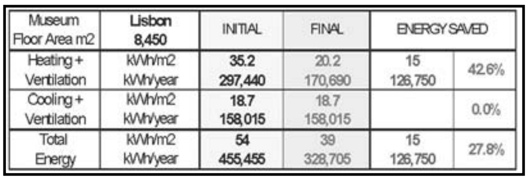
To calculate the energy associated with electrical lighting, daylight factors have been used to determine the number of hours during which artificial lighting would be required and, based on the installed power rating and likely operation hours the energy use has been determined.



Museum Floor Area m2	W. Bromwhich 11,330	INITIAL	FINAL	ENERGY SAVED	
Heating + Ventilation	kWh/m2 kWh/year	180 2,039,400	70 793,100	110 1,246,300	61.1%
Cooling + Ventilation	kWh/m2 kWh/year	15 169,950	2.5 28,325	12.5 141,625	83.3%
Lighting (electrical)	kWh/m2 kWh/year	50 566,500	19.2 217,536	30.8 348,964	61.6%
Auxiliaries (electrical)	kWh/m2 kWh/year	50 566,500	24.2 274,186	25.8 292,314	51.6%
Total Energy	kWh/m2 kWh/year	295 3,342,350	116 1,313,147	179.1 2,029,203	60.7%

Predicted energy savings for THEpUBLIC Arts Centre, West Bromwich

5.6 National Archaeological Museum, Lisbon



Museum Floor Area m2	Lisbon 8,450	INITIAL	FINAL	ENERGY SAVED	
Heating + Ventilation	kWh/m2 kWh/year	35.2 297,440	20.2 170,690	15 126,750	42.6%
Cooling + Ventilation	kWh/m2 kWh/year	18.7 158,015	18.7 158,015		0.0%
Total Energy	kWh/m2 kWh/year	54 455,455	39 328,705	15 126,750	27.8%

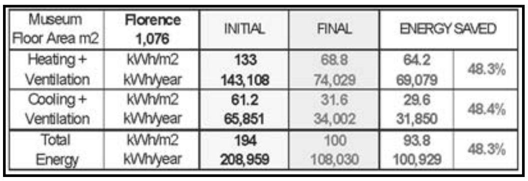
Energy savings for the National Archaeological Museum, Lisbon

The main conclusions may be summarised as following:

- Simulations have been quite detailed and many scenarios have been studied. The results have been validated by running the model in free-floating mode and then comparing the simulated temperatures with the corresponding monitored values which show quite good agreement.
- The economic aspects of the investments needed for the implementation of heat recovery and free-cooling are very unfavourable: the local climate is quite mild, the visitor density is low (fresh air needs are small) and working hours are short.
- Heat recovery would become economic, even with such a mild climate as in Lisbon during winter, if the number of visitors to the museum were to increase by a factor of at least three.
- The building envelope has been optimised where possible (insulation in the roof alone, good shading of glazing) and the thermal quality of whole building is so good in Summer that free-cooling is not necessary.
- The power plant has been also optimised, and a solution with a payback of two years selected. A geothermal solution had to be discarded because payback times would have been too high (greater than 10 years).

5.7 Bardini Museum of Florence, Italy

The application of the innovative retrofitting energy design features on a full scale basis, linked to the recent scientific and technical achievements, is beneficial because indoor comfort conditions were greatly improved, energy use for heating as well as for cooling was considerably reduced, while the required investment cost was within acceptable levels.



Museum Floor Area m2	Florence 1,076	INITIAL	FINAL	ENERGY SAVED	
Heating + Ventilation	kWh/m2 kWh/year	133 143,108	68.8 74,029	64.2 69,079	48.3%
Cooling + Ventilation	kWh/m2 kWh/year	61.2 65,851	31.6 34,002	29.6 31,850	48.4%
Total Energy	kWh/m2 kWh/year	194 208,959	100 108,030	93.8 100,929	48.3%

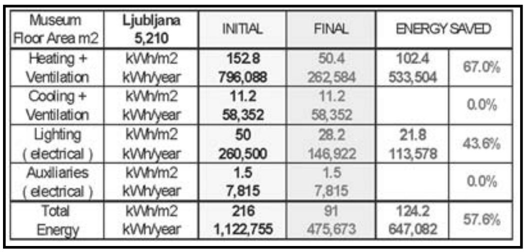
Energy savings for the Bardini Museum of Florence, italy

This resulted in the ability to maintain acceptable conditions with reference to the indoor environmental parameters for the preservation of the exhibits, as well as the achievement of high thermal comfort and air quality levels for occupants in the museum rooms.

5.8 Slovene Ethnographic Museum, Ljubljana

The most important results of the project are: the reduction of the investment for HVAC from €530,319 to €434,075, a reduction in energy consumption, an efficient cooling system, advanced illumination harmonised with available daylight and improved thermal comfort in winter and summer period.

