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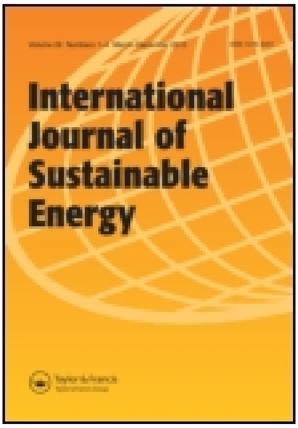

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Marco Sala [a] & Paola Gallo [a]

[a] Centro Interuniversitario ABITA, Dep. TA&D Tecnologie dell'Architettura e Design, University of Florence via san Niccolò 89/a, 50125, Florence, Italy

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Energy efficient and sustainable ancient museum buildings: a case study in Florence

MARCO SALA* and PAOLA GALLO

Centro Interuniversitario ABITA, Dep. TA&D Tecnologie dell'Architettura e Design, University of Florence via san Niccolò 89/a, 50125 Florence, Italy

The Historical Bardini Museum in Florence is a representative paradigm of the Italian Museum Building, and it is very suitable to serve as an exemplary pilot project for the restoration of historical museums. This article presents results of the architectural and energy retrofitting carried out applying appropriate and strategic low-energy and sustainable techniques and of the monitoring campaign (IAQ, thermal comfort, light, acoustic) performed first to evaluate the existing situation and then to verify comfort parameters and the energy consumption after works. The Bardini Museum participates, as Italian case study, to the European MUSEUMS project, financed by EU Commission in the Fifth Framework Programme. The result of this project is to provide also with a direct guidance, complete with architectural and engineering examples, for design professionals and museum authorities, setting a new standard for energy consumption in museum buildings. In parallel, it has aimed to disseminate effective information for designers and local authorities and to demonstrate the efficiency of the measures in order to promote them in efficient market promotion, penetration and utilization.

Keywords: Museum; Energy efficiency sustainable design

1. Project's objectives

The MUSEUMS project (NNE5/1999/20), started in 2000 and financed by EU for more than 3 million euros, looks at nine different retrofitting, conversions and new museum projects (including one arts centre) that have been carried out to produce showcases of energy efficient and sustainable museum design. The first intention was to demonstrate that an energy efficient and sustainable museum building design can fully meet the architectural, functional, comfort, control and safety requirements, but the main objective was to apply and test new and innovative technologies in museums in order to achieve total energy savings of over 35% (for retrofit) and 40% (for new buildings) and reduce CO_2 emissions over 50%, directly contributing to the preservation of European cultural heritage and to the acceptance of innovative and renewable technologies in public buildings.

*Corresponding author. Email: abita@taed.unifi.it

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2. Background

The Municipality of Florence, Italian Partner of the project, selected the Bardini Museum as case study and paradigm of the Italian Museum Building. This historical museum is also one of the most important buildings of the Italian Renaissance; therefore, the intervention of retrofitting has taken account of these architectonic and artistic values. The building is located in the centre of Florence, Italy, near the Old Bridge in a densely built residential area (as shown in figure 1). The building is free on all sides, except on the East part and its only entrance is from the West. This building represents one of the most important buildings of the Eclectic period, and it was projected and realized in 1883 by the Italian architect Bardini restructuring an old church with monastery in order to contain and show his art collection.

Figure 1. Aerial plan of the Bardini Museum area.

3. The building before the interventions

This historical museum is a representative paradigm of the Italian Museum Building and is also one of the most important buildings of the Italian Renaissance; therefore, the intervention of retrofitting has taken account of these architectonic and artistic values (figure 2).

The exhibition space is 3200 m^2, with 6.00 m ceiling height and the total volume is 15,000 m^3. All the storeys are occupied for work art exposition, with an operating schedule for visiting starting from 09:30 to 19:00 on a daily basis except during the summer period.

Except for the administration area, there is no heating, cooling, mechanical ventilation and environmental control systems (no surveys for thermo-hygrometric, CO_2 and illumination evaluation). In fact, the building, north–south oriented, is naturally ventilated and has no air conditioning system installed. The building has a very heavy structure: in fact, the traditional stone construction is characterized by a massive wall but the older shell has many problems of structural and functional obsolescence as follows:

- obsolete environmental conditions for visitors and staff related to air quality, thermal and visual quality;
- no environmental monitoring and control; *i.e.* no controlled ventilation: unfavourable and changeable conditions for object and visitors;
- excessive energy consumption; *i.e.* lighting represents 70% of the total energy consumption due to insufficient and obsolete devices in the exhibition spaces, absence of detectors, absence of day lighting compensation system;
- inefficient use of energy due to bad building maintenance and obsolete equipment;
- damaged windows and windows frames;
- high air infiltration rates;
- inadequate exhibit handling and display;
- inadequate spatial organization of exhibition space.

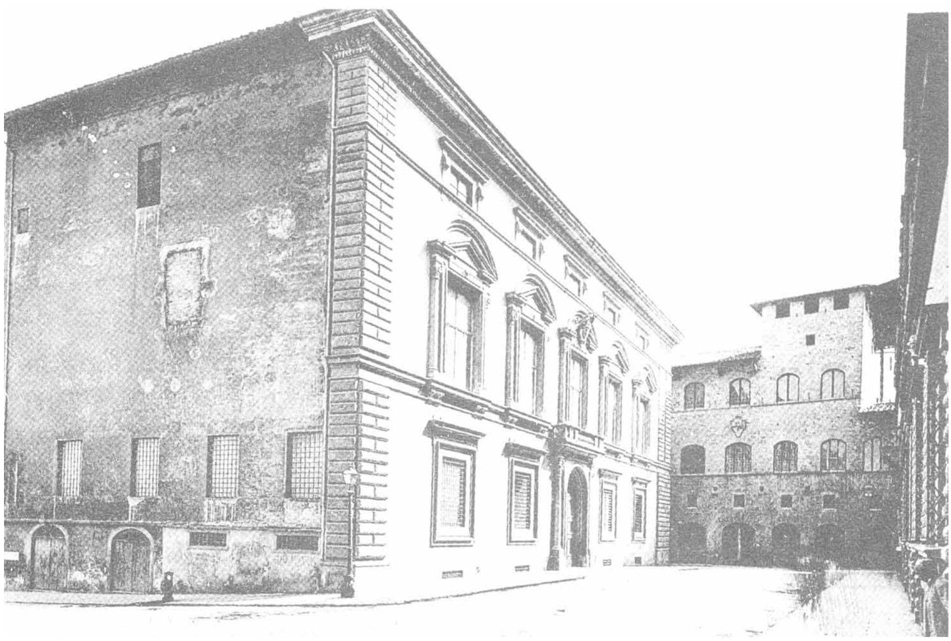

Figure 2. Historical photograph of the Bardini Museum.

4. Innovative design strategies

The task project was primarily to modulate spaces and services to users' and workers' demand in order to correspond to technological and serviceable requirements, also according to legislative regulations because when design works started, the building was not fully used and in a very bad state of maintenance.

Three main purviews have been individualized:

1. Improvement of the building envelope (insulation, glazing, natural ventilation and daylighting techniques) to reduce the thermal losses of the building.
2. Improvement of energy systems used for heating, cooling, ventilation and artificial lighting to decrease the specific energy requirements in each sector.
3. Improvement of control strategies (BEMS, distribution/demand control strategies, intelligent control, etc.) to optimize the performance of the various systems and properly adjust their operation.
4. According to these strategies, the retrofitting measures adopted can be schematized as follows, ramified in four main actions:
   a. *Building improvements*:
      i. improved U-value of windows;
      ii. reduced infiltration: weather stripping of windows and doors;
      iii. replacement of window frames in bad condition;
      iv. ventilated roof and roof insulation;
      v. additional shading devices for the third floor.
   b. *Use of passive cooling techniques*:
      i. modulation of heat gains. Night ventilation.
   c. *Electric lighting improvement*:
      i. change the type of features to improve their efficiency;
      ii. replacement of existing skylights.
   d. *HVAC system improvements*:
      i. use of automatic controlled natural ventilation;
      ii. installation of a new energy efficient heating system.

5. Monitoring

In order to integrate detailed retrofitting actions regarding energy aspects, to calibrate simulations tools and to carry out the study on the retrofitting actions, a monitoring campaign was performed to evaluate at first the existing situation and to verify indoor climate, visual, acoustic and thermal comfort and the energy consumption after works. Referring to Common Monitoring Protocol, reported from the responsible in charge for *Museums project* (University of Athens), the monitoring activity for the Bardini Museum was planned to start before intervention and after the commissioning phase.

5.1 *Methodology and actions*

The monitoring was programmed for the following representative seasons: winter and summer, to test the efficiency in the characteristic unfavourable period. In order to assess a real performance of the implemented strategies and features for the Bardini Museum, a detailed monitoring methodology was defined as follows:

- Long-term monitoring (monthly measurements): this monitoring campaign was performed in the summer and winter periods;
- Short-term monitoring (hourly measurements): this monitoring campaign was performed in the summer and winter periods;
- Spot monitoring: a spot monitoring period was carried out during the short monitoring period (in winter and in summer).

The local measurements (in order to evaluate microclimatic conditions) were continuously verified with the nearest meteorological station in the centre of Florence, particularly the outdoor air temperature and humidity, sky radiant temperature, global and diffused solar radiation on horizontal and vertical planes and wind speed and direction.

6. Building improvements

6.1 *Energy features*

It is important to notice that existing facades cannot be altered, particularly the main facade (figure 3).

Related to the retrofitting measure proposed, the materials used can be schematized in table 1.

6.1.1 Improved U-value of windows using double glazing. Reduction of heat losses through the transparent components is a major problem to solve in this case study. In fact, all existing windows of the building are single-glazed, causing excess heat losses in winter, unavailable leakage. However, double-glazing will permit us to reduce heat flow through all openings.

