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"La Specola" Museum in Florence: Environmental Monitoring and Building Energy Simulation

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Abstract

Among the existing heritage, a specific case is represented by the museums, buildings which need to maintain specific internal environmental conditions for the purpose of preserving the artefacts. In Italy many important museums are in historical buildings that are characterized by inadequate thermal envelope and HVAC system. This paper regards "La Specola" Museum in Florence and analyzes the results obtained from one-year environmental monitoring, undertaken to evaluate the microclimatic conditions of the exposition rooms and showcases considering assessment criteria derived from technical standards and scientific literature. Aim of the research was to create a three-dimensional energy model of the building, calibrated according to commonly used error indexes, and to run a dynamic simulation of their energy behaviour validated by the measured values in the field. The creation of a calibrated energy model of the museum will be useful to evaluate in the future the effectiveness of different strategies (active or passive) for the museum refurbishment.

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Keywords: environmental monitoring; preventing conservation; historical buildings; dynamic simulation; energy model.

1. Introduction

Indoor microclimate is very important in the deterioration processes of the objects exhibited inside museums; in particular, incorrect absolute values and sudden and intense time fluctuations of air temperature and relative humidity can lead to physical (dimensional and shape variation of objects), chemical (chemical reactions) and microbiological

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(microorganism growth) problems for the exhibits (Thomson, 1986; Corgnati et al., 2009). To reduce the risk of degradation of the objects, the trend is oriented to preventive conservation (Sciarpi et al., 2015).

In museums without a heating, ventilating and air conditioning system (HVAC), showcases play a fundamental role in the artefacts conservation, dampening the microclimate variations and protecting against vandalism, robberies and other direct damage that could come from visitors (Thomson, 1986; Stolow, 1987; Camuffo, 1998).

Microclimate monitoring of museum rooms and showcases is fundamental to assess the museum environment suitability to conserve the artefacts and to define the strategies to reduce their degradation risk (Pavlogorgatos, 2003; La Gennusa et al., 2005; Ferdyn-Grygierek, 2014).

Technical regulations about cultural heritage conservation (UNI, 1999; CEN, 2010) establish guidelines and methods to measure temperature, humidity and lighting level inside museums. Moreover, guidelines for the museums operation and management have been drawn up by the Italian Ministry for Cultural Heritage, giving information about quality standard and technical equipment inside museums (MiBAC, 2001).

In the Florence district, as well as all over Italy, there are many museums located in historical buildings (90%) and most of all are not equipped with HVAC systems or sealed showcases. Moreover, in almost 25% of museums of Florence, poor conditions are pointed out (water infiltration from roof or windows, low windows performances, absence of light and solar control systems, poor thermal performance of the building envelope), and in almost 33% of them there isn't any heating system (Sciarpi et al., 2015, 2018).

Together with microclimate data monitoring and analysis, in the last years Building Energy Modelling (BEM) and Building Energy Simulation (BES) have received growing consideration as a fundamental tool to identify and assess energy retrofit measures for existing building and, by extension, preventive conservation strategies for museum located in historic buildings (Lucchi, 2018; Ferdyn-Grygierek, 2014; Widström and Mattsson, 2011; Kramer et al., 2015; Wang et al., 2014). However, building energy models, to represent an effective support tool, should duplicate as closer as possible the actual energy and thermal behavior of the real building and, to this end, must be validated through a proper calibration process (Coelho et al., 2018; Roberti et al., 2015).

Energy model calibration is an iterative process that aim, by means of refinement of input model data, to reduce the differences between measured and simulated values assumed by significant parameters that characterize building energy and thermal behavior. Model calibration can be carried out with various methods (Coakley et al., 2015, 2014) and could implies different steps such as (Pernetti et al., 2014):

- Input data gathering (building, HVAC, occupants and weather)
- Base model construction
- Sensitivity analysis aimed to identify the input parameters that mostly affect energy and thermal behavior of the building (e.g. thermal transmittance of walls, internal gains, infiltration air change rate, etc.)
- Selection of proper calibration control variables among those parameters (energy consumption and/or temperature parameters) that characterize building energy and thermal behavior
- Measured data collection regarding control variables by means of energy bills, energy metering or microclimate monitoring
- Definition of calibration criteria (error indexes and related acceptability ranges) in order to assess the difference between measured and simulated values assumed by chosen control variables
- Model validation by means of iterative energy simulations where different values are attributed to selected input parameters since calibration criteria are met and the model can be considered validated.

