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ScienceDirect

Energy Procedia 133 (2017) 219–230

Energy Procedia

www.elsevier.com/locate/procedia

Climamed 2017 – Mediterranean Conference of HVAC; Historical buildings retrofit in the Mediterranean area, 12-13 May 2017, Matera, Italy

Environmental monitoring and building simulation application to Vasari Corridor: preliminary results

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Abstract

The Vasari Corridor has been used in the past and present for storage and presentation of works of art which require control of microclimate for optimal preservation. To this end, it was started the collaboration between the Uffizi Gallery and Laboratory of Environmental Physic of the Florence University for the environmental monitoring of microclimatic parameters, of which this work presents the preliminary results.
It's was also created a three-dimensional model of the building in the stretch from the Uffizi Gallery to Ponte Vecchio, for the dynamic simulation of the energy behavior of the building validated by on-field measured values.

Peer-review under responsibility of the scientific committee of the Climamed 2017 – Mediterranean Conference of HVAC; Historical buildings retrofit in the Mediterranean area

Keywords: environmental monitoring; preventing conservation; historical buildings; dynamic simulation

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Peer-review under responsibility of the scientific committee of the Climamed 2017 – Mediterranean Conference of HVAC; Historical buildings retrofit in the Mediterranean area
10.1016/j.egypro.2017.09.393

1. Introduction

In Museums, the preventive conservation is fundamental for the preservation of the artifacts exposed and to reduce the process of exhibits degradation and restoration [1,2].

Preventive conservation is a combination of actions directed to reduce the risk of degradation of the exposed object and to identify optimal environmental conditions to show the object in the safest way [3]. It implies both passive techniques, aimed to minimize the potential damage to the object from the exhibition environment, and environmental monitoring and management directed to minimize fluctuations of indoor environmental parameters and to reduce impacts from outdoor (windows openings, visitors crowding, irregular HVAC operation, wrong positioning of HVAC terminals and lighting elements, etc.). In particular the stability of temperature and relative humidity plays a key role in the deterioration processes of the cultural heritage [4,5]. Microclimatic monitoring of museums rooms, as well as lighting level measurement and sampling of indoor air pollutants, is necessary to assess the museum environment suitability to conserve exhibits and to plan any actions required to reduce degradation risk [6,7].

Italian technical regulations about cultural heritage conservation [8,9] establish guidelines and methods to measure indoor temperature, humidity and lighting level. It is important to underline that, pursuing the goal of cultural heritage conservation, it is impossible to fix for each object absolute values or ranges of optimal values of the environmental parameters. An optimal compromise between various issues concerning museums must be looked for. Especially in historical buildings turned into museums is very often necessary to carry out a compromise between objects conservation, public fruition and both visitors and occupants comfort [10].

To study and analyze thermo-hygrometric parameters values that can affect the exhibits conservation, in July 2016 an environmental monitoring campaign has been started in the Vasari Corridor of Florence. The monitoring system consists of several data loggers located in different parts of the museum.

Aim of this study is to analyze the monitoring results and to create a three-dimensional model of the building, to run a dynamic simulation of the energy behavior validated by the measured values. This will allow to analyze the responses of the building to weather solicitations, the behavior of the building with a possible HVAC system also for reducing management costs, and the effectiveness of passive strategies for the energy refurbishment, such as thermal insulation of the roof, replacing windows and natural ventilation, etc. Finally, the results constitute the knowledge base essential if we want to change the setting of the corridor or consider other destinations.

Nomenclature

g	Solar factor, (-)
PI	Performance Index, %
RH	Relative humidity, %
U	Thermal transmittance, W/(m²K)
U_g	Thermal transmittance of the glass, W/(m²K)
U_w	Thermal transmittance of the window, W/(m²K)
θ	Dry bulb temperature, °C
θ_s	Surface Temperature, °C
$\Delta\theta_{24}$	Daily gradient of temperature, °C
ΔRH_{24}	Daily gradient of relative humidity, %
τ_v	Light transmittance, (-)

2. Description of the Vasari Corridor in Florence

The elevated passage known as the Vasari Corridor is an enclosed and privileged connection built to join Palazzo Vecchio with Pitti Palace. It was commissioned by Cosimo I de' Medici on the occasion of the wedding between his eldest son, Prince Regent Francesco, and Archduchess Joanna of Austria, sister of Emperor Maximilian II, celebrated on the 18th of December 1565. It was designed by Giorgio Vasari and realized in just eight months, from March to December 1565, excluding the assembly of fixtures whose installation took place in December 1568.