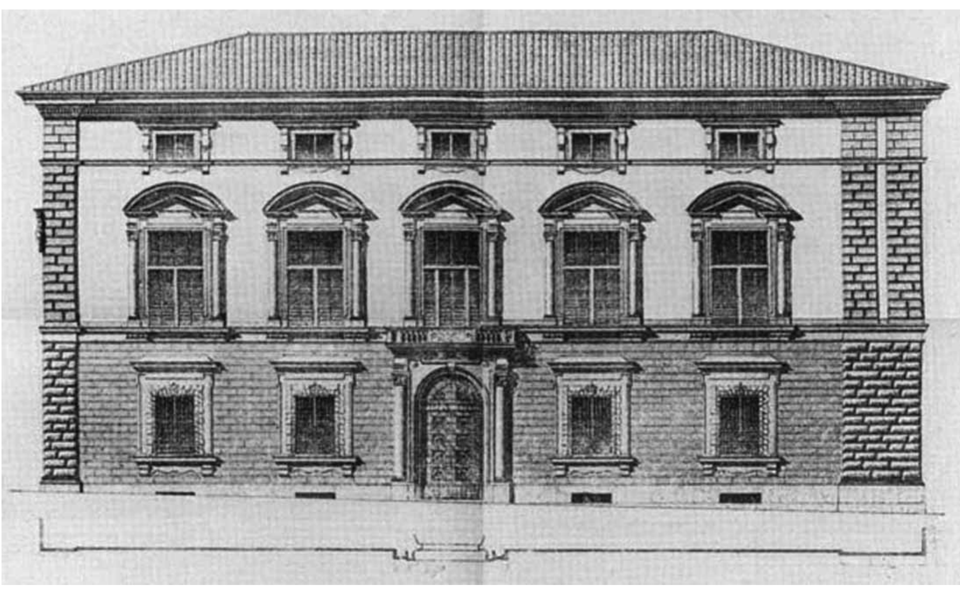

Figure 3. The existing main facade.

Table 1. The construction materials.

	Type of material	Thickness (cm)	U-value (W/m^2 K)
Interior partitions	Brick partition	30	n/a
Roof	Caly tiles	40	–
Roof insulation	Granulated cork	10	0.36
Ground floor	Baked tile	–	–
Ground floor insulation	Ground floor loose stone foundation	–	–
Intermediate floor	–	–	–
Window glazing	Double-glazing	0.02	2.80
Window frames	Wood/steel	–	n/a

6.1.2 Reduced infiltration: weather stripping of windows and doors. This retrofitting measure leads to the reduction of outside air infiltrating into the building through cracks and opening gaps around windows and doors. As is well known, the infiltration of the external cold air into the building replenishes the warm air leaking out.

6.1.3 Replacement of window frames in bad condition. Losses through the envelope are mainly caused by infiltration due to the bad condition of windows, so appropriate levels of insulation and decrease in air leakage were required in order to achieve a reduction in convective and irradiative losses. The retrofitting actions were proposed in order to reduce heat losses by changing all windows in bad condition. This action assures air tightness as well as double-glazing for all openings and increases insulation levels of the roof. Replacement of old window frames in bad condition drastically reduces infiltration rates. The reduction concerning the energy demand for heating and cooling will be more or less 2% and 5%, respectively, greater than the previous measure.

Figure 4. The new shading system.