Model calibration of old existing building not provided with HVAC system represents a particular case since, even though affected by a higher grade of uncertainty, only indoor air temperature and relative humidity can be used as a control variable (Coelho et al., 2018; Pernetti et al., 2014; Roberti et al., 2015). Commonly used error indexes employed to evaluate the accuracy of BES with regard to actual monitored data in terms of temperature and relative humidity are Mean Bias Error (MBE), Root Mean Square Error (RMSE), Coefficient of Variation of Root Mean Square Error CV (RMSE) and Pearson Index (r) (Coelho et al., 2018; Giuliani et al., 2016; Pernetti et al., 2014; Roberti et al., 2015). Well-known technical standards regarding measurements of energy savings in buildings (ASHRAE

Guideline 14/2002 and IPMVP) provide acceptability ranges just for model calibrated on the base of hourly or monthly data of energy consumptions (ASHRAE, 2002; Efficiency Valuation Organization, 2002). Since technical literature doesn't explicitly mention any acceptability criteria for calibration processes that make use of temperature or relative humidity as control variables, some authors applied ASHRAE Guideline 14/2002 and IPMVP criteria even to this methods of model calibration (Coelho et al., 2018; Giuliani et al., 2016).

Aim of the research is to investigate hygrothermal conditions inside one of the oldest museums of Florence, "La Specola", by means of one-year monitoring and to calculate dedicated performance indexes, in order to outline main conservation problems for the exhibits. Moreover, aim of the research is to create a three-dimensional energy model of the building, calibrated according to commonly used error indexes, and to run a dynamic simulation of their energy behaviour validated by the measured values in the field. The creation of a calibrated energy model of the museum will be useful to evaluate in the future the effectiveness of different strategies (active or passive) for the museum refurbishment.

2. The case study: "La Specola" Museum of Florence

"La Specola" is one of the most important museums of Florence and is situated in Palazzo Torrigiani, in the historic center of the city. It can be considered the first European scientific museum and it was opened to the public on February 21, 1775, at the wish of Pietro Leopoldo di Lorena, Grand Duke of Tuscany, who had expressly ordered the reorganization of the Medici collections (Contardi, 2012). Most of the specimens displayed in the museum date to between the second half of the 1800s and the first decades of the 1900s, and almost all of them were collected during scientific expeditions organized by the Museum. The Museum is open six days of the week. Inside "La Specola" Museum are collected objects with different conservative requirements; the rooms contain showcases, of great historic and artistic value, in which different specimens are exposed, such as diorama, protozoa, insects, carnivores, anatomic waxes, etc. Both zoological exhibits and anatomical waxes are mostly vulnerable to high temperature, which can cause biological growth and activate putrefaction in the former and the dissolution of portions of material in the latter. Wooden showcases particularly suffer from relative humidity quick temporal variations that can cause their dimensional alterations; moreover, the anatomical waxes, for their safe exhibition, are securely coupled to showcases so any shift of the wooden support structure have repercussions on the exposed object and can cause its damage (Cresti, 2006). Relative humidity variations are particularly important for the mammals exhibited that have an inner filling made of gypsum instead of straw; this filling presents a different behavior than the animal skin and can cause its break due to high temperatures that determine a quick and uncontrolled reduction of RH values in summer periods (Sciarpi et al., 2015).

"La Specola" is a non-air conditioned museum; only in the anatomic waxes section (rooms XXIV–XXXI) a heat pump system with ceiling fan coils was installed in the '80s to maintain indoor temperature between 20 and 22°C; air temperature control system consist of a thermostat placed in every room (Sciarpi et al., 2015). Artificial lighting in the museum is guaranteed by discharge lamps that are turned on for all the opening hours, from 9 AM to 5 PM from Tuesday to Sunday; in some rooms there is also artificial lighting inside showcases (discharge lamps and LED). The Museum is closed for maintenance since September 2019.