The Corridor starts from Palazzo Vecchio, the heart of the Florentine political government, crosses Via della Ninna by means of a single dizzying overpass, continues over the roof of the Church of St. Pier Scheraggio, then enters inside the Uffizi (the seat of the Magistrates' offices) and leads to Lungarno Archibusieri. At the time of the realization of the Corridor, the premises to accommodate the Magistrates' offices were under construction, and in 1565 only the ground floor of the long eastern wing was finished, while on the first floor only the side opposite to Palazzo Vecchio was accomplished and therefore the Corridor stretched over the building site with works in progress. Indeed, the second floor was still an open loggia which was closed later with large glass windows and turned into an "art gallery" on the occasion of the renovation commissioned by Francesco I [11].

The Corridor runs along Lungarno Archibusieri and, at its intersection with the bridge, it bends again by ninety degrees and crosses the Arno river by passing over the mezzanines of the fourteenth-century shops. On the other side of the river, it rests on the corbels protruding out the houses and the Mannelli Tower, crosses Via de' Bardi over a single large arch (rebuilt in its present shape after the damages of World War II), lays against the façade of the Church of St. Felicita, enters into Guicciardini Garden and leads to Boboli Garden from an exit beside the Buontalenti Grotto; another path running along Boboli Garden leads inside Pitti Palace. Seriously damaged by mines placed by the retreating German army in August 1944, the Corridor was restored and partly rebuilt in the '50s. Owing to the flood of the Arno river occurred on the 4th of November 1966, the Corridor suffered many structural problems and was again restored to be reopened in 1973 [11–13].

The total path is about 760 meters and its width ranges from 1,3 meters to 4 meters; from the current entrance on the second floor of the Gallery to the exit beside the Buontalenti Grotto, the Corridor is about 500 meters long and covers a floor area of just over 1900 square meters.

According to the original intentions of the buyer Cosimo I de' Medici and the architect Giorgio Vasari, the Corridor was meant for a private and exclusive use allowing the Duke and his heir to move from the government seat of Palazzo Vecchio to their pleasant residence of Pitti Palace with its spectacular garden in total safety. Grand Duke Ferdinando I maintained the private nature of the Corridor and he even decided to extend it from the Buontalenti Grotto to the ducal apartments, as well as to realize an opening on the wall of the Church of St. Felicita in order to create a stage for the Grand Ducal family; after 1600, he commissioned also a staircase in the southern part of the Uffizi, which is the current access to the Corridor. After three centuries of such a private use, it was open to the public in 1866, by permission of the House of Savoy.

The Corridor complies to criteria of maximum economy: the shortest, fastest and less expensive path. Where it was possible for property reasons, like on Lungarno Archibusieri which is public property, it was preferred to proceed with a new building, even if it involved the demolition of the Loggia del Pesce (fish market), built just six years before. The guidelines of the project and the shape of the path were dictated by some buildings, such as the XIII Magistrates' palace under construction, the houses-shops on Ponte Vecchio, the Mannelli Tower, the Church of St. Felicita; Vasari exploited the preexisting buildings as supports to the Corridor.

The Corridor has a Roman typological matrix, with particular reference to the ancient aqueducts (see the stretch of Lungarno Archibusieri), also for the lack of orders and the sophisticated simplicity of the architecture aiming at efficiency and functionality. The linguistic simplification corresponds to the use of poor materials, namely recycled or found in the Florentine plain: bricks came from the furnaces of Campi Bisenzio, San Piero a Ponti, Sesto Fiorentino and Lastra a Signa; the stones used for the part above Ponte Vecchio were extracted from the Arno; the stone window frames – in round shape those looking over the city and rectangular shape those looking over the river – came from Fiesole; the stones and columns from the destroyed Loggia del Pesce were reused in the new building. The wood used for temporary works as well as for the final ones (trusses, floors and timber frames) was purchased by the Opera di Santa Maria del Fiore [14,15].

In 1568 the installed fixtures were 56 frames for rectangular windows and 42 frames for round windows; currently, as a result of successive interventions, there are 47 rectangular windows and 39 round windows. The most evident change concerns the three windows in the central part of the stretch above Ponte Vecchio on the west side, transformed into a "temporary terrace" in 1860 to honor the arrival of King Vittorio Emanuele II of Savoy in Florence. In 1866, in view of the forthcoming opening of the Corridor to the public, the Direction of the Royal Galleries decided to close the terrace by walling up the two side compartments. Thanks to subsequent restoration works after World War II, the two side compartments were reopened and the three large tripartite windows replaced [14,15].

As for the systems, at present the Corridor is equipped with an artificial lighting system, emergency signals, one anti-intrusion system, a video-controlled one and a smoke detector [16].

3. Description of the Vasari Corridor in Florence

3.1. Materials and methods

Environmental monitoring inside historical buildings can contribute to prevent damages of the objects exhibits due to inadequate thermal and hygrometric conditions also suggesting the curators' strategies to carry out to improve climatic indoor conditions.

Starting from this point of view, from 29 July 2016 an environmental monitoring system has been wired in the Vasari Corridor of the Uffizi Gallery of Florence to investigate and control the indoor microclimatic conditions as well as to point out damage causes for the objects exposed. The instruments installed are the "Tinytag" model of the Gemini Data Loggers LTD (www.geminidataloggers.com) and has been placed in the positions reported in Figures 1, 2 and 3. The external data logger (EXT), protect from rain and solar radiation, is located in an internal courtyard. In general, the internal measuring positions have been chosen considering the fruition of the Rooms, the operating requirements of the instruments (avoiding proximity to heat sources, direct light, direct contact with pollutants or other local disturbance causes that may affect the proper functioning of the instruments), as well as the geometric characteristics of the environments.

Figure 1. Photographs of the data loggers in positions A, B and C.

Figure 2. Photographs of the data loggers in positions D, E and F.

The data loggers named A, B, C and D collect measures concerning dry bulb temperature (θ) and relative humidity (RH), while the data loggers named E and F measure the surface temperature of the inner surface of the glass windows of Ponte Vecchio, with west and east exposure, respectively. The sensors have been set up to record the values of the measured parameters every 15 minutes.

In Table 1, as well as a picture of the type of sensors used, are the main characteristics of the same, that are consistent with what is stated in the Ministerial Decree of 10 May 2001 [17] and in the UNI 10829 Standard [8].

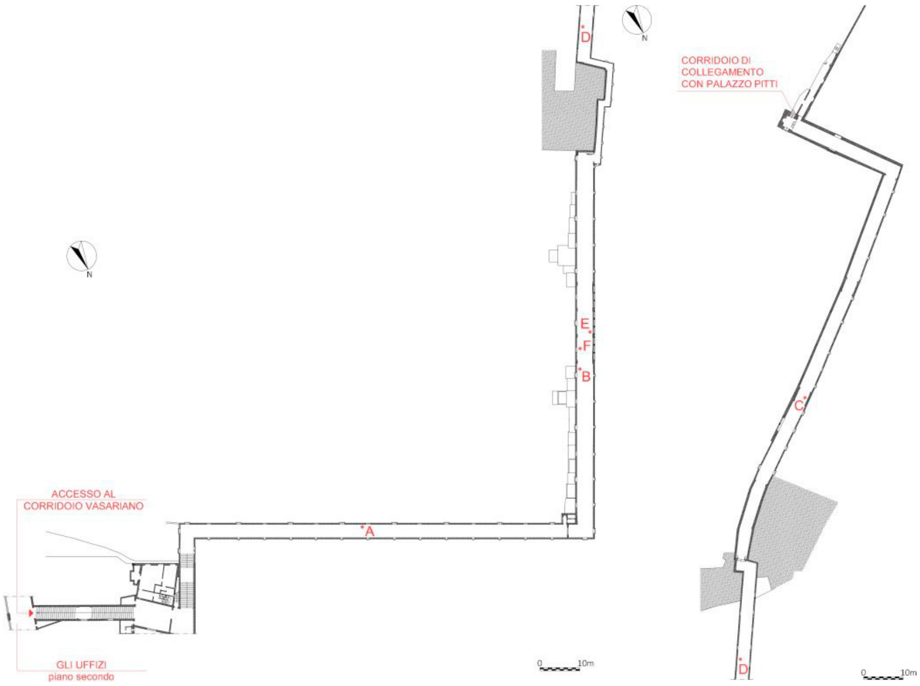

Figure 3. Plan of the Vasari Corridor with the positions of the data loggers

Table 1. Main characteristics of the sensors used. From (http://www.geminidataloggers.com).

	Battery	3,6 V Lithium
	Dimensions	72 x 60 x 33 mm
	Temperature Reading Resolution	0,01°C
	Temperature Accuracy	0,4 °C
	Temperature Reading Range	- 25 to + 85 °C
	RH Reading Resolution	0,3%
	RH Accuracy	3%
	RH Reading Range	0 to 95%

As for the conservation, optimal parameters can be defined both by the curators and by technical documents and UNI Standards, such as DM 10.05.2001[17], UNI 10829 [8], EN 15757[18] and UNI 10969 [9]. These optimal values should be defined on the basis of climatic history of the exhibits, their material and structural characteristics. Table 2 lists the recommended reference values of the monitored parameters for the conservation of the category of objects exhibited in the Vasari Corridor, “Paintings on canvas, oil paints on canvas" [8,17].

Table 2. Recommended reference values for the conservation of “Paintings on canvas, oil paints on canvas" [8,17].

Source	θ (°C)	$\Delta\theta_{24}$ (°C)	RH (%)	ΔRH_{24} (%)
D.M. 10.05.2001	from 19 to 24	≤1.5	from 35 to 50	≤6
UNI 10829:1999	from 19 to 24	≤1.5	from 40 to 55	≤6

3.2. Monitoring campaign analysis, results and discussion

The monitoring campaign is still in progress; in the present paper, data monitored until December 2016 are analyzed and discussed, according to the methods for elaboration and analysis of data suggested by UNI Standard 10829 [8]. For each monitoring position, the temporal profiles were evaluated, the frequency distributions and cumulative frequency distribution of temperature and RH were examined. Minimum, medium and maximum values of temperature and RH, daily gradients of the thermo-hygrometric parameters were also evaluated. From the knowledge of the cumulative frequency of the monitored values, the Performance Index (PI) was evaluated. This index expresses an evaluation on the quality of the indoor environment in relation to the conservation of the object exhibited on it: in brief, it represents the percentage of time during which the measured parameters fall within their acceptable ranges set [6,10,19]. Museum Conservators accepted values for the conservation of artefacts are: 19°C $\leq\theta \leq$24°C; 35%≤RH≤50%; $\Delta\theta_{24}\leq$1.5°C; $\Delta RH_{24}\leq$6%.

The results are critically analyzed with the aim to point out main problems for the object conservation.

In Figures 4 and 5 the time profiles respectively of temperature and relative humidity measured in positions B and C are presented and compared with the corresponding outdoor values (EXT) and the accepted values.

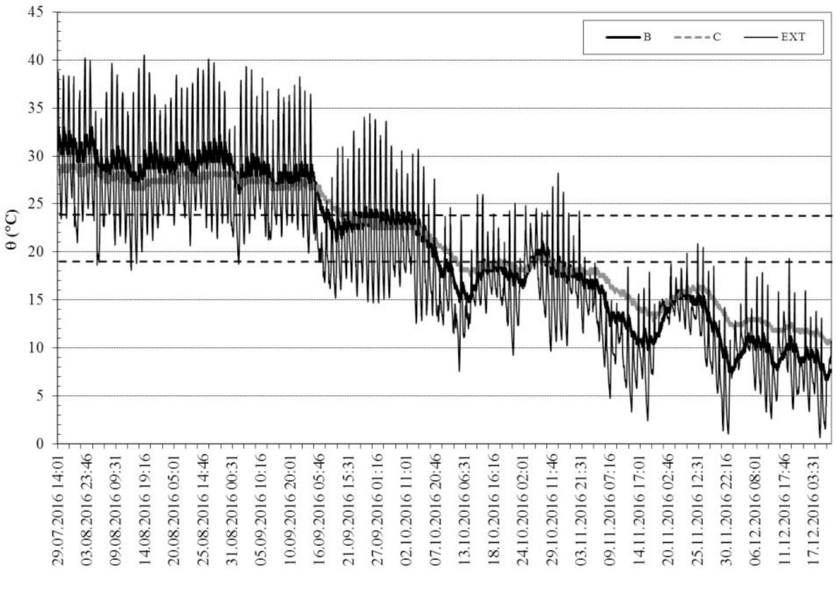

Figure 4. Time profiles of temperature values measured in positions B, C, EXT and the accepted values.