It has been shown that the previously designed air conditioning system was not necessary. As a result of this decision 158m^2 of space was liberated for much needed storage space. Annual gross energy demand for heating was reduced by 67%, from 156 to 50.4 kWh/m^2. The average measured consumption in similar buildings is 120 to 140 kWh/m^2.



Museum Floor Area m2	Ljubljana 5,210	INITIAL	FINAL	ENERGY SAVED	
Heating + Ventilation	kWh/m2 kWh/year	152.8 796,088	50.4 262,584	102.4 533,504	67.0%
Cooling + Ventilation	kWh/m2 kWh/year	11.2 58,352	11.2 58,352		0.0%
Lighting (electrical)	kWh/m2 kWh/year	50 260,500	28.2 146,922	21.8 113,578	43.6%
Auxiliaries (electrical)	kWh/m2 kWh/year	1.5 7,815	1.5 7,815		0.0%
Total Energy	kWh/m2 kWh/year	216 1,122,755	91 475,673	124.2 647,082	57.6%

Energy savings for the Slovene Ethnographic Museum, Ljubljana

The project achieved achieved a very low specific energy consumption for cooling (11.2 kWh/m^2). The selection of a ventilation system under the window resulted in a negligible additional energy use (0.98 kWh/m^2). General lighting consumption was reduced from an initial 50 kWh/m^2 to 28.2 kWh/m^2 (by 43%).

The introduction of wall heating and cooling panels resulted in significant energy savings and much improved indoor comfort because of the large horizontal heating and cooling areas with optimal surface temperatures.

The greatest contribution and the most difficult part of the project was the design and fine tuning of harmonised control of temperatures, relative humidity and CO_2, levels as well as the use of cooling oriented ventilation with the application of a central control system designed specially for this project.

6. CONCLUSIONS

Museums house the treasures of World history and are showcases of our cultural heritage. They are often buildings of great importance as well as of significant representative character for a region, country or Europe as such. In the context of energy and the environment museums not only constitute a large number (tens of thousands) of buildings in Europe, but are also visited by millions of people. Consequently, they have great signific-sance for the tourist economy. As such, they are buildings of tremendous importance with the according demonstrational and educational potential.

Despite their importance, existing as well as new museum buildings are very rarely energy-efficient and often provide unsatisfactory comfort conditions. A number of buildings that house Museums of Antiquities in European regions, were studied and analysed in the framework of the present EU programme in order to apply retrofitting measures to them to improve their energy and thermal comfort performance.

Retrofitting of and conversion into a museum, are of at least the same importance as new museum buildings. This is simply due to the procurement of the large number of existing museums which will have to be retrofitted within the coming decades due to deterioration, changing functional and spatial needs and the need to upgrade the energy-efficiency, quality of exhibit conservation and occupant comfort.

The consortium of museums in this project encompassed some very important museums of world wide significance such as the National Archaeological Museums in Lisbon and Archaeological Museums of Delphi, the Herzog-Anton-Ulrich Museum, the new THEpUBLIC Arts Centre, as well as some smaller buildings which represent a very large quantity of museum applications in Europe (such as the Bardini, Marzabotto, and Kristinehamn). The eight sites in this project were located in seven different member states which are representative of Europe as such due to their various locations and climates from north to south, including one site in Slovenia to representing a rising market in Eastern Europe with an immense application potential in the near future.

In that respect, a large variety of technical innovations regarding the energy design and control systems was implemented in the retrofitting, conversion or new erection of the museum buildings involved in this MUSEUMS project. General conclusions based on the buildings studied were derived regarding the efficiency and the applicability of these energy retrofitting solutions in museum buildings, based on either simulation work and / or monitored results. This was mainly due to various unforeseen delays in the different projects, some of have yet to reach the construction stage, while for those that had just finished, preliminary or full-time monitoring was performed before sufficient time was allowed for the settled operation of these museum buildings.

A summary of these results and conclusions is presented here, along with the evaluation results of the energy designs for some of the sites involved. Guidelines and solutions for the efficient energy rehabilitation of old or for the design of new museum buildings in Europe, have been presented in more detail in the previous chapters providing improved energy demand and thermal comfort performance.

6.1 Targets Achieved

6.1.1 Improved quality of exhibition spaces

- Provision of excellent environmental conditions for staff and visitor comfort and exhibit conservation:
  - Thermal
  - Indoor air quality
  - Optical - reduced glare
  - Acoustic
- Optimised daylight performance; control and integration with artificial lighting for improved illumination quality and exhibit display.
- Improved architectural layout, to facilitate increased spatial or functional needs, retail or multimedia facilities and for adequate handling of visitor flow to alleviate comfort problems related to congestion.
- State of the art storage handling and display of exhibits.