3. Microclimatic monitoring campaign of the Museum

To investigate the indoor microclimatic conditions and to point out damage causes for the objects exposed, a microclimatic monitoring system has been installed in the Museum on 2011, with fixed data loggers (resolution: 0.1°C/0.1%; accuracy: $\pm 0.5^\circ\text{C}/\pm 2\%$) to collect values of dry bulb temperature (θ) and relative humidity (RH) with fifteen-minute time step. The system, described in Sciarpi et al., 2015, consists of 20 loggers, placed in 14 rooms, inside 5 representative showcases and outside the museum, in an internal courtyard (Fig. 1a).

In the present work, data monitored during one-year (from May 2012 until May 2013) are analyzed and discussed, according to the methods for elaboration and analysis of data suggested by UNI 10829. For each monitored point, the temporal profile of temperature and RH, minimum, medium and maximum values of temperature and RH, daily

gradients of temperature ($\Delta\theta_{24}$) and RH (ΔRH_{24}) were evaluated. Moreover, in order to express a brief evaluation of the quality of the indoor environment in relation to the conservation of the object contained in it, the Performance Index (PI) of each parameter has been used. This index represents the percentage of time during which the measured parameters fall within their ranges considered as “acceptable” for the conservation of the objects exhibited.

Optimal parameters for objects conservation can be defined both by the curators and by technical documents and UNI standards, such as DM 10.05.2001 (MiBAC, 2001), UNI 10829 and UNIEN 15757 (CEN, 2010). Based on the climatic history of the exhibits, their material and structural characteristics, values for the conservation of artefacts accepted by the museum conservators are the following:

- for anatomic waxes: $20^{\circ}\text{C} \leq \theta \leq 22^{\circ}\text{C}$; $40\% \leq \text{RH} \leq 60\%$; $\Delta\theta_{24} \leq 1.5^{\circ}\text{C}$; $\Delta RH_{24} \leq 5\%$
- for all other objects: $15^{\circ}\text{C} \leq \theta \leq 24^{\circ}\text{C}$; $40\% \leq \text{RH} \leq 60\%$; $\Delta\theta_{24} \leq 1.5^{\circ}\text{C}$; $\Delta RH_{24} \leq 5\%$.

4. Model construction for museum energy simulations

In order to get a complete tool useful to analyze the indoor conditions to evaluate the effects of future possible retrofitting strategies, a model of all the museum was made in Energy Plus®, through the Design Builder® interface (Fig. 1b).

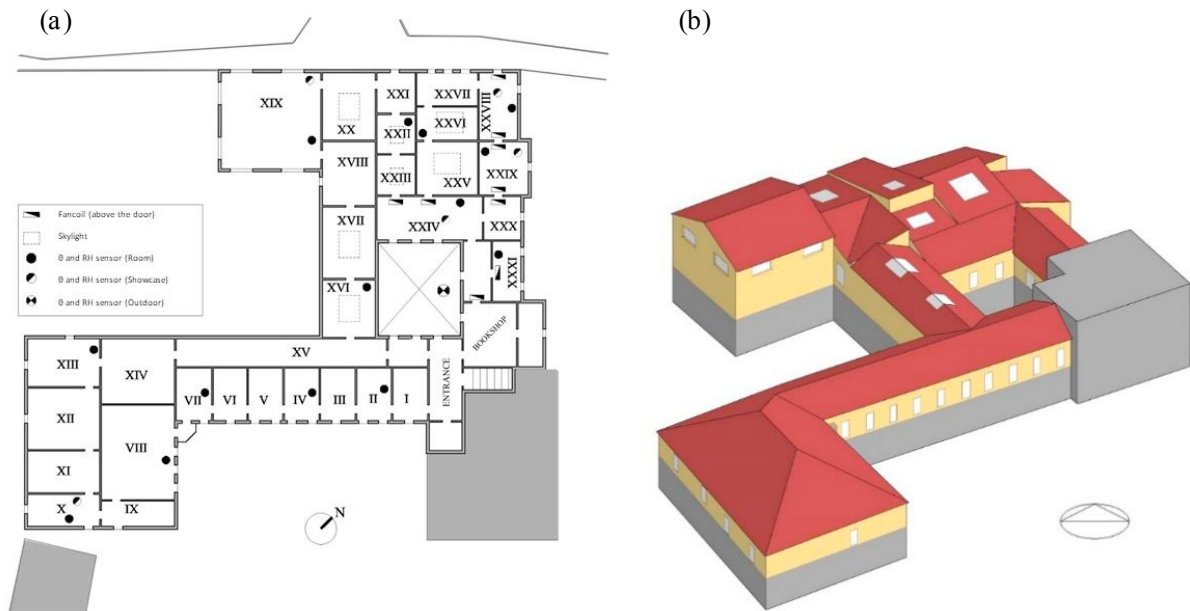


Fig. 1. (a) Plan of the museum with the monitored points; (b) 3D energy model of the museum.