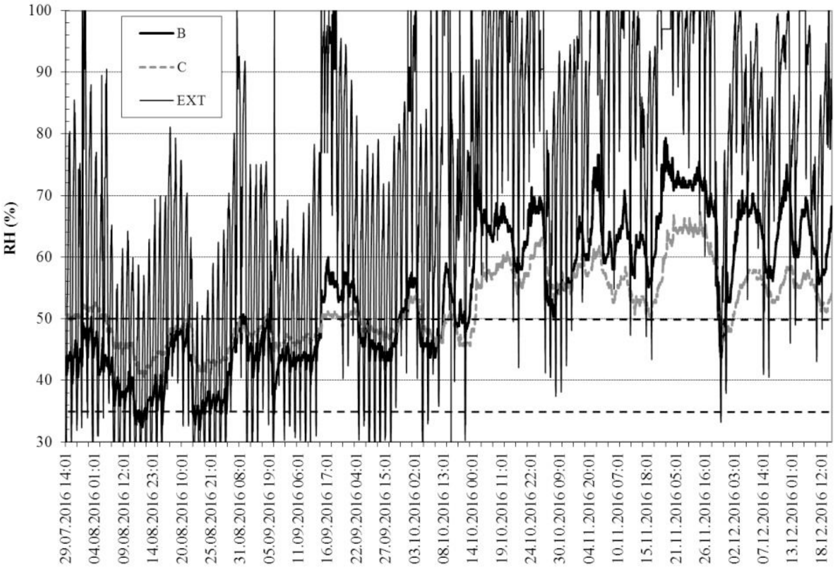

Figure 5. Time profiles of relative humidity values measured in positions B, C, EXT and the accepted values.

Since all the Vasari Corridor is without an HVAC system, data collected point out that the temperature and RH trend inside the uncontrolled environments follows the outdoor climate, although very dampened in sudden hourly and daily changes. The parameters monitored in the first part of the Corridor (positions A, B and D) have a similar trend, which is different from that of the second part (position C). In particular, position B on Ponte Vecchio is characterized by large windows and is much more exposed to atmospheric agents; this results in the highest temperatures (and the lower RH) in summer and in the lower temperatures (and the highest RH) in winter period. The values measured in the position C are instead characterized by a more stable trend with less hourly and daily variations; this is because the second part of the Corridor passes through the Florentine historical buildings with few and small size windows, thus dampening the influence of the outdoor climate.

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. In Table 3 maximum daily gradient of temperature and RH for the analyzed environment are reported, together with the PI of the thermo-hygrometric parameters analyzed for all the monitored period.

Table 3. Maximum daily gradient and PI of thermo-hygrometric parameters.

Position	A	B	C	D	EXT
$\Delta\theta_{24\,max}$	3,1 °C	3,5 °C	1,3 °C	3,4 °C	20,5 °C
$\Delta RH_{24\,max}$	19%	19%	10%	12%	65%
$PI_{\Delta\theta24}$	38%	37%	100%	40%	-
$PI_{\Delta RH24}$	58%	56%	98%	99%	-
PI_{θ}	22%	15%	17%	17%	-
PI_{RH}	35%	41%	42%	37%	-
$PI_{\theta,RH}$	5%	7%	10%	3%	-

In Figure 6, for a typical summer and winter day, the time profiles of temperature and relative humidity measured in positions B and C are compared with the corresponding outdoor values (EXT).

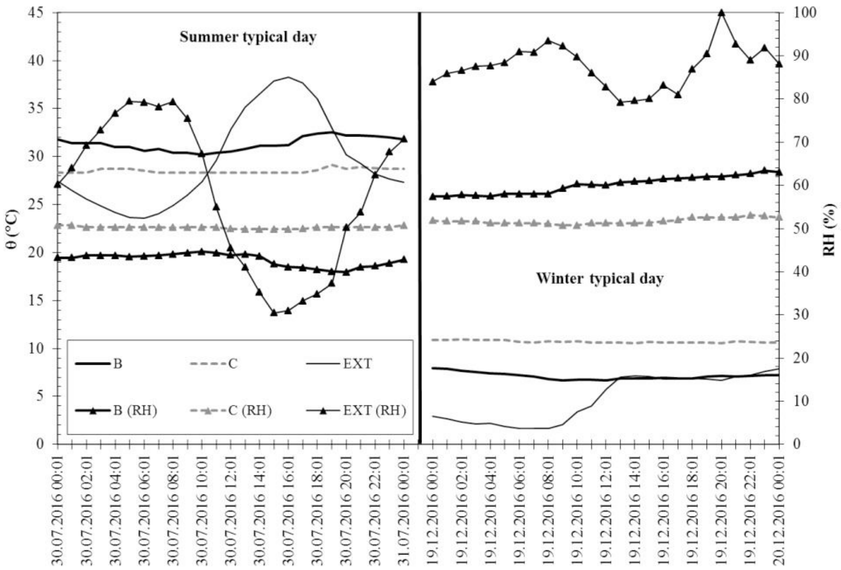

Figure 6. Time profiles of temperature and relative humidity values measured in positions B, C, EXT, for a typical summer and winter day.