6.1.2 Improved energy performance

- Efficient design and use of energy to ensure minimal CO_2 emissions, reduced energy consumption and environmental impact.
- Reduced and optimised use of the heating, cooling and ventilation systems, with economically efficient operation.
- Innovative and flexible control of energy performance and environmental conditions through use of BEMS.

6.1.3 Higher environmental protection

- Highest health, safety and architectural standards. Minimised environmental impact during construction and operation of the buildings and their installations.
- Optimised viability within the energy and environmental targets.
- Use of healthy, environmentally friendly and renewable materials.
- Predicted success of the design implementation through the support of a team of internationally acclaimed experts in the field.

6.2 Social Benefits in the EU

Since museums are public buildings of high cultural and social importance, their social impact (positive or negative) is enormous. This concerns not only the direct impact of the building in terms of energy consumption and sustainability but its role as an icon or focal point of our culture and as an exemplar, of which sadly, these are still very few that demonstrate optimal integration of energy technologies and address environmental sustainability concerns in an architecture that is aesthetically stimulating and responsive

6.2.1 Improvement in quality of life, health and safety

The application of design measures and technological features in the museum buildings of this project improve comfort conditions and control possibilities in the museum buildings as described above. Additionally, the use of healthy and environmentally friendly materials helps create favourable conditions in the indoor spaces.

Comfort conditions and healthy materials in the built environment are of great significance for the well being of building occupants. People for whom the museum is their workplace are those most affected by the prevailing indoor environmental conditions. Where the psychological effect of natural light and visual contact with the outside and its diurnal and seasonal variations are of great importance along with comfort conditions. Museum staff will therefore benefit from the improvement of their working environment and the resulting well being can have a significant positive impact on their health and productivity.

Visitors are also affected by the conditions in a museum building. While they do not spend nearly as much time in the building as staff they are still affected for the time they are there. And since museums are visited by enormous numbers of people the cumulative difference that favourable environmental conditions can make in a museum is great. Moreover, the visitors' appreciation of the materials on display in a museum and their enjoyment of the whole experience can be greatly enhanced through the quality of the museum environment.

Museums that employ natural or hybrid solutions to environmental control and incorporate intelligent control systems as in the case in this project, improve health and safety in the building. Such problems can occur through excessive reliance on air conditioning systems in combination with a lack of maintenance and control. Possible hazards include pollutants in the air, and in the worst case, for example legionella bacteria.

6.2.2 Impact on employment, development of skills and the opening of new markets

The trend for the building professions to follow is clear. In future, new buildings (but also retrofitted / converted ones) will have to become much more energy efficient while their environmental standards will need to be improved and the building professions will have to adjust to this development.

This project has anticipated this development and enhanced the skills and knowledge base of all parties involved, architects, engineers, consultants, contractors and clients. The dissemination activities of this project will allow other professionals in this field to benefit from the experience gained for application in future projects. Increased knowledge and skills in this area can provide a competitive edge in a changing market. there are also significant, increasing employment and commercial opportunities in building retrofit and energy-efficient projects.

The market is of course not only restricted to Europe but stretches out to other countries in the world where building typologies such as in this project apply. This means increased competitiveness of European companies in this field.

6.2.3 Contribution to preserving or enhancing the environment and conservation of natural resources

The contribution of this project to the preservation and enhancement of the environment and conservation of natural resources is obvious through the saving of energy and corresponding reduction of pollution. Fossil fuels are preserved and CO_2 emissions are significantly reduced depending on the efficiency levels achieved. Furthermore, although the buildings incorporate technologies that cut peak electricity consumption, there is a potentially great contribution to homogenising energy needs.

This is due to the fact that the capacity of power stations has to cover peak demands. Cutting the peaks may not only eliminate or at least reduce the need for more installed power, but through a more homogeneous distribution of the energy demands, the electricity can actually be produced more efficiently as the efficiency improves in a power station if it runs at higher, more constant output levels. Thus there can be a trend towards fewer power stations operating more efficiently and less danger of the grid being unable to cover peak demands. Such demands can occur e.g. through unusual weather spells (resulting in increased heating or cooling demand), that occur more and more frequently and unpredictably as a result of global climatic changes.

6.3 Implementation of EU Policies

This demonstration project addressed the following European policies:

Key Action 6: Economic and efficient energy for a competitive Europe

- Incorporation of technologies for the rational and efficient end use of energy, encompassing all relevant technologies for energy efficiency in such buildings
- Energy savings and CO_2 reductions exceeding the targets set out under 6.1.2 building sustainability and 6.1.3 efficient space heating, cooling, ventilation, lighting systems and domestic appliances and integration of renewables into buildings.