For the geometric 3D model construction, a survey of the various rooms and the showcases of the museum was carried out. Based on the relief, a CAD plan was created, then transferred to the software and appropriately scaled and oriented according to the correct axis. Using the plan, the volumes of the various rooms were created, and the windows were added. Thanks to a series of photographs taken around the perimeter of the museum and on the observation tower, the roofs were built on the model and the skylights shown on them.

To build up the energy model of the museum, thermal loads (number of visitors during opening time, type of artificial lighting, etc.), HVAC system characteristics, building envelope thermal properties and external climate were set. No area of the museum was left thermally isolated from the others; in this way it was possible to evaluate an

effective response from the simulation runs of each environment in relation to the surrounding ones. Thermal properties of the building envelope are described in Table 1.

Table 1. Thermal properties of the building envelope.



Building elements	Description	Thickness (m)		U (W/m ² K)
External wall	Internal plaster (0.02 m), stone blocks (0.2 m), concrete filling (0.19 ÷ 0.39 m), stone blocks (0.2 m), external plaster (0.02 m)	0.63 ÷ 0.83		0.95 ÷ 1.31
False ceiling	Lime plaster (0.01 m), reed trellis (0.01 m)	0.02		3.42
Roof	Wood rafters, brick tiles (0.03 m), roof tiles (0.02 m)	0.05		2.99
		g-value (-)	τ_v (-)	U _w (W/m ² K)
Skylight	Metal frame without thermal break (frame: 0.01 m wide / 0.02 m thick; dividers: 0.04 m wide / 0.02 m thick); Single clear glass (3 mm)	0.86	0.90	5.83
Windows	Wood frame (0.06 m wide / 0.05 m thick); Single clear glass (3 mm)	0.86	0.90	4.96

5. Results and discussion

The data received from all the sensors in the museum were collected and analyzed through Excel and graphics were created to comprehend the trend of temperature and relative humidity values during the analysis period, divided by the whole year, the months, the weeks and singular days. Besides, some graphics were created showing the values of the PI of each environment for all the period, comparing monitored and optimal values suggested by MiBAC.

From these analyses it was possible to elaborate a series of observations on the conditions and issues of the various rooms, thus allowing the environments to be compared and grouped by similar characteristics. These groupings were chosen on the basis of the following criteria: conditioned or non-conditioned rooms, presence of windows or skylights, types of solar shading present, surface and state of conservation of the external walls, type and relevance of the exhibits, tendency of visitors to remain in a specific room. These rooms (X, XXII, XXVIII) were chosen because they presented themselves as representative of a group of rooms with the common characteristics among those listed above. Rooms X and XXII are without conditioning system, while in room XXVIII only a air temperature is controlled throughout the year by fan-coils. Moreover, because of most of the objects are exhibited inside showcases, monitoring results in a typical showcase, inside Room X (Xs), was reported and compared. Main characteristics of the chosen environments are reported in Table 2.

Table 2. Main characteristics of the analyzed rooms.

	<p>Room X</p> <p>Object Exposed: various mammals (aquatic environment).</p> <p>Room dimensions:</p> <ul style="list-style-type: none"> - Plant surface: 67 m² - Volume: 261 m³ 	<p>Technical system: No HVAC system; direct artificial lighting of the room with tubular fluorescent lamps; LED light inside showcases.</p> <p>Architectural features: Two external wall (SE and SW oriented); one window with external and internal solar shading; not insulated pitched roof.</p>
	<p>Room XXII</p> <p>Object Exposed: marine reptiles.</p>	<p>Technical system: No HVAC system; direct artificial lighting of the room with tubular fluorescent lamps; no light inside showcases.</p>

**Room dimensions:**

- Plant surface: 34 m²
- Volume: 217 m³

Room XXVIII

Object Exposed: anatomical waxes.

Room dimensions:

- Plant surface: 46 m²
- Volume: 164 m³

Architectural features: no external walls; one skylight without external solar shading; not insulated pitched roof.