From the diagram, it is evident the stabilization of temperature and relative humidity inside the Corridor; faced with an external $\Delta\theta_{24max}$ of 20,5°C and ΔRH_{24max} of 65%, the parameters maximum daily variations occur in position B, which is the most exposed to outside weather conditions having two external walls with large windows and a roof. The $PI_{\Delta\theta 24}$ is low for all the positions monitored, except for the sensor C, thanks to the fact that this part of the Corridor, passing through the Florentine historical palaces, it is more protected from external climatic influences; RH values remain much more constant especially in positions C and D, characterized by a $PI_{\Delta RH24}$ very high (up to 99%). During the monitored period, indoor temperature and RH are not within the recommended range, with a PI_{θ} ranging from 15% (position B) to 22% (position A) and a PI_{RH} ranging from 35% (position A) to 42% (position C).

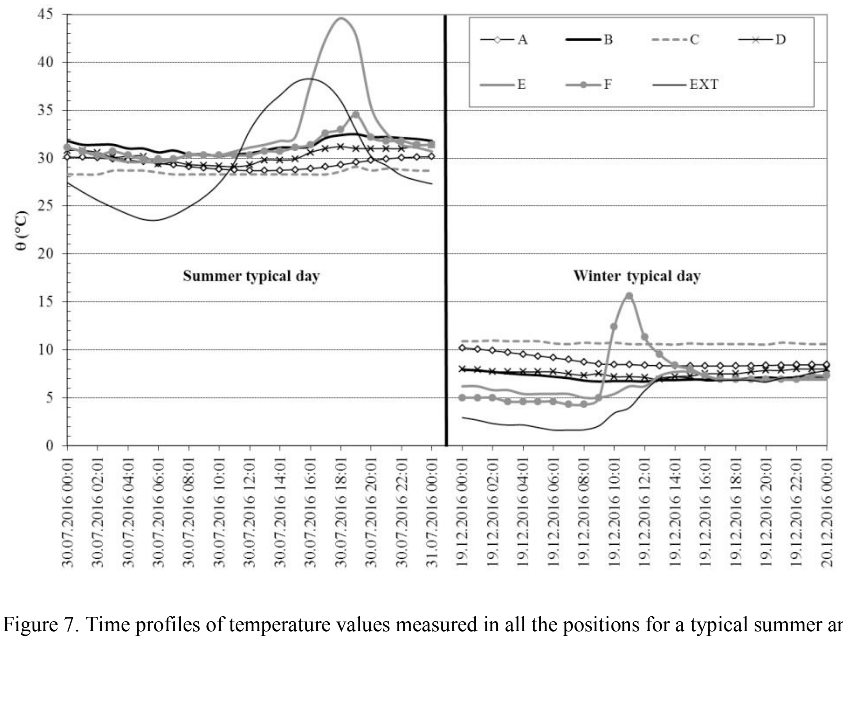

Figure 7. Time profiles of temperature values measured in all the positions for a typical summer and winter day.

In Figure 7, for a typical summer and winter day, the time profiles of temperature measured in positions A, B, C, D and EXT are compared with the surface temperature values measured on the inner surface of the glass windows on Ponte Vecchio, with west (E) and east exposure (F).

From Figure 7 is clearly visible the influence of the solar radiation on the surface temperature of the large glass windows opening onto Ponte Vecchio; in summer, the windows exposed to the west reach the highest temperature in the afternoon (E), while in winter the higher temperature is reached on windows exposed to the east in the morning hours (F).

In Figure 8, regarding the monitored period and the positions B and C, they are reported the values of temperature and RH that simultaneously fall within the accepted values (θ and RH) for the conservation of artefacts. The Figure shows that temperature and RH conditions, during the monitoring period, were not reasonably acceptable for the preservation of the kind of objects exhibited.

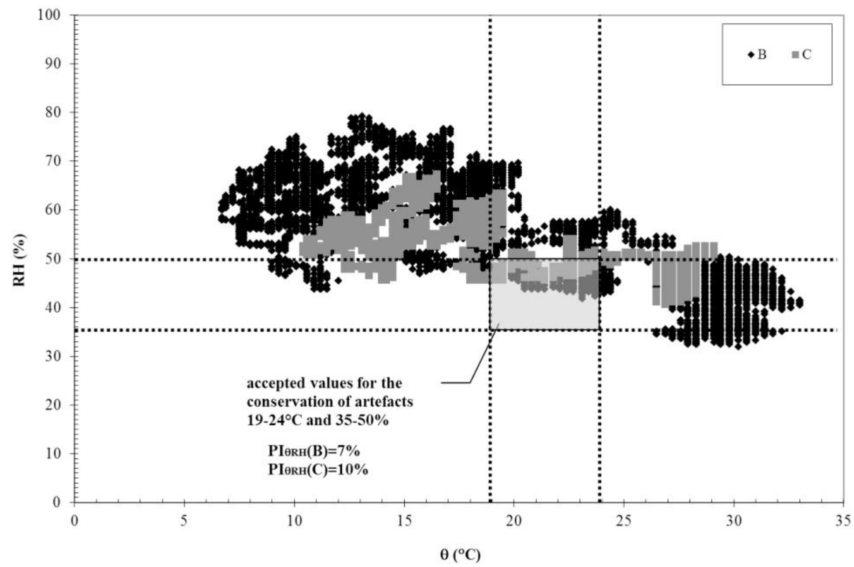

Figure 8. Global PI on temperature and relative humidity matrix, for the positions B and C.

4. Energy modelling of the building

A detailed computer model of Vasari Corridor (Figure 9) has been prepared by means of Design Builder® user interface of Energy Plus v.8.5 dynamic energy simulation software in view of future refurbishment interventions. The surrounding urban geometry has been drawn in detail, to consider any shading or reflection from building or natural elements (e.g. Arno river body of water) that could affect building energy balance. Other aspects of inter-building effect such as heat flow from adjoining buildings, will be considered assigning typical energy attributes to neighboring buildings according with their use, occupancy pattern and location.

The key input elements for a reliable and validated energy modelling are represented by building features (geometry technology and thermophysical properties of materials), HVAC system characteristics, operating conditions and weather data [20]. Building geometry was extensively analyzed by documents provided by Uffizi Gallery staff combined with on-site survey. Thermophysical and optical properties of the building envelope, reported in Table 4, were preliminary defined on the base of visual analysis, made removing internal layer of plaster, combined with documentation on historical construction materials and techniques.

Since dynamic simulation software allows to consider the actual climate of building location, detailed hourly data of weather variables registered at the Uffizi site is necessary to effectively calibrate the energy model. Proper definition of weather data for energy simulation is essential in particularly for historical building with no HVAC system, whose energy balance is mostly influenced by external inputs. An hourly data weather file will be developed by the research team of the University of Florence on the base of dry bulb temperature and relative humidity data collected during the monitoring campaign and solar radiation data collected from Ximeniano Observatory weather station, which is in the city center of Florence 500m far from the Uffizi Gallery.

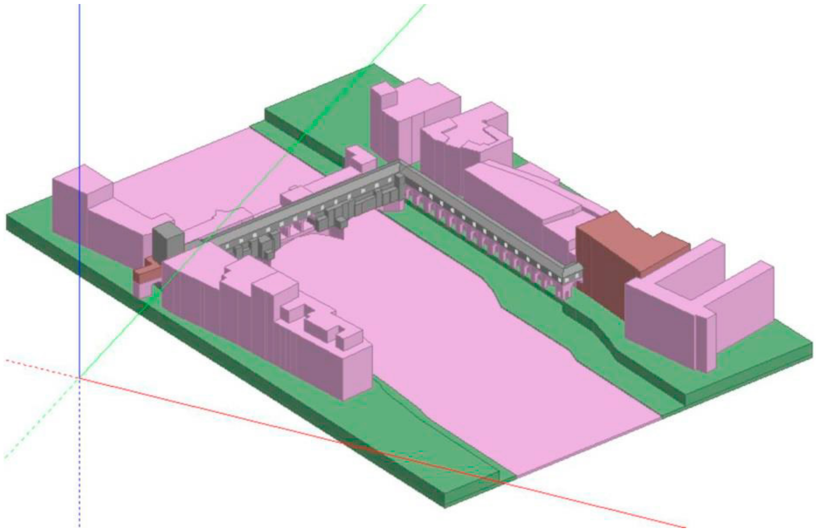

Figure 9. Computer model of the Vasari Corridor and surrounding buildings (software Design Builder).