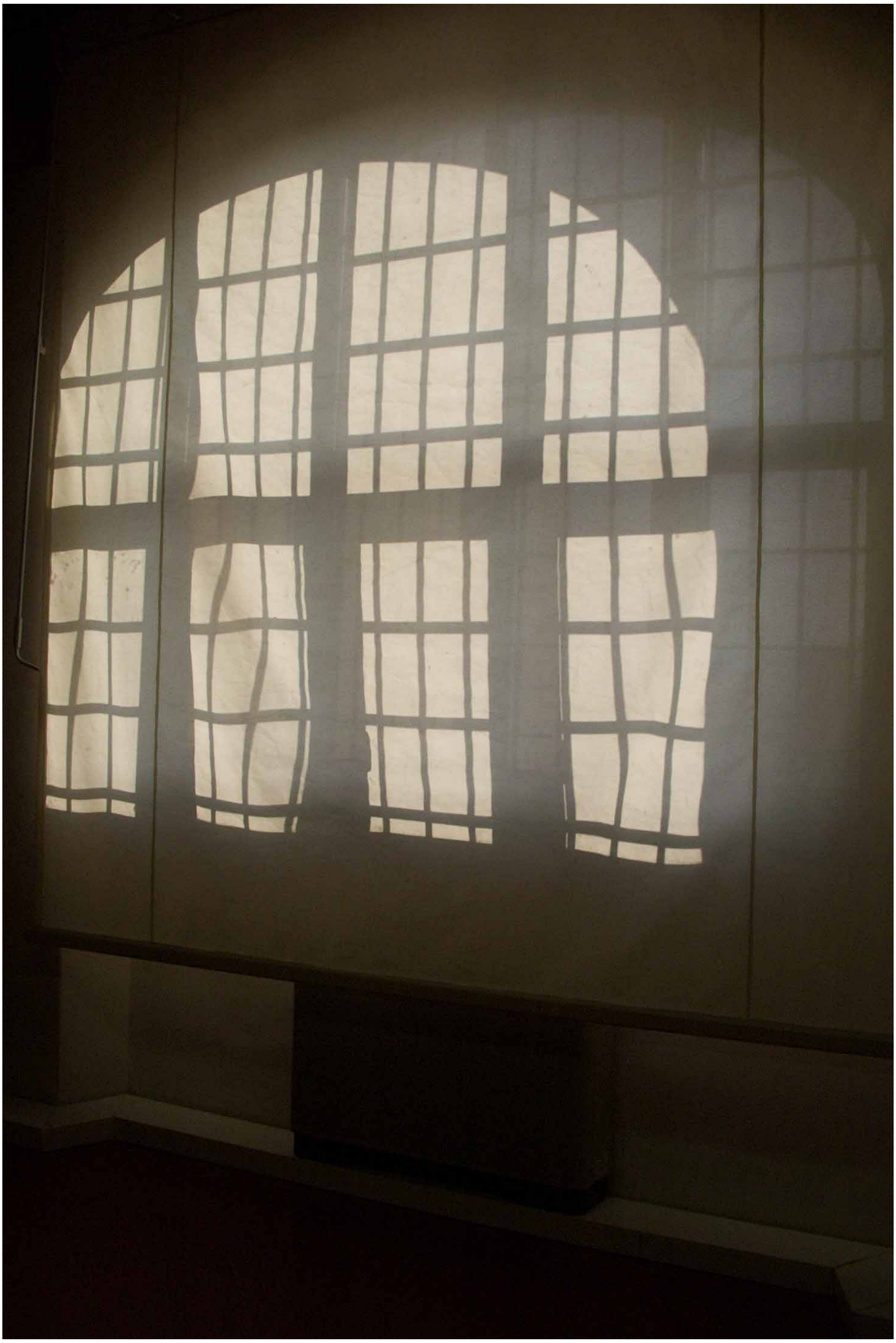

Figure 5. The new shading system, part 2.

Figure 6. The ventilated roof structure.

Figures 4–5 show the new windows installed have a thermal insulated frame and are also equipped with light curtains that assure light crossing, avoiding overheating and glare and also protecting exhibits from direct sunlight.

6.1.4 Ventilated roof and roof insulation. The building's roof was not insulated, and the preliminary analysis has shown that the top floors have higher thermal losses. Reduction in the heating losses through the envelope has been achieved mainly by using a good insulation: it was proposed to increase the insulation of the roof, and a 10 cm thick insulation has been added. The insulating panels are made of natural cork installed without artificial additives and adhesives. Besides the insulation, a ventilated roof system has been designed (see the new roof in figure 6) in order to carry out two different kinds of 'air circulation' into the roof:

- a first micro-ventilation under tiles, essential to prevent humidity stagnation;
- a second macro-ventilation under the roof, activated between the tile and the insulating layer.

7. Building performance

7.1 *Simulation*

In order to complete the energy and environmental design phase, several simulations were performed using validated simulation tools (Esp-r and Radiance) to optimize the design of each specific measure applied in the museum (Bartolo, 2003).

To evaluate the internal comfort of visitors and exhibited materials, particularly to calculate the distribution of the indoor temperatures, as well as the energy required for heating and cooling purposes, Esp_r software has been used. The model has been divided into six thermal zones at the ground and first floor of the building. These zones represent the main exhibition halls and service spaces. In particular, a detailed thermal analysis was done of the thermal behaviour of the building. To do this, a number of energy simulations were performed that estimated the indoor temperature in each zone as well as the heating and cooling loads for the winter and summer periods.

In the following images, five thermal zones used for the simulation are shown (figures 7 and 8).

- Zone 1 represents the spaces of great expositive interest. It includes four rooms on the first floor, with west-north/west orientation.
- Zone 2 includes only an exhibition room at the intermediate floor facing double volume of the atrium.
- Zone 3 is related to the volume of the principal staircase and two rooms of the first floor; one is oriented to east-south/east, whereas the other is oriented to the double volume of the atrium, without a direct external opening.
- Zone 4 is the reception on the ground floor, with corridors and open spaces used to connect rooms.
- Zone 5 includes the big expositive room with the skylight on the ground floor, the atrium and the adjacent room.

A second simulation was performed to optimize the day lighting design phase. For the evaluation of visual performance, the Radiance tool has been used for the calculation of daylight in interior spaces, the analysis of glare problems, luminance and so on. Radiance simulations were used to compare results related to luminance and illuminance values between the actual state and the project of the following areas of the museum:

- Ground floor, entrance hall, atrium;
- First floor, Sala del Terrazzo, Sala dei Quadri.

Simulations have been done in the rooms that are considered interesting from the point of view of works exposed and in days and hours that have the maximum and minimum insulation values in order to measure luminance and luminance values. These simulations have shown a significant reduction in transmittance using high diffuser in place of the existing glass (figure 9).

7.2 *Acoustics*

Acoustic measurements carried out in the Bardini Museum concerned the following two parameters particularly significant for the case study: normalized sound insulation of façades

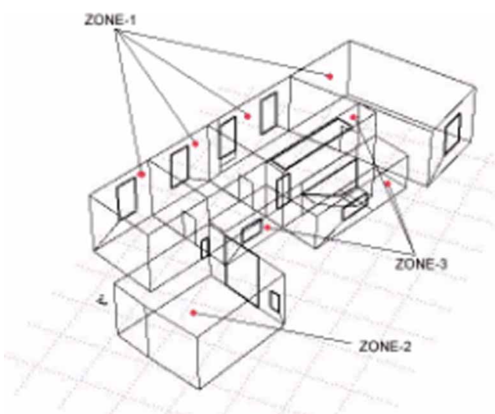

Figure 7. Location of thermal zones 1-2-3 of first floor.

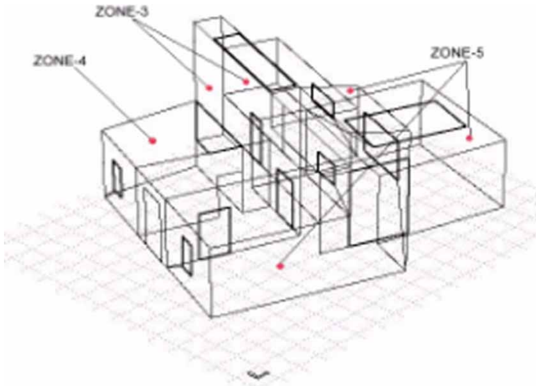

Figure 8. Location of thermal zones 3-4-5 of ground floor.

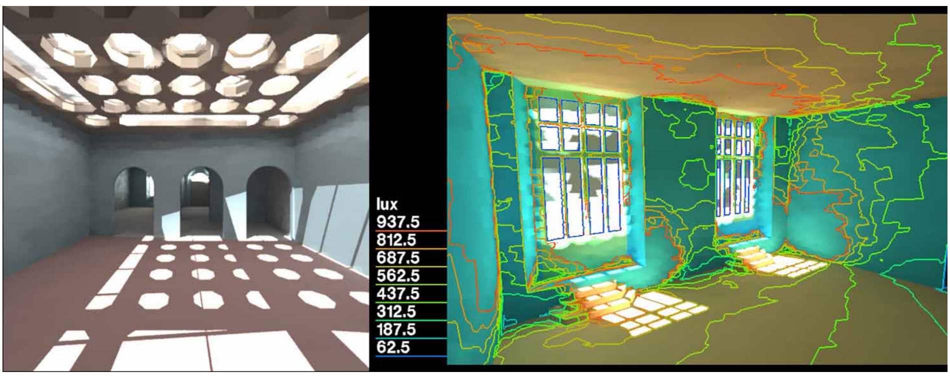

Figure 9. Examples of Radiance simulation.

($D_{2\,m,nT,w}$) and reverberation time (T_R). Measurements have been carried out using a two channel sound analyser (01 dB Symphonie) equipped with half-inch microphones and preamplifiers (Gross).

The instrumentation used is of class 1, according to the international standards. For the measurements, the procedure defined by ISO 140-5 was strictly followed. The results of measurements, comparison with limiting values, demonstrate that both façade sound insulation and reverberation time require to be improved. In particular, the correction of the façade sound insulation requires a doubling of the window or at least of the glass pane.

8. Exhibits

Ancient historical buildings, converted into museums, offer a great occasion to show collections in an impressive context, but in the meantime, this implies limited possibility for intervention because these buildings were not originally conceived for exhibition purposes and many compromises need to be made also because the installation of the HVAC system may not be compatible with the architectural characteristics. In fact, from a exhibit point of view, the Bardini art collection does not require an extreme control of indoor conditions because the exhibit materials are mainly metals (weapons, armours, silver, copper, bronze, brass, lead, coins) and minerals (terracotta, maiolica, stones, marble), which do not need particular care because they are not much affected by light and temperature/humidity parameters.

On the first floor, where more delicate objects such as paintings – watercolour, drawings, pastel, oil paint, tempera – and tapestries, strategies are adopted to avoid deteriorations due to direct lighting: double glazing windows have been installed, changing the old frames, and equipped with internal shading systems to reduce light entry. Temperature and humidity are set and controlled by the HVAC system.

9. Elements of the environmental design and innovations

9.1 *Daylight and artificial lighting*

The specific consumption for lighting of the Bardini Museum is high because it has high lighting loads installed unnecessarily, with poor control and low efficiency of the system; priority has been given to actions aiming to reduce the installed power and improve the lighting efficiency, avoiding high heat gains from the old lighting system. In fact, good lighting design means not only lower energy consumption but also, as recent research has shown, increasing exhibition condition and comfort.

9.1.1 Use of improved luminaries: change the type of features to improve their efficiency. The improvement of the old luminaries without efficient reflector is a very important measure because the surface inside the luminaries should be more reflective so that more light is now 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 increased the illumination levels.

The day lighting level has been optimized by the replacement of existing skylights with new ones (see the skylight project in figures 10 and 11). The first step was to change the skylight roofing structure in the main room near the entrance. The improvement of the old luminaries with efficient reflector is a very important measure because the surface inside the luminaries should be more reflective so that more light can be directed onto the exhibition space.

In place of the heavy glazed roofing, we have used luminaries that are transparent 30 mm twin-welled polycarbonate panel with a special reflector which can reduce glare and increases illumination levels (see figures 12–14).

Skylight roofing structure with glazing light transmittance	$\tau = 80\%$
High transmittance diffuser for false ceiling with light transmittance	$\tau = 70\%$

A second measure regards the existing wooden false ceiling: all the bulletproof glasses will be replaced with special high-transmittance diffuser components (see figures 15 and 16) made of a high-grade flexible plastic in a position to assure a uniform luminance distribution at the ceiling in the room, apart from a good acoustic.