Technical system: fan coils system to control air temperature; direct artificial lighting of the room with tubular fluorescent lamps; no light inside showcases.

Architectural features: two windows (one NW and one NE oriented) with external and internal solar shading; two external walls (NW and NE oriented) and not insulated pitched roof.

For one-year monitoring, the time profiles of mean daily temperature measured in the rooms X, XXII and XXVIII are presented and compared with the corresponding outdoor values (OUT) (Fig. 2).

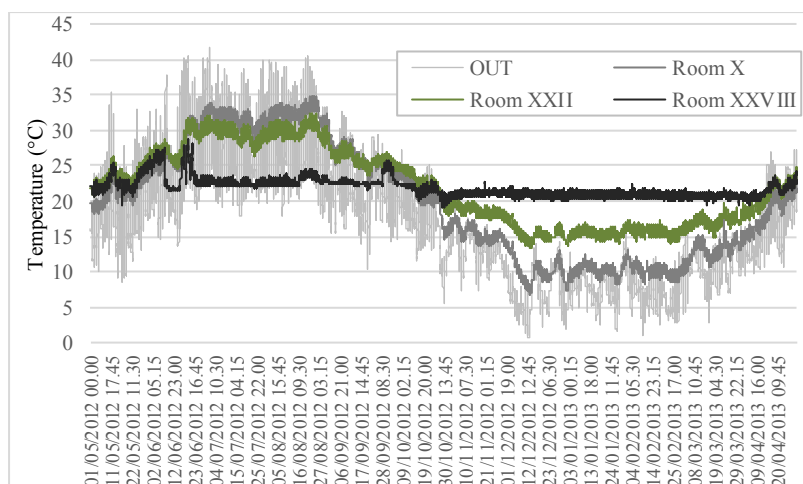


Fig. 2. Trend of mean daily temperature measured in rooms X, XXII and XXVIII compared with the outdoor values (OUT).

The analysis of the microclimatic parameters measured shows that temperature and RH conditions, during the monitoring period, were not reasonably acceptable for the preservation of the kind of objects exhibited.

The temperature and RH trend are similar for the uncontrolled rooms (X and XXII) and follows the outdoor climate, although very dampened in sudden hourly and daily changes. In spring and autumn indoor temperature and RH are within the recommended range, whereas in summer and in winter temperature is respectively above and below the limits, with an annual PI of 31%, and RH is respectively below and above the limits, with an annual PI of 47%. Regarding the room XXVIII, the fan coils system keeps constant temperature values and reduces indirectly RH variations, except when the system is not working: in these moments the values are aligned to those of the other rooms, with consequent maximum daily gradient of temperature of 6.6°C. Moreover, variations in the temperature values can also be due to the presence of an unlocked thermostat that can be easily reached by visitors.

Particularly significant are the values of temperature inside the showcase in the Room X (Xs) that are similar to the ones in the room (Fig. 3).

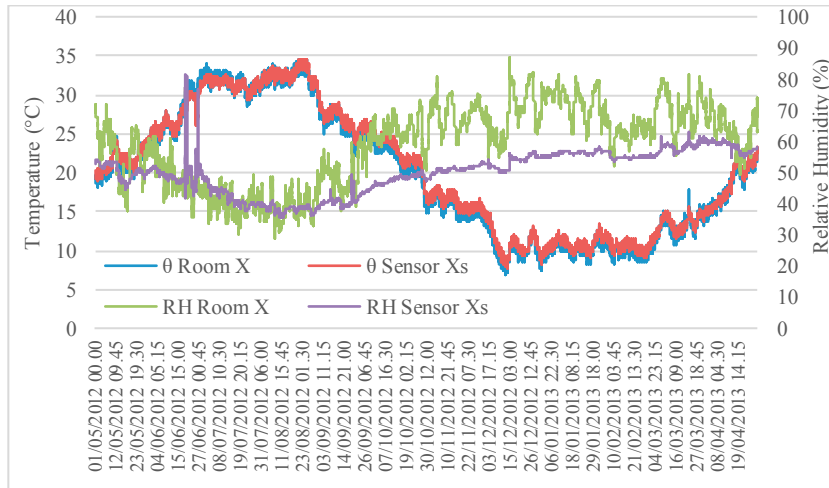


Fig. 3. Trend of mean daily temperature and RH measured in Room X compared with the values in the showcase in the same room (Xs).