Once the Vasari Corridor energy model is completed a calibration process will be performed to validate the model itself. Calibration is a refining process oriented to minimize the deviation of simulation results with respect of real measured data, caused by the many sources of uncertainty present in input variables (building /HVAC characteristics, occupants behavior, etc.). Calibration process is an unavoidable step to make reliable simulation model with the purpose of indoor climate analysis to support preventive conservation or to improve occupants comfort [21,22].

Table 4. Thermal and optical properties of the existing building envelope.

Main Building elements	Description	Thermophysical properties		
	Opaque elements	U (W/m2K)		
External wall (section of the corridor running over the river)	Internal plaster, solid brick masonry, external plaster	1,50 ÷ 1,65		
External wall (other sections)	Internal plaster, mixed stone-brick masonry, external plaster	1,90 ÷ 2,30		
Semi external and internal floor	Ceramic tiles, cement and sand screed wood boards	1, 40 ÷ 1,63		
Pitched Wooden Roof	Truss, double layer of joists, flat tile, bitumen sheet, tile covering	1,28 ÷ 1,86		
External floor over vaults brick	Ceramic tiles, cement and sand screed brick slab, external plaster	0,93 ÷1,23		
	Transparent elements	g (-)	τ_v (-)	U_w (W/m^{2}K)
Windows	Wood frame with single and double glass and roller shading (dimensions variable from 0,6 to 4 m^2)	0,87	0,90	3,00
		0,70	0,70	5,00

Since all the Vasari Corridor is without any HVAC system, the calibration will be done comparing indoor temperature and relative humidity by means of appropriate error indices such as MBE (Mean Bias Error), RSME (Root Mean Square Error) and Pearson's index, with the latter accounting for correlations strength between simulated and measured data [20].

At the end of the monitoring campaign, all necessary data for the model calibration will be available and the research will proceed to the construction of the real weather file and to the energy simulation of the Vasari Corridor.

5. Conclusions

Indoor environmental conditions play a fundamental role in the deterioration process of the objects exhibited inside museums, and can be strongly affected by the values of temperature and relative humidity, and their time and space fluctuations.

The environmental monitoring campaign carried out in the Vasari Corridor of Florence pointed out some critical aspects: temperature and relative humidity conditions were not reasonably acceptable for the preservation of the kind of objects exhibited ($PI_{\theta,RH}$ ranging from 3% to 10%). Since all the Vasari Corridor is without any HVAC system, temperature and RH trend inside the uncontrolled environments follows the outdoor climate, although very dampened in sudden hourly and daily changes. The most problematic part of the Corridor is the first stretch from the Uffizi Gallery to Ponte Vecchio, which is the most exposed to outside weather conditions having two external walls with many and often large windows (with single glazing) and a non-insulated floor and roof; this results in the highest temperatures (and the lower RH) in summer and in the lower temperatures (and the highest RH) in winter period, as well as in more hourly variations and low PI ($PI_{\Delta\theta24}$=37%; $PI_{\Delta RH24}$=56%). Furthermore, the direct solar radiation on large glass windows opening onto Ponte Vecchio causes in summer period high surface temperatures on the west and east exposed glazing.

European Standard UNI EN 15757 [18] identifies passive intervention strategies for buildings (such as the improvement of thermal performance of external walls, enhancement of building air tightness, occupant density control, etc.) as a priority to reduce thermal loads of an HVAC system and minimize temperature and relative humidity variations. Moreover, HVAC upgrade in museums located in historical buildings, should grant a proper climate control ensuring the architectural preservation of the structure. That's why the synergy between passive and active climate control strategies can meet better the preservation and performance requirements of these buildings.

To evaluate the effectiveness of passive strategies for the energy refurbishment, such as thermal insulation of the roof, replacing windows and natural ventilation, etc., a three-dimensional model of the building has been created. Moreover, the model, validated by the measured values in the field, will allow to analyze the responses of the building to weather solicitations, the behavior of the building with a possible HVAC system also for reducing management costs. Finally, the results achieved will constitute the essential knowledge to plan the future setting of the Vasari Corridor.

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