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Procedia Structural Integrity 29 (2020) 25–33

Structural Integrity Procedia

www.elsevier.com/locate/procedia

Art Collections 2020, Safety Issue (ARCO 2020, SAFETY)

An experimental methodological approach aimed to preventive conservation and sustainable adaptive use of the cultural heritage

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Abstract

Microclimatic conditions play a key role in the conservation of art collections and architecture, results obtained by monitoring campaign are essential to define preventive conservation strategies. An experimental methodological approach was identified to analyze the microclimatic conditions, to evaluate environmental damage and decay phenomena and support the conservation of artworks. Results obtained from experimental measurements performed inside a historical Dominican convent, which is now the San Marco museum in Florence (Italy), were compared and discussed. The detailed investigation of thermo-physical and thermo-hygrometric behavior of building in response to internal and external stress, allows to define preventive conservation strategies and plant solutions in a perspective of its acclimatization and adaptive reuse of internal ambient.

Peer-review under responsibility of Marco Tanganelli and Stefania Viti

Keywords: microclimate monitoring; non-invasive measurements; cultural heritage; adaptive reuse; sustainability; acclimatization solutions

1. Introduction

The goods that make up the cultural heritage are very varied and complex, so much so that the research activity currently carried out on deterioration processes has not yet led to univocal and conclusive results. Today, there is no single and unique protocol internationally accepted: there are guidelines and recommendations (UNI 10829 (1999); MiBAC (2001); EN 15757 (2010); ASHRAE (2011)) aimed at establishing the basic criteria and providing indications

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Peer-review under responsibility of Marco Tanganelli and Stefania Viti
10.1016/j.prostr.2020.11.135

on the recommended threshold levels for the main environmental parameters for conservation. Moreover the complexity of the involved factors and actors in the museum system, the need to arrange the people reception, who ask for different levels of cultural offer and services, the development of studies and research, having to cope with different legislations adopted in different Countries, the costs reduction, energy consumption reduction and energy use rationalization, are needs that require strong skills and specializations but, above all, interdisciplinarity, transversality, coordination and cooperation between different professionals and experts.

In particular, as regards the decay prevention of museum collections connected to microclimate, there are fundamental references as Thomson (1986) and Camuffo (1998), but only in recent years monitoring campaigns, carried out aimed at microclimatic, thermo-hygrometric and luminous control, as well as air quality control, became increasingly common (Corgnati et al. (2009); D'Agostino et al. (2015); Ferdyn-Grygierek (2016)).

Experimental measurement campaigns are really a complex task, when the museum is housed in an historical building that usually requires conservation parameter values very different from those of works of art therein contained. The difficulty of defining an experimental set-up and a methodological approach connected to a specific measurement protocol is even more complex when the historical building has changed its functions and uses over time. Furthermore, the indoor microclimate study would be an essential tool for preventive conservation strategies, sustainable management of both artworks and historical building, and definition of reversible, sustainable, efficient and effective, minimally invasive and adaptive plant system solutions. The plant system placement in historical buildings is always a delicate and complex issue, because the environments have generally been thought and designed without any plant system, often based on natural ventilation and passive cooling strategies (Camuffo et al. (2004); La Gennusa et al. (2005); Sciurpi et al. (2015); Litti and Audenaert (2018)).

The main aim of our present research concerns the study of the microclimate of museum environment, for guaranteeing CH preventive conservation, based on the systemic analysis of the interrelation effects due to thermodynamics of building system and operation and control conditions of the plant system.

2. Methods and materials

2.1. Experimental set-up

The proposed methodological approach was based on crucial levels of investigation: literature search and archive research aimed at retrace the history of the building both in geometrical and material characteristics and change in use; geometrical and material survey and thermo-physical characterization; information and technical data on plant system (i.e. HVAC, lighting) and building management and usage profile; identification of timing and different periods of the year for microclimatic monitoring performing; experimental data recording and post processing; results analysis and comparisons. The environment monitoring was based on stratigraphic and altimetric continuous measurements of the air temperature (T) and relative humidity (RH). The air velocity and mean differential pressure variations in specific zones (i.e. grids placed on the base of the walls separating the cells and the access doors to these latter) were also evaluated by spot measurements using a hot wire anemometer. Data were acquired every minute, using T and RH sensors and processed every 15 minutes. Some spot measurement performed by an infra-red FLIR thermo-camera (FLIR T600) with a data matrix of 480 × 360 pixels, an accuracy of ±2% or ±2 °C reading; thermal sensitivity 0.04 °C at 30 °C; temperature range −40 °C to 650 °C, provided information on the surface temperature of the various building materials, objects and components.

2.2. Setting

The monumental section of the Dominican convent, currently San Marco Museum, in Florence, is the case study. The original structure of the convent dates back to the 13th Century and it was built by the Sylvestrian monks, while the present shape of the monumental complex dates back to the 15th Century when Cosimo de' Medici financed building renovation and extension, which was planned and executed by the architect Michelozzo. Between 1437 and 1442 the works were completed and in 1443 the convent was officially consecrated. After centuries, due to the suