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AN EXPERIMENTAL STUDY OF MUSEUM SHOWCASES IN FLORENCE UNDER REAL OPERATING CONDITIONS

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Abstract

The aim of this research was to analyse museum display case performance in three very famous museums of Florence, during their actual operation conditions, by means of experimental monitoring campaign results assessment and comparison. In particular, the boundary conditions (synergic) effects, i.e. thermophysical behaviour of building and exhibition ambient within which the showcase is located, time profiles of space use, high peaks of sensible and latent thermal loads due to visitor influx, on internal microclimate stability and their influence on the showcase efficacy for preventive preservation, were investigated. Findings concerned fundamental indications on how to achieve an optimal control of macro and micro-environment for preservation. Search results highlighted that the efficacy of any kind of display cabinet, to ensure the thermohygrometric conditions at real operative functioning, necessary for Cultural Heritage (CH) protection and preservation, depends on building thermophisycal performance (museum and exhibition room), the presence or absence of a specific type of heating ventilating air conditioning system (HVAC) and its operating and regulation conditions, but, in particular, on the showcase position, use and maintenance.

Keywords: *Showcase, Museum, Experimental measurements, Preventive preservation, Microclimate control*

Introduction

Most of the CH in Italy consists of historical buildings that have changed their original function and use over time. This is particularly frequent for those buildings that have been converted into museums. Recent research has highlighted the importance of the environmental impact on cultural heritage conservation, due to natural and artificial light, temperature, relative humidity, indoor and outdoor microclimate and air pollution, building architectural-structural features and materials, pointing out their correlated and cumulative effects on building heritage preservation [1-12]. Any historical building and plant system refurbishment and retrofitting is a complex task [8-10, 12-18]. Many literature studies have shown that the main risks for user health and comfort and historical building preventive protection are due to indoor environment thermo-hygrometric conditions and air quality [9-13].

The annual variations of indoor and outdoor thermal and hygrometric parameters are characterized either by slow stress cycles spread over time, due to seasonal thermohygrometrical drifts, or by the most rapid impulsive variations of environmental

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conditions, that can occur on a daytime base (e.g. the effects due to strong, uncontrolled artificial lighting, or uncontrolled heating and cooling), where the second effects proved to be the most threatening ones for the CH preservation.

The microclimatic condition stability is the most binding. The reduction of thermo-physical parameter variation is crucial, because an excessive thermohygrometrical condition instability over time, even if the absolute values of environmental parameters are maintained within the target region most suitable for preventive preservation, it is as damaging as inappropriate microclimatic absolute conditions. Furthermore, the macroenvironment thermohygrometrical conditions must also cover the suggested requirements for health, safety, protection, and well-being of works of art and users. Extensive studies and research on the subject, show how degradation processes are due to the most influential environmental parameters such as the air temperature, relative humidity and vapour presence (i.e. absolute air humidity or humidity ratio) [1-4, 6, 12], that can cause cumulative and irreversible effects, especially when material tolerance to ageing factors is reduced. Typicality, variety and complexity of the CH are such that the extensive and in-depth literature on the subject has not led to a univocal and conclusive result [1-3, 10, 19]. On the other hand, the current international and Italian standards concern different materials, and/or objects of historical, cultural, and artistic value, and separately the exhibition/museum environment in which they are contained [17-25].

Although many sustainable solutions, complying with current standards for building envelope and plant systems, can be identified, in practice, i.e. on the operational/implementation side, they cannot be easily realized and generalized, because of their historical value and many different architectural constraints imposed for protection and preventive preservation, whereas the building hosting the museum is listed as part of the CH, as demonstrated by recent studies on this kind of protected/listed building energy efficiency [8, 9, 16]. In many complex situations, the museum showcase solution can be a good compromise to guarantee both, the microclimate suitable for the preventive protection of the exhibition environment and the historic building (museum), and also that micro-environment and microclimate necessary for the preventive preservation of particularly sensitive artworks and materials [24-36].

Most of the recent literature on this subject concerns: experimental monitoring campaigns with transient simulations on the performance and efficacy of existing museum showcases, generally passive and active systems, for preservation and microclimate stabilization [27-31] and, in particular, simulation “lamped” parameter that has been suggested as a useful tool for new showcase design (i.e. for its form, construction materials, glass and extruded aluminium profiles, considering the oxygen partial pressure variations [32]), development of solutions for control and regulation optimization and maintenance, but also for the existing showcase assessment [32, 33]; analysis and comparison on the air and gas tightness influence on the relative humidity variations of a museum cabinet, through testing procedures (e.g. pressurization tests and tracer gas measurements) in order to deduce general recommendations for air tightness testing and choosing the most suitable air tightness value connected to the RH desired control level [29, 33-35]; development and improvement of design, realization and installation of passive controlled atmosphere cabinets and advantage and benefit effects, due to energy saving and optimal microclimatic control [36]; in depth studies on water vapour exchange of museum display cases for minimizing case leakage and on increasing the mass of sorbent to extend hygrometric half-time [30]; experimental results carried out in flow chambers with test apparatus, combined with numerical studies and simulation aimed at assessing the hygroscopic finishing materials potential in stabilizing relative humidity in display cases, that are characterised by different ventilation conditions [31]; experimental investigations on the indoor air quality (using active and passive sampling with chemical analysis techniques) inside passive museum cabinets of different construction materials and age, that have shown that the air pollution levels of new type showcases are higher than those of traditional-old ones [37]; the development and application of an integrated modelling approach to measure and simulate at transient conditions the internal microclimate of the exhibition room and passive showcase; the HVAC system operating conditions, that has demonstrated how important it is to consider the connections between the variability of the indoor climate of the museum cabinet, and those of the internal exhibition environment determined by the existing HVAC plant [15].

In particular, the authors have suggested a new regulation controller system for the HVAC to obtain an optimal damping effect with temperature value stability and, as a consequence, stable specific humidity and temperature inside the showcase [15]. A fundamental crucial research [26] has shown that the choice for any type of showcase is really correct only in ideal conditions, i.e. when an HVAC plant system has been designed on the basis of the adaptive and acclimatization concepts, radiative and greenhouse effects due to lighting systems, latent and sensible heat due to visitors, organic gases and airborne particles are totally absent.

The authors carried out many in situ and laboratory experimental measurements for the assessment of the response of the showcases studied to climatic and biological environmental factors [26]. They have also provided a useful approach for the quantification of the index quality levels, each corresponding to thermal, hygrometric, biochemical, biological and luminous (visible and infrared effects) parameters [26].

Our present research provides the results of critical analysis and comparison of the experimental monitoring campaign carried out in three showcases under their actual operating conditions. In particular, the effects of thermophysical building behaviour and its exhibition ambient, within which the showcase is located, time profiles of space use, high peaks of sensible and latent thermal loads, due to visitor influx, on internal microclimate stability and their influence on showcase efficacy, for a preventive preservation guarantee, were investigated. The incidence of climatic stresses and thermohygrometric variations of macro environment (museum, exhibition) on the microenvironment (showcase), for assuring preventive preservation of the CH, were investigated, paying attention to the effects produced in terms of physical, chemical and biological deterioration, and taking into account the main factors due to the presence or not of the HVAC plant system. Obtained results, that are in accordance with the major studies on this subject, allowed the identification of some reversible, easily modifiable and adaptable, non-invasive and low-impact, fundamental indications on the investigated showcases under their real operating conditions for making the best use, with a view to preventive preservation and the protection of the CH, but also a better use and vision in the exhibition environment.

Experimental part

Materials and Methods

Setting

Three different free-standing showcases, each one located in a different museum environment, were the object of study. They are housed in three very important museums of Florence and differ in terms of specific building, microclimatic control system, exhibition room context, but are very similar regarding construction materials (e.g. four sides glazed envelope, bottomed with a metallic thermal insulated panel that separates the internal microenvironment from the technical compartment), airtightness, work of art housed (all organic and in particular wooden artifacts), indoor microclimatic condition threshold values.

Referring to the current standards [16, 18-24, 37, 38] the works of art contained in the showcases were identified and classified as follows: “paintings on wood” for “Virgin Mary with Child” by Filippo Lippi-Medici Riccardi Palace Museum, and Wooden Crucifix-Bargello Museum; “lacquer, inlaid, decorated or lacquer furniture” class for the wooden inlaid casket in the “Opificio delle Pietre Dure” Museum. The internal lighting systems of all three showcases have no infrared emission, therefore, the inside released heat is negligible. The main features of each case study are as follows:

The Lippi painting showcase-Medici Riccardi Palace Museum

The first showcase was made for the “Virgin Mary with Child” by Filippo Lippi, a 15th-century wooden panel painting. This artwork is located in the Medici-Riccardi Palace, a stately mansion also dating back to the 15th century (1444 – 1459), built according to the severe style of the fortress-mansion in rusticated blocks.

The exhibition room context (macro-environment): The Fireplace room, where the display case stands, does not belong to the original building, but to the architectural addition required by the Riccardi family (around 1700). This important room has four doorways constantly open and one glazed door leading to an internal courtyard. There is a single large window South-West oriented, shaded by a white curtain, in front of which the studied showcase is placed. No HVAC system is present, but only a radiator system for winter heating (Fig. 1).

Fig. 1. Medici Riccardi Museum: the macro-environment (Fireplace room; left); the microenvironment, front view of the showcase with “Virgin Mary with Child” by Filippo Lippi (centre) and the back view of the showcase (right)

The showcase microclimatic control system (micro-environment): This is a typical active system showcase, whose external size is about 2,3m^3, of which 0,77m^3 used for a technical compartment. The manual opening system consists of a sliding glass rear side on a horizontal track, the so called "monorail" system. The four sides of the display cabinet are made of clear glass with an 8 mm thickness and an anti-reflective coating. The showcase is equipped with the HAHN RK-2 clean air and relative humidity control unit that assures filtered air and the chosen humidity for the cabinet, with respect to the indoor environment. The resulting air over pressure in the cabinet prevents risks from dust and contaminant leakage. RK-2 units are typical active systems equipped with a catalyst inside the water tank for relative air humidity control and air purification. The internal atmosphere is controlled by recirculating air through a filter with a high particulate removal degree, and a Peltier-cell cooling system for air-moisture control: the relative humidity (RH) set-point is assessed to 55%. The display lighting system is the SWARO® Lite system: i.e. technology specifically designed for museum applications, where the source is an HQI-T 70W/4000 K metal halide discharge lamp; the light is transported inside the showcase by a glass optical fiber, which ends inside, with adjustable spotlights, carrying UV and IR deprived light into the micro-environment (Fig. 1).

The wooden inlaid casket - “Opificio delle Pietre Dure” Museum

The second showcase studied belongs to the passive showcase typology, has an appreciable capacity (one cubic meter air volume), and is equipped with its own LED lighting system (Fig. 2); the technical compartment below the internal display floor is occupied by a silica gel brick system in the dedicated drawers, but it can also be easily set up for active air conditioning systems. It houses an inlaid wooden casket, in traditional “commesso fiorentino”, i.e. the particular technique of semi-precious stone inlay and mosaic typical of Florence, existing long before 1588 when Grand Duke Ferdinand I de' Medici established a specialized court-funded semi-precious stones laboratory, precisely the "Opificio delle Pietre Dure" institution.

The exhibition room context (macro-environment): the showcase is located on the ground floor of the "Opificio delle Pietre Dure" museum, in the historical site of the institution, the former "San Niccolò di Cafaggio" monastery. The room consists of a long, narrow open space portion of the South-West wing of the building; it is sectioned by a wooden mezzanine, underneath which the space is subdivided into several rooms communicating by one open side with the common exhibition environment. The monitored showcase stands in one of these space-partitioning rooms, opening onto the South-West windowed side looking onto the internal courtyard, and strongly illuminated by natural light (Fig. 2). There are four-pipe fan coil units connected to the heating/cooling plant system in the exhibition room.

The showcase microclimatic control system (micro-environment): the display case is set up only for air moisture control, through a 970 g brick of self-buffering ProSORB silica gel, conditioned to 55% relative humidity. In particular, the specific characteristic of the ProSORB silica gel are as follows: composition 97% SiO_2 and 3% Al_2O_3, density 0,75kg/l, porosity volume 0,5 ml/g, internal surface 750 m^2/g, no chloride content. It is equipped with a LED lighting system on the ceiling of the showcase.

Fig. 2. "Opificio delle Pietre Dure" Museum: the macro-environment (exhibition rooms and main corridor; left), the micro-environment, front view of the showcase with "The wooden inlaid casket" (centre) and the back view of the showcase illuminated by natural light (right)

The Wooden Crucifix- Bargello Museum

The third study case consists of a free-standing glazed showcase, with a polychrome wooden sculpture of "Christ crucified", by an anonymous 16th century Florentine artist. The hosting building is the Bargello Museum, whose original nucleus dates back to the second half of the 13^{th} century. Initially conceived as a governamental building, during the Medicean period this stone/brick square building has been used as a prison and hosted the "Bargello", i.e. the commander of the ancient city "police force".

The exhibition room context (macro-environment): the exhibition room is the Podestà or Maddalena Chapel with frescoes by Giotto's workshop, 1330-1337. This is a typical example of conversion/transformation of the original intended use of the building into a museum (Fig 3). It is well known that in an environment intended for a church, natural light is designed for liturgical purposes: therefore, also considering the dimensions of the chapel and the considerable height of its exterior walls, on which there are narrow single-arched windows, the exhibition rooms luminous environment turns out to be quite dark; this can only be an advantage for the current exhibition-museum use, either from the preventive preservation point of view, since the daylight impact over artifacts can be considered totally absent. Moreover, this assumption is supported by the fact that the large white glass windows are almost opaque to sunlight, being made according to the antique technique of glass craftmanship, where windows were glazed using thick glass pebbles lined with lead.

The showcase microclimatic control system (micro-environment): this is a display case without an active or passive microclimatic control system and it is equipped with a LED lighting system installed on the enclosed space floor (Fig. 3); therefore, its position, form and dimension, thermophysical characteristics of the glass and airtightness can contribute to mitigating the climatic environmental factors.

Fig. 3. Bargello Museum: the macro-environment (Podestà or Maddalena Chapel with frescoes by Giotto's workshop, 1330-1337; left), the two single-arched windows and showcase (centre); the micro-environment, front view of the showcase (right)

Monitoring

Microclimatic measurement - Timing

Microclimate data, air temperature and relative humidity, both for the internal environment of the studied showcases and all the surrounding external exhibition environments, were recorded in continuum during 2019, from April 8 to July 31. These data were analysed, and post processed on an hourly basis [38-40]. The Marconi Spy data loggers, with a radio data transmission, were the instruments used, located both in the micro-environment (showcase) and the macro-environment (exhibition room). The sensors were installed minimizing their impact on the ambient fruition and exhibition vision of the visitors. Their technical characteristics are given in Table 1.

Table 1. Technical characteristics of the instruments

	SPY RF TH				
	Temperature		Relative Humidity		
Range	- 30°C / + 70°C ± 0,4°C	-20°C≤T≤30°C ± 0,5°C	10%≤UR<20% ± 3,5%	20%≤UR≤80% ± 2%	80%<UR≤90% ± 3,5%
recorder interval	from 1 s to 90 min				
memory capacity	20000 measurements				

Meteorological data

Concurrently with microclimatic monitoring, outdoor temperatures and relative humidity data, provided by the Centre LAMMA CNR IBIMET of Florence, were assessed for the identification of the representative days of the worst weather conditions (i.e. standard days in precautionary conditions). Referring to the modelling method suggested in [41], hourly values of the direct, diffused and reflected solar radiation were calculated taking into account the specific latitude (i.e. for Florence 43°47′14″64 N Latitude) by the hourly Sun position evaluation (hourly values of the Sun height and azimuth from sun-rise to sun-set).

Correspondingly, the hourly variation both incidence angle, on the splayed arched windows of each case study, and its corresponding transparency coefficient were calculated.

Statistical analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences Version 20.0 (SPSS Inc. Chicago, IL, USA). All the recorded parameters were described as mean, maximum, minimum, median and standard deviation. Data error analysis on microclimatic experimental measurements was carried out by standard deviation (absolute and percentage error values) [42].

Results and discussion

The experimental data were analysed and post-processed for the following fundamental research objectives:

- the assessment of the showcase system efficacy for internal (micro-environment) microclimatic parameters stabilization and damping effect on the high variability of thermohygrometric parameters of the exhibition room (macro-environment);
- the evaluation of the effects on microclimatic stability inside the showcase, caused by the presence of a heating/cooling plant with or without a regulation system;
- the identification of the fundamental parameters that allow the optimal choice for a passive and/or active display case to ensure the preventive protection and preservation of both the historic building and the exhibition environment in which it is located, and the works of art contained therein.

The exhibition rooms that make up the macro-environments for the three types of showcases studied, which in turn are the micro-environments (i.e., respectively, the active showcase of the Medici Riccardi Museum, the passive showcase of the OPD Museum and the display case with no air conditioning or control system of the Bargello Museum) are housed in CH buildings with a very high historical-architectural value. However, they all consist of buildings that did not start life as museums, but were converted into this use: the Medici Riccardi Palace is what is called a " house/museum ", the OPD museum dates back directly to one of the ancient artisan and artistic manufactures, established in 1588 in the former monastery of San Niccolò by the First Grand Duke Ferdinand Medici as a manufacture of semi-precious stone works (the so-called art of the "commesso fiorentino") while the Bargello Museum environment belongs to a historical church, then converted into the Podestà or Maddalena Chapel. Therefore, the assessment of the existing state of three macro-environments (i.e. hygrothermal conditions and the amount of internal gains due to lighting, heat and humidity from people) was necessary to determine both, the optimum microclimatic conditions in the exhibition rooms for preventive preservation, material/object degradation prevention and the identification of well-being conditions for visitors, and the variable and different boundary conditions of the three studied showcases. Table 2 provides, for each hygrothermal parameter, the assessment method used for the experimental measurements post-processing.

Table 2. The method used for parameter evaluation

Parameter	Symbol	Assessment method
Temperature (°C)	T_0	on an hourly bases
	ΔT_2	excursion between two following hours
	ΔT_{24}	daily temperature excursion (in 24 hours)
	T	mean monthly value of air temperature
Relative Humidity (%)	RH_0	on an hourly bases
	ΔRH_2	excursion between two sfollowing hours
	ΔRH_{24}	excursion in 24 hours
	RH	mean monthly value

Referring to the current standards [20-25, 37, 38, 43] the parameter range of values describing the optimal microclimatic condition for preventive prerservation was identified (Table 3).

Table 3. The air temperature and RH limit values for preventive preservation

Organic materials/objects	T_0 (°C)	T_{24} (°C)	RH_0 (%)	ΔRH_{24} (%)
Lacquer, inlaid, decorated or lacquer furniture	19 – 24	±1,5	50 - 60	±4
Polychromatic wood carvings, painted wood, paintings on wood, icons, wood pendulum-clocks, wood musical instruments	19 – 24	±1,5	50 - 60	±4
Unpainted wood carvings, wickerwork, wood or bark panels	19 – 24	±1,5	45 - 60	±4

Using the data set from the entire monitoring period for each exhibition room and showcase (i.e. macro and micro-environment), the statistical analysis of all the parameters, i.e. the average value, median, maximum value, minimum value, standard deviation and percentage standard deviation as:

$$\sigma_{\%} = \frac{100 \cdot \sigma}{\bar{x}} \quad (1)$$

Table 4 and Table 5, respectively, show these results obtained by the experimental data post-processing. From results analysis, the assessment of the microclimatic protection system performances, due to the display case typology, (active and passive microclimatic control system, and no-microclimatic control) was carried out. In particular, the analysis of temperature data monitored shows the acquisition period related seasonality: although the thermal variability range covers typical summer values, the median value always sets below mean value one and therefore, the region of greatest data thickening falls between the first and second quartiles.

Table 4. Statistical analysis of the air temperature in the showcase and exhibition room

Temperature (°C)	Medici Riccardi Palace		OPD Museum		Bargello Museum	
	Showcase	Exhibition room	Showcase	Exhibition room	Showcase	Exhibition room
$\bar{x}$	24,6	24,0	24,2	24,0	23,9	24,7
$x_{0.5}$	23,2	22,6	23,7	23,3	22,0	22,8
σ	4,522	4,546	3,031	3,030	4,879	4,876
$\sigma_{\%}$	18,4%	19%	12,5%	12,6%	20,4%	19,8%
T_{max}	33,0	32,5	30,1	29,3	31,5	32,6
T_{min}	17,9	18,2	19,3	19,2	17,1	17,1

Table 5. Statistical analysis of the relative air humidity in the showcase and exhibition room

RH (%)	Medici Riccardi Palace		OPD Museum		Bargello Museum	
	Showcase	Exhibition room	Showcase	Exhibition room	Showcase	Exhibition room
$\bar{x}$	58,1	50,9	47,1	48,3	50,7	49,2
$x_{0.5}$	58,8	50,3	47,9	49,2	50,1	49,1
σ	2,583	6,835	2,568	4,218	5,720	3,983
$\sigma_{\%}$	4,4%	13,4%	5,4%	8,7%	11,3%	8,1%
$UR\%_{max}$	62	70,5	51,2	64,6	64,9	57,8
$UR\%_{min}$	47,7	28,9	41,4	38,0	37,4	40,2

This shift extent can be related, not so much to the climatic nature of the months, during which the measurements were conducted, as to the climatic anomalies of the year 2019, characterized by particularly cold conditions in May and air temperature values still below the seasonal average values for June.

Comparing the results obtained for the environments of the OPD museum, with those of the other two museums, it is possible to note that, in the first case the measuring points thicken more around the central value, and air temperatures of 30°C are reached only in the marginal area of the distributions. This fact is the experimental evidence of the plant working for the summer conditioning of the OPD Museum exhibition rooms, not provided within the other two museums. As for the relative humidity results, it is possible to note that, in any environment where there is a humidity control system, the median value of parameters are comparable with the mean ones: this is due to the humidification/dehumidification process provided by the microclimatic control systems, providing a buffering effect over the seasonal RH fluctuations. The RH control effectiveness, i.e. RH stabilization, can be deduced from the amplitude of the interval in which the central two quarters of the experimental data are included: the more it is restricted, the lower the parameter variability (RH%) around the mean value. Comparing all the microclimatic experimental data with the corresponding limit values, suggested by the current standard, and in particular by [43], for the preventive preservation and protection, it can be pointed out that the overall microclimatic conditions of the two showcases, respectively located in the Medici Riccardi Palace and Bargello museum, do for a certain period fall within the ranges of allowed microclimatic variability, while this never occurs for the OPD case, at least during the monitoring period (Figs. 4-6).

Referring to [43], the showcase effectiveness for ensuring over time optimal environmental conditions for preventive preservation, was also investigated by means of the deviation index calculation (DI). The DI index, which represents the percentage of time in which the considered parameter remains outside the chosen values range deemed acceptable, was calculated for all the three studied showcases. The aforementioned percentage of time was obtained directly from the monthly cumulative frequency diagram for the data from the whole monitoring campaign [43]. In Table 6 the DI results obtained for temperature and relative humidity, with the assessment method for the outlier values given in Table 2, are provided for the three micro-environments.

From results comparison (Table 6), the seasonal drift in air temperature, which leads to a progressive increase of the DI index values, when the summer season takes over, can be clearly deduced. This is a common feature for each showcase since none of them is provided with an effective air temperature control system. As a matter of fact, the effectiveness of the Peltier system (active showcase of Medici Riccardi Palace) was compromised, because the periodic recalibration of the hygrometric sensor, with which the system communicates with the internal environment of the display case, was not carried out: therefore, the actual RH set point value for the plant to maintain did not match the selected one of 55%, since the internal sensor was underestimating the real parameter value.

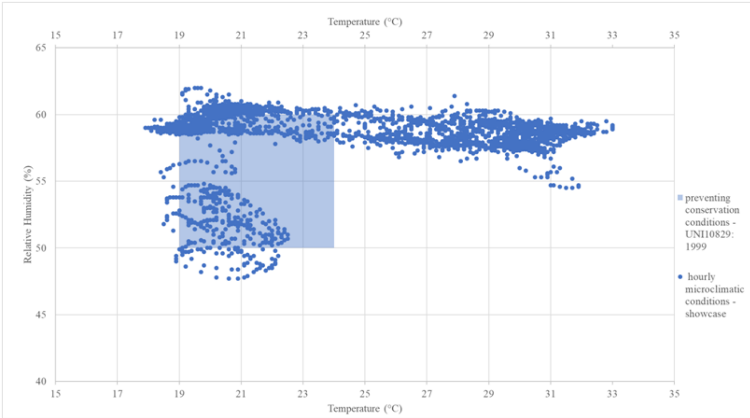

Fig. 4. Comparison between the microclimatic conditions suggested by the standard UNI 10829:1999 and the measured microclimatic conditions in the showcase – Medici Riccardi Museum

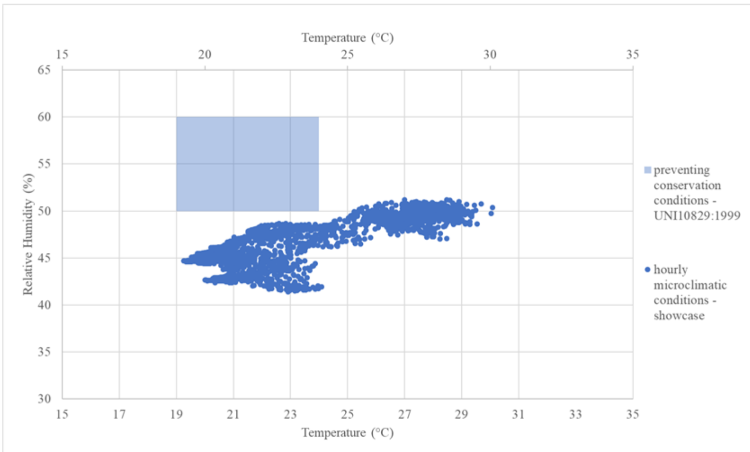

Fig. 5. Comparison between the microclimatic conditions suggested by the standard UNI 10829:1999 and the measured microclimatic conditions in the showcase – OPD Museum

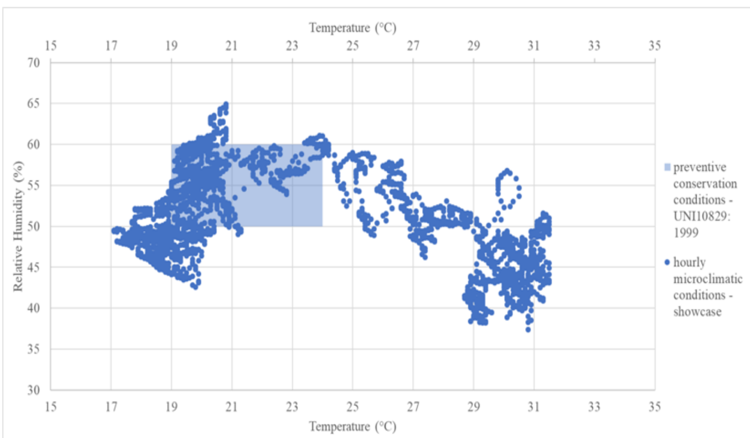

Fig. 6. Comparison between the microclimatic conditions suggested by the standard UNI 10829:1999 and the measured microclimatic conditions in the showcase – Bargello Museum

Table 6. The DI results of the studied parameters for the three micro-environments

Deviation Index (%)	T_0	RH_0	ΔT_{24}	ΔRH_{24}
Medici-Riccardi Palace showcase				
April	6,99%	25,74%	100%	21,74%
May	11,04%	46,3%	100%	0%
June	82,36%	6,81%	100%	0%
July	100%	2,05%	96,77%	4%
OPD museum showcase				
April	0,19%	100%	77,27%	0%
May	2,28%	100%	83,87%	0%
June	81,53%	87,5%	63,33%	0%
July	100%	82,44%	70,97%	0%
Bargello museum showcase				
April	55,15%	62,68%	0%	13,64%
May	14,78%	37,23%	3,23%	16,13%
June	70%	20,56%	0%	36,67%
July	100%	96,57%	0%	29,03%

Figures 7-9 show the temperature and RH trend inside (micro-environment, showcase) and outside (macro-environment, exhibition room) the investigated showcases: the solar radiation effect on the air temperature daily excursion is evident and consequently, the highest DI values for the parameter ΔT_{24} throughout the monitoring period belong to those showcases exposed to natural light.

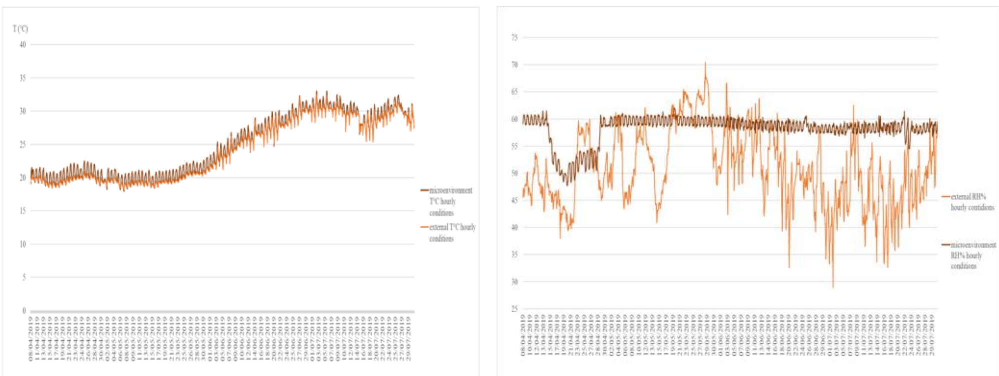

Fig. 7. Air temperature and RH trend in the showcase and exhibition room – Medici Riccardi Museum

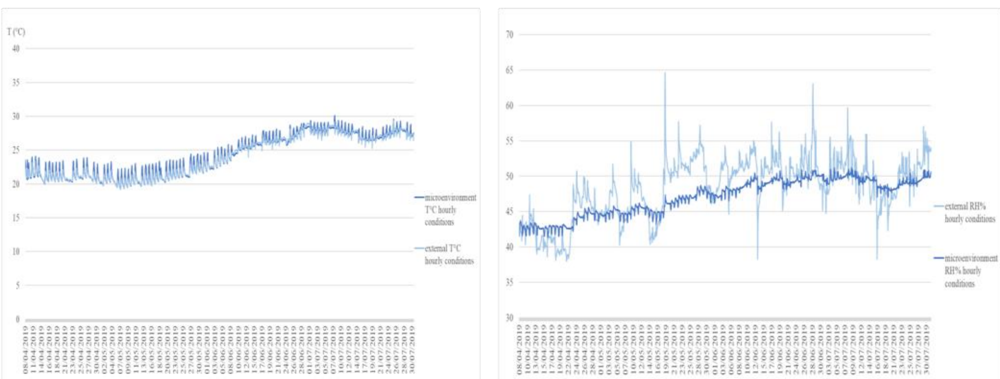

Fig. 8. Air temperature and RH trend in the showcase and exhibition room – OPD Museum

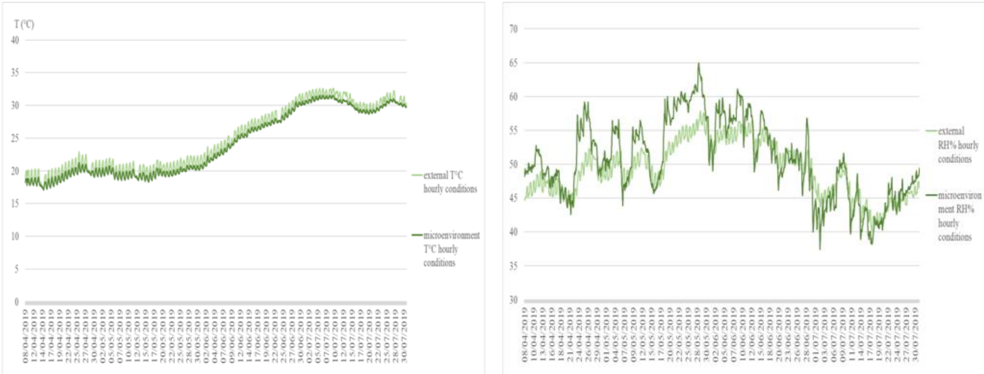

Fig. 9. Air temperature and RH trend in the showcase and exhibition room – Bargello Museum

The showcases exposed to solar radiation are those of the OPD museum and Medici Riccardi Palace museum: despite the first being located at an appreciable distance from the large window, is still exposed to daylight for a long time, while the second is located very close to the glazed surface. Medici Riccardi exhibition glazed openings face South-West and OPD museum faced North-East. Solar radiation impact can be found the internal air temperature value trends of the cabinets, showing evidence of green house effect since their absolute values are always higher than those of the exhibition room. This does not happen for the Bargello museum showcase, because it is located in a dark environment resulting from the building's architectural features (in particular from its historical glass windows, some of which are coloured), that prevent a remarkable amount of solar radiation to enter the room: the air temperature values in the showcase are always lower than those of the exhibition room.

As an example, the results of the calculation of the total solar radiation entering through the large windows of the two museums (Medici Riccardi Palace and OPD museum) for 21st June are shown in figure 10, together with the comparison between the trend of the air temperature inside the showcase and the corresponding one in the display environment.

Looking at the RH results, temperature changes in the showcase can be read in RH fluctuations. Usually, to moderate these rapid fluctuations and ensure the long-term maintenance of proper RH value, an appropriate amount of humidity buffer (e.g. as silica gel, Artsorb, or molecular sieves) is inserted just before the case is sealed.

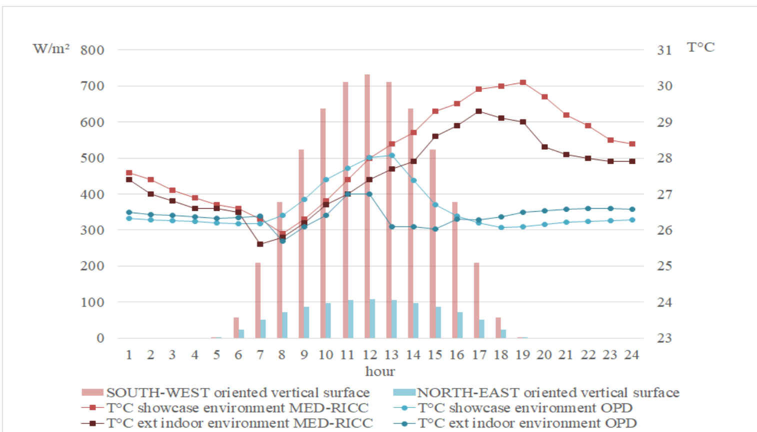

Fig. 10. Solar radiation incoming the exhibition room W/m^2 - 21st June compared with the resulting indoor environment's and showcase microenvironment's air temperature trend

The dew point temperature of the micro-environment of all the cases was evaluated as suggested in [44, 45] and compared with the corresponding dry bulb air temperature: inside all the cases, the dew point values are lower than the dry bulb ones (Fig. 11) and the internal air never reaches the saturated vapour condition. As expected, the internal RH conditions of the Bargello showcase, which is not equipped with any microclimate control system, are completely dependant on the external ones, at least for daily mean values. The case envelope airtightness seems to guarantee an appreciable damping effect on the external thermal loads, as shown by the corresponding DI index values (Table 6).

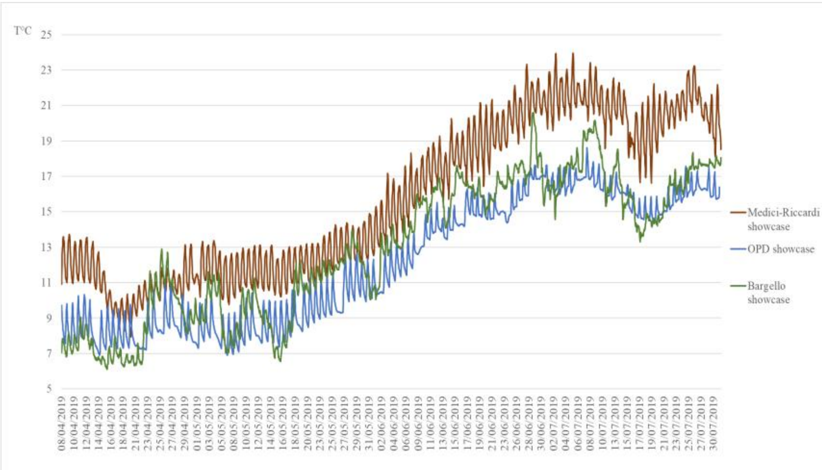

Fig. 11. Dew point temperature values inside the three showcases studied during the whole experimental measurements campaign

The efficacy of active and passive cases for guaranteeing RH stabilization is comparable and equivalent. Moreover, a buffering system employing silica gel is much more reliable and undergoes almost no maintenance if compared to an active system.

During the experimental measurements campaign, the RK2 air moisture conditioning system of the Medici-Riccardi case experienced failure, due to water runoff in the moisturizing tank, that caused RH levels to drop consistently. This hygrometric control system breakdown resulted in an abrupt variation of internal microclimatic conditions up to ΔRH_2 values of –0.9%, and 4.3% in ΔRH_{24}. Furthermore, RH daily variation reached 6.4% at the restoring of the plant functionality. This was a very challenging situation to deal with for a painting that already experienced colour drops over time. On the other hand, the solution obtained by using a passive silica gel buffer, can not always contrast the RH shifts, especially if these are due to long term trends in external load values, to which the progressive degradation process of the material buffering capacity must be added.

Referring to a crucial piece of research [26] the internal temperature normalized change (NC) and the thermal damping (TD) i.e. the index that provides the temperature variation inside the case in response to an external variation (exhibition ambient), were calculated. Since all the exhibition rooms have no HVAC system, the thermal stress does not show a square wave pattern and has strong daily and seasonal fluctuations. The TD index was calculated, over time of 1h, by means of the ratio between the mean hourly variation of internal temperature of the showcase (i.e. the average daily value) and the corresponding mean temperature hourly variation of the external ambient (exhibition room; Table 7).

Table 7. Thermal Damping of the studied showcases

TD Thermal Damping [1/h]	Medici-Riccardi showcase	OPD showcase	Bargello showcase
$\overline{TD}$	1,946	1,509	0,481
$TD_{0,5}$	1,860	1,574	0,487
TD_{MAX}	4,111	3,500	0,895
TD_{MIN}	0,796	0,380	0,227

It is interesting to note that for the two showcases directly exposed to solar radiation, the TD assessment is not properly relevant, because the temperature variation in the showcase is much more sudden and stronger than the external one: the values of the TD index are significantly greater than the unit. In this situation, the air-tightness properties of the display case are no longer appreciable and seem to be counterproductive to the thermal stability of the internal environment. The Bargello showcase is housed in an environment characterized by microclimatic conditions suitable for CH preservation and protection, so much so that the air-tightness properties of the showcase are effective for damping the external thermal stress: this entails translating an hourly variation of the internal temperature almost halved compared to the average entity of the external stimulus.

The calculation of the TD index on a daily basis was not carried out, because it was not significant, due to the variability as a sign of the $\Delta T_{out-(h)}$, which has a daily cyclical aspect, so that its net variation at the end of the day is rather underestimated, compared to the extent of the actual stresses that make it up.

Conclusions

This research was performed on real operating conditions of three showcases housed in three important museums in Florence. The experimental results pointed out that, only if properly designed, built, but above all correctly positioned in the museum exhibition space, any type of showcase can be an effective solution to improve preservation conditions. According to what is to be found in most of the literature [26-36], our findings highlighted that the knowledge of boundary conditions (thermohygrometric and thermophysical settings of the macro-environment/exhibition room combined with its use and visitor influx and heating/cooling plant presence) is a mandatory requirement, so that the best conditions for the museum showcase to be effective in minimizing deterioration, physical, chemical and biological risk, due to time and space microclimate variations, diurnal cycles, fluctuations, rapid and strong air temperature and relative humidity gradients, combined with heat and mass exchange, could be set up. Showcase utilization allows appreciable energy saving connected to the air conditioning of the museum or exhibition space, providing an optimal compromise solution between the needs of safeguarding, preserving and protecting the CH, and the needs for quality of vision/perception, fruition and thermal comfort of visitors.

Furthermore, the use of museum display cases is highly recommended when mixed collections are in the same room and the thermohygrometric requirements of room and works of art are very different. Nevertheless, results analysis showed the need for a consistent improvement of display case management: under real operating conditions of the cabinet, greater attention must be paid to design and setting up phases and appropriate maintenance, whereas the installed control system requires it. The environmental stresses, consequent to the system failure of an active cabinet system, in many situations could be avoided, simply by scheduling maintenance, or at least including inspections in calendar, whenever a moisturizing water runoff is expected. Furthermore, the performances and efficiency of an active air humidity control system in maintaining stable conditions can be undermined by the non-compliance in the periodical calibration of the internal hygrometer system. This results in a permanent gap between the nominal set-up value of 55% and the mean RH value actually detected in the display case. As a matter of fact, in the Medici-Riccardi Palace showcase, an actual mean value over the monitoring period of 58.1% RH, that is to say the effective set-up value for the conditioning system to maintain, was recorded and, consequently, the microclimatic safety zone was overstepped, despite the important RK2 system buffering capacity. A correct procedure for introducing a self-buffering salts brick in the case environment should be followed: a passive buffering system is effective in maintaining the balance conditions at its introduction within the showcase environment, only if the internal microenvironment has been conditioned to set its RH value, up to the same target value of silica gel pre-conditioning. Inside the OPD showcase the air relative humidity, never reached the 55% value to which the silica gel brick was pre-conditioned, thus resulting most of the time lowered in comparison with the RH values of the safety region (i.e. standard limits for preservation). The assessment and control of the luminous climate of the museum environment, within which the display case is located, can be an economical, easy and reversible solution in controlling the internal air temperature daily excursions. In preparing an exhibition, the control of visible and thermal effects due to solar radiation and artificial lighting, to make the showcase an optimal, efficient and effective solution, should be the basic criteria always met. Our study shows that any typology of showcase is strongly affected by the luminous conditions of the surrounding ambient. Results obtained show the negative influence on microclimatic parameter stability inside museum showcases, and then, on their efficacy for assuring preventive preservation requirements, of the uncontrolled boundary conditions of the macro-environment (exhibition room) and incorrect exhibition design, lack of maintenance and control interventions. This highlights the need for a different approach that takes into account the synergic combination and effects due to the thermophysical and thermohygrometric internal and external transient conditions, the building/museum and exhibition features and the aims of the curator/conservator.

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