Key Action 5: Cleaner energy systems, including renewables

Integration of renewable energies in museum buildings, improving the acceptability of renewables through the comprehensive integration in the overall bioclimatic architecture and exhibition building design (5.3.3), the enhancement of comfort and the improvement of the overall quality with the support of the respective experts in the consortium.

Key Action 4: City of tomorrow and cultural heritage

Beyond the application and dissemination of technologies concerning energy, emissions and environmental issues, the project contributes greatly to the objectives set out under the key action 4:

- Improvement of the quality of life in the urban environment where cases are located in cities through reduction of air pollution of the buildings and improvement of the indoor environment (and outdoor environment if the case incorporates improvements in the micro-climate) in the buildings (4.1.2)
- Protection, conservation and enhancement of European cultural heritage (4.2). Concretely concerning the development of innovative conservation strategies (4.2.2) the project incorporates the advancement of environmental control systems for exhibition spaces as well as showcases.
- Development and demonstration of technologies for safe, economic, clean, effective and sustainable preservation and renovation of the built environment. This point applies to retrofitting and conversion of buildings that are actually part of the cultural heritage, which is usually the case with museums.

6.4 General Conclusions

It must be noted here as a general conclusion, that museum buildings (and especially those that house ancient artifacts) are unique regarding the scope for the application of energy saving technologies, since special consideration must be taken for the preservation of the exhibits. Thus, when an energy saving measure is implemented, this must lead not only to the improvement of the indoor conditions for the visitors but also comfort in conditions for the artifacts. Bearing in mind, that the indoor thermal conditions or preservation requirements for ancient and sensitive artifacts are not always the same as are comfort condition for human beings (but are usually more stringent), the designers of the energy retrofitting measures must take into consideration all those standards and specifications mentioned above. So, the aim when designing these interventions is not only to reduce the energy consumption of such a museum building, but at the same time to provide indoor comfort conditions in the space for the visitors or employees and for the preservation of the exhibited artifacts as well.

This sometimes leads to restrictions regarding the potential for the application of specific energy saving techniques. For instance, certain types of antiquities must be always kept under fixed (or quite low) temperatures, under low humidity conditions, or under special daylighting conditions (for low UV exposure). In other cases the application of passive cooling techniques, such as night ventilation or the use of ceiling fans, etc. may not be suitable despite the fact that the prevailing indoor conditions provide comfort to the visitors and the energy consumption is minimised, as the use of these techniques leads to conditions which do not satisfy the preservation requirements. The retrofitting of museums buildings must often be a compromise, in which often quality is more important than quantity.

In parallel with their historic and economic importance, museums have the potential to represent today’s culture and state of the art in a way that only few other building types can. As an expression of its time their highest purpose is to be an exemplary building that show a way to the future. Mostly, however, architects approach this task mainly from an aesthetic stand point and can produce amazing shapes, materials and effects in the process. Today, however, showing the way to the future must mean taking the needs of our environment into full account in an integrated, holistic approach and not as an unavoidable addition to a design exercise.

This handbook is the outcome of a demonstration project dealing with energy efficiency in museum buildings. The idea for this project originated from two preceding ones, a research project carried out within the framework of the Joule III programme of the European Commission and a further SAVE II project. Both projects dealt with energy efficiency in a specific building type - archaeological museums - and in a specific climatic region - the European member states around the Mediterranean. The former was a research project, the latter developed design guidelines for the energy efficient design of museum buildings in the Mediterranean region. Having reached this point, the time had come to implement the results of the research, and to test in real-life conditions its outcome so as to have the necessary feedback for future use. The opportunity for this implementation was provided within the framework of the European Commission's ENERGIE programme.

However, this project differed from the previous ones in two aspects: Its spectrum became much broader in the sense that it included a wider range of museums (not only archaeological) in an extended geographical region covering the whole European continent. Eight suitable building projects were selected. Seven of these museums were to be retrofitted and one was to be a new building.

The purpose of this handbook is to communicate to interested parties the experience and the knowledge gained during the implementation of this project. In this sense it neither attempts to provide exhaustive information on the subject of museums and energy efficiency nor does it document extensive research covering all aspects of the subject. It is merely a record of the outcome of the MUSEUMS project and of the activities which took part during its five year duration. The eight projects involved cover a wide range of museum types and as such have a high replication potential, but on the other hand they do focus mainly on art (visual arts and handicraft) and do not include, for example, other museum types such as historical museums, natural history museums, etc. In this respect the handbook has a particular focus.

This handbook addresses not just the scientific community, but aims to reach a wider audience: Museum building owners, architects, designers, consultants, students - anyone involved in the building process for a new museum. It has an informative and non-commercial nature for which reason it can also be accessed through the web at http://www.sustainable-european-museums.net.