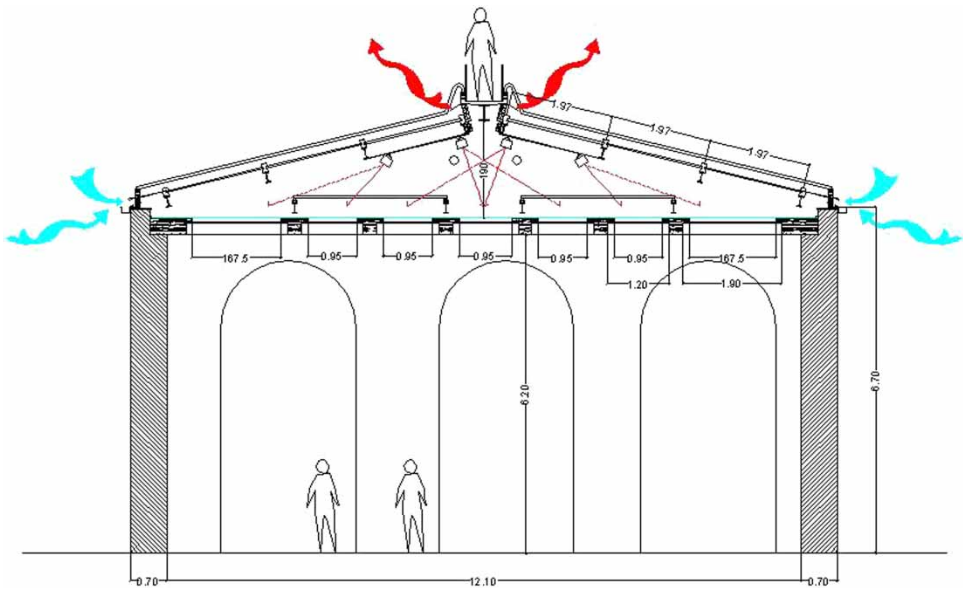

Figure 10. Project section of one of the skylights.

9.2 *Heating*

9.2.1 Installation of a new energy efficient heating system. The museum building was lacking in a heating system. The use of a heating system will contribute to indoor comfort improvement in the winter season. The typical heating control system incorporates thermostatic valves on the distribution system and an outdoor air temperature sensor for the system control.

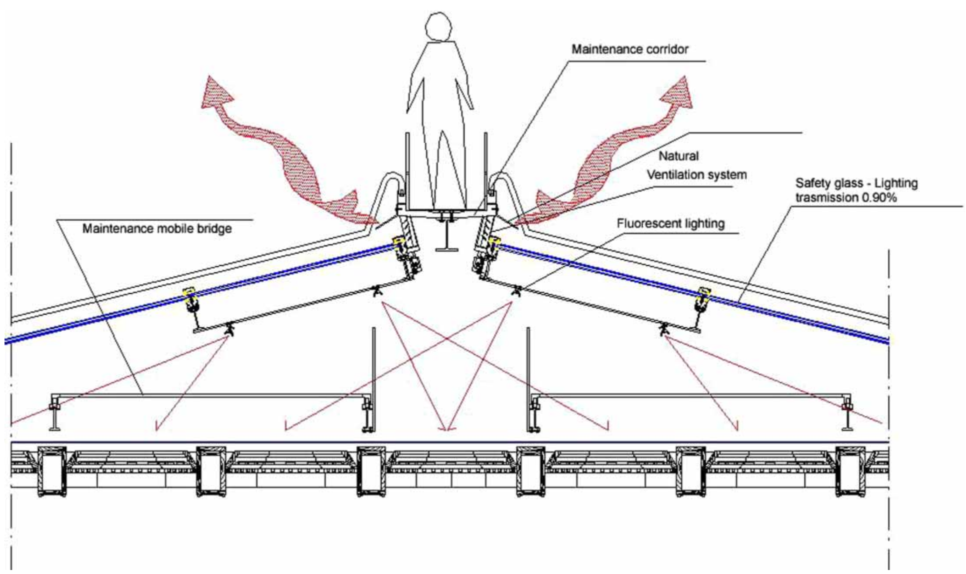

Figure 11. Detailed section of the external structure of the main skylight.

Figure 12. The existing skylight: external view.