In this case, the lack of thermal insulation of the room is reflected in higher and lower temperatures inside the display case. Although the showcases are not sealed, they reduce RH variations respect those of the room and guarantee a damping of RH changes greater than temperature ones. The RH trend inside the cases is related to the indoor temperature trend rather than to the outdoor RH variations.

In Table 3, for the year monitored, maximum daily gradient of temperature ($\Delta\theta_{24\max}$) and RH ($\Delta RH_{24\max}$) for the analyzed environments are reported, together with the PI of the thermo-hygro-metric parameters analyzed (θ , RH, $\Delta\theta_{24}$, ΔRH_{24}).

Table 3. Maximum daily gradients and PI values of the thermo-hygro-metric parameters.

Room	$\Delta\theta_{24\max}$ (°C)	$\Delta RH_{24\max}$ (%)	PI_{θ} (%)	PI_{RH} (%)	$PI_{\Delta\theta_{24}}$ (%)	$PI_{\Delta RH_{24}}$ (%)
X	2.3	9.1	30.8	40.6	49.7	49.6
Xs	1.6	1.6	30.0	86.7	74.1	98.4
XXII	2.8	7.5	52.8	62.8	32.0	73.8
XXVIII	3.0	7.5	95.3	60.9	64.8	68.5
Outdoor	22.6	63				

The energy model has been calibrated considering two sample thermal zones: Room X and XXII which are both not provided with air conditioning system. Therefore, the quality of the model has been assessed adopting indoor temperature as calibration control variable. In particular, hourly values of indoor air temperature collected during the above-mentioned monitoring campaign have been compared with simulated values of the same parameter, by means of three error indices: MBE, CV (RMSE) and Pearson index (r).

Since validation criteria for models calibrated by means of air temperature are not available (Roberti et al., 2015), “La Specola” calibration output has been compared with acceptability ranges recommended for model calibration on the basis of hourly values of energy consumption (Coelho et al., 2018; Giuliani et al., 2016). For example ASHRAE Guideline 14/2002 (ASHRAE, 2002) suggest that MBE should be less than $\pm 10\%$ and CV (RMSE) below 30%. As regards as Pearson Index, it presents an optimal value of 1 corresponding to a perfect direct correlation between measured and simulated values trends; however, a value bigger than 0.5 can be considered a minimum limit of acceptability for a good correlation (Pernetti et al., 2014). During the iterative simulation phase, the model has been optimized, varying the value attributed to the infiltration air change rate, that have been regarded as the uncertain parameter mostly influential on simulation results. Considering an infiltration air change rate of 1.0 h^{-1} , calibration

error indexes reached the lowest values within ASHRAE Guideline 14 ranges of acceptability (MBE = -8 % and CV RMSE = 9.9 % for room X and MBE = -1.2 % and CV RMSE = 9.8 % for room XXII, Person Index = 0.99 for both rooms) and the model was considered validated and viable for future analysis of energy retrofit measures.

6. Conclusions

Microclimate monitoring of museum rooms and showcases is fundamental to evaluate the museum environment suitability to conserve the artefacts and to define the strategies to reduce their degradation risk.

To investigate the indoor microclimatic conditions, a temperature and relative humidity monitoring system has been installed in “La Specola” Museum of Florence on 2011. The monitoring campaign pointed out some problems: for the uncontrolled rooms, the low values in winter periods but especially the high values in summer of the temperature, as well as their high daily variations, can be particularly hazardous for the proper conservation of the kind of objects exhibited; moreover, the indoor temperature is the main cause of RH variations inside the showcases. Regarding the controlled rooms, the fan coils system keeps constant temperature values and reduces indirectly RH variations, except when the system is not working. In order to get a complete tool useful to evaluate the effects of future possible retrofit strategies, a 3D energy model of all the museum was made in Energy Plus®, through the Design Builder® interface. From the analysis of the microclimatic conditions inside the museum and the study of the characteristics of the building, it was possible to group the rooms by similar characteristics and to choose the rooms where to calibrate the dynamic model, following the guidelines of ASHRAE 14.

The creation of a calibrated energy model of the museum will be useful to evaluate in the future the effectiveness of different strategies (active or passive) for the museum refurbishment.

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