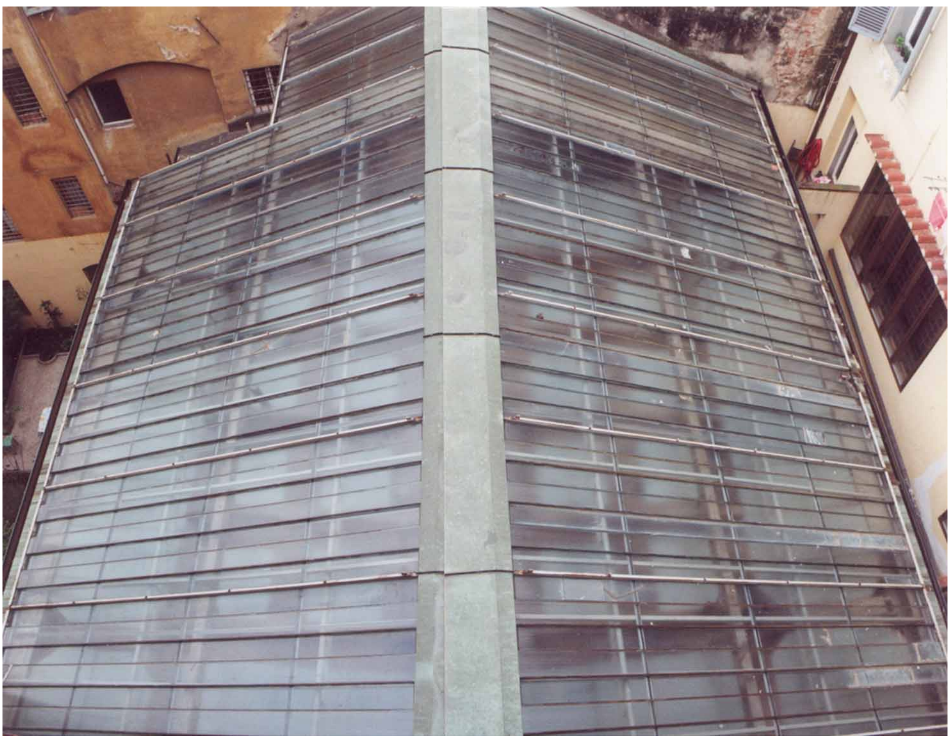

Figure 13. The old skylight: external view.

Figure 14. The new skylight: external view.

9.3 *Indoor climate: cooling and ventilation*

9.3.1 Use of night ventilation. It is well known that night ventilation is one of the more efficient passive cooling techniques for reducing the cooling load during summer. In fact,

Figure 15. The existing skylight: internal view.

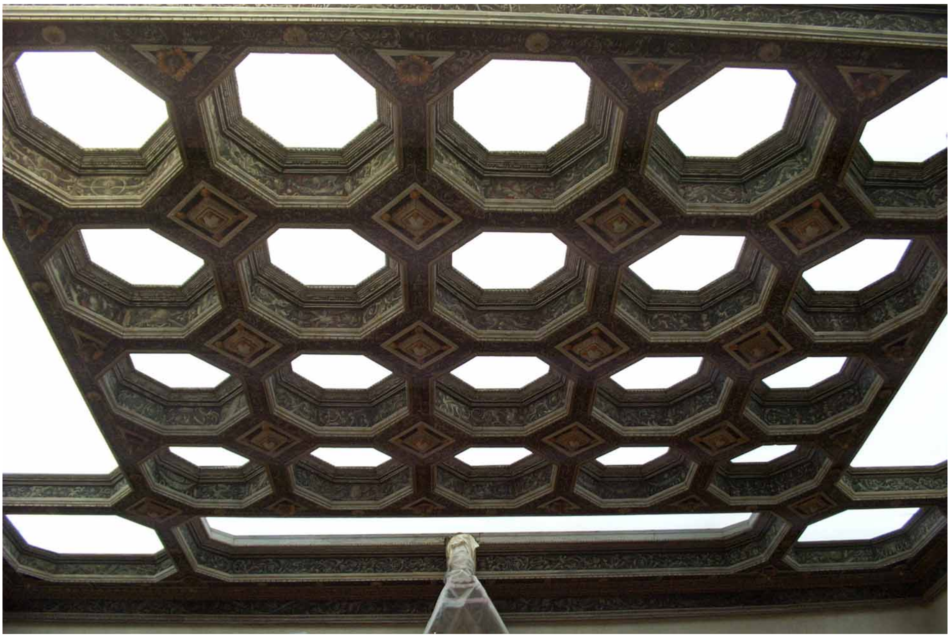

Figure 16. The diffuser panels installed on the old wood ceiling.

night ventilation can reduce peak indoor temperature during the day (∼1–2 °C), resulting in significant energy savings. Heat stored in the thermal mass is dissipated to the indoor air and can be removed during the night by opening special grids, when outdoor air temperature is lower. On the basis of this principle and in conjunction with the high thermal mass of the building, a retrofitting action has been considered, assuming an exchange rate of an ACH during night time from 10:00 pm to 8:00 am. Windows will be provided with special grids, which can be easily kept open in the summer to improve stack effect ventilation (figure 17). Besides, this system can allow us:

1. to reduce the energy wastes due to uncontrollable openings of windows during the heating and cooling period of the building;
2. to prevent the damage due to the high internal damp: deterioration of the frames, the corrosion, the condensation and mould problems;
3. to assure the visitors, in the cold season, homogeneous thermal comfort without high differences in temperature and without fastidious draughts;
4. to regulate a 'secure' airflow rate even when the building is closed and also prevent the admittance to unauthorized personnel and to rain, dust and insects. Besides, this system can allow night ventilation during the warm season to cool the museum space;
5. to reduce significantly the cooling load; to allow a constant ventilation rate in noisy urban areas, without leaving the windows open. It is important to note that the Italian museum building is located in the centre of Florence near a major road with heavy traffic throughout the day. This system can solve problems of noise, dust and pollution without using a mechanical and air-conditioning system;
6. to ensure the health of the occupants, avoiding high humidity levels and CO/CO_2 concentration and improving air distribution.

Figure 17. The special grids integrated in the windows frame.

9.4 *BMS*

In a museum, is difficult to preserve constant indoor conditions without the use of additional artificial systems. Hence, to have a microclimate without variations, these artificial systems are supported by advanced control systems. In addition to integrated building automation control systems (for lighting, ventilation, overall energy consumption, etc.) or special components such as the Intelligent Windows, controls systems for optimized building energy management are essentially oriented in three fields: thermal control systems; artificial lighting control systems and solar radiation control systems; ventilation and air quality control systems.

Moreover, today there are sophisticated intelligent systems, such as the building management systems, that integrate a larger number of sensors for fire alarm, smoke ventilation, control security systems, the HVAC system according to the internal requirement and so on.

The basic elements of an intelligent control system are as follows: 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. In the specific project of the Bardini Museum, BMS will be used to regulate thermo-hygrometric conditions and daylighting control also.

The control system for optimized indoor climate for exhibit preventive conservation and people 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 desirable indoor temperature at a specific period;
- ventilation control system, which can be used to control passive measures to promote natural ventilation, including the opening and closing of the grid installed under windows;

- occupancy sensor, which can be used to turn the lights off when the space is unoccupied or periodically occupied. We will use the most efficient one, which turns the 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 wind;
- lighting sensor, which makes it possible to keep the level of illumination in the room at the design level as daylight varies. It also permits a considerable saving of electricity, longer life for the lighting equipment and simple management of reserve lights.

An advanced energy management system, including a smart control for the ventilation system, will be installed. The system will contribute to obtain a low-energy consumption and will ensure that this saving will be maintained; in particular, the installation of this system will allow full control and monitoring for the function of all the components of ventilation systems. We plan to use this control system in order to assure the quality of indoor air, especially in relation to the measured CO_2 contents, which should be kept below a fixed level by ventilation.

9.5 *Assessment*

This demonstration project aims to contribute to significant decrease in energy consumption and peak electricity demand for lighting of this museum building, as well as to obtain a considerable improvement of comfort and indoor conditions through the application of high-energy measures. In parallel, it aims to disseminate effective information for designers and local authorities and to demonstrate the efficiency of the measures in order to promote them in efficient market promotion, penetration and utilization.

A preliminary analysis has highlighted the following problems:

- obsolete environmental conditions for visitors and staff related to air quality, thermal and visual quality;
- no environmental monitoring and control; *i.e.* no controlled ventilation: unfavourable and chargeable conditions for objects and visitors;
- excessive energy consumption; *i.e.* lighting represent 70% of the total energy consumption due to insufficient and obsolete devices in the exhibition solaces, no presence detectors, no day lighting compensation system;
- no efficient use of energy due to bad building maintenance and obsolete equipments;
- inadequate exhibit handling and display;
- adequate spatial organisation of exhibition space.

The qualitative impacts expected are as follows:

Environmental impacts. Important indirect environmental benefits are expected with the reduction of CO_2, CFC and the reduction of pollution caused by the use of electricity and thermal energy. Furthermore, the application of retrofitting measures will result in the improvement of indoor air quality, allowing the correct level of thermal comfort and avoiding the health hazards resulting from inadequate indoor conditions.

Health impact. Application of retrofitting actions will contribute to improve indoor air quality and to avoid health hazards.

Social impacts. Application of retrofitting actions will have a significant impact by creating healthy and comfortable indoor environment and increasing the diffusion of sustainable consciousness in users and owners.

Increased comfort. The present proposal contributes to achieve a substantial improvement in the indoor conditions. The creation of a comfortable and healthy indoor environment will seriously contribute to the quality of museum spaces and will contribute to increase the present value of the museum building's stock.

10. Conclusions/results

The proposed demonstration building is a representative example of a common type of museum in Italy and therefore is very suitable to serve as an exemplary pilot project for an historical museum retrofitting.

The aim of the project was to apply appropriate and strategic low-energy and sustainable techniques for a better energy retrofitting, without altering historical characters. This project had intended to demonstrate that this type of historical building suits very well the application of sustainable design and energy conservation systems.

Particularly, the objectives of this demonstration were:

- to set a new standard for energy consumption as this type of museum through energy efficient retrofitting;
- to enhance indoor environmental conditions and to improve working conditions for staff and visitors;
- to minimize the environmental impact of the building;
- to reduce total energy consumption;
- to reduce CO_2 emissions;
- simple payback of eligible installation and design cost in less than 15 years.

The final products of this project involve:

- an application of new developed, tested and fully documented measures for retrofitting, combining the scientific and technical knowledge in order to improve the energy performance and the indoor environment of museum buildings;
- a complete analysis with a specific monitoring of the energy, environmental and economic benefits connected to a direct application of high-energy efficiency measures; the production of complete data utilizable through appropriate dissemination activities suitable to provide specific guidance to designers who wish to reduce energy use in existing museums or to refurbish a museum with latest energy saving and environmentally friendly techniques.

The importance of this proposal is to transfer recent E.U. research achievements in practical applications: in fact, the real scale basis application contributes to the integration of new products and will assist efforts of the European industry in order to commercialize these products and will permit a better penetration of solar and energy efficiency systems and products into the building sector. Moreover, this application of retrofitting actions foresees some radical interventions in order to ameliorate the building functionality and its energy performance.

The application of an innovative retrofitting design in a real scale basis, linked to the recent scientific and practical achievements, has a good effect because comfort conditions will be greatly improved, energy use for heating as well as for cooling will be largely reduced and, at the same time, the required investment is acceptable.

Reference

Bartolo, R., Verifiche illuminotecniche degli ambienti con Radiance. Luce & Design n°7, Tecniche Nuove, Milano, 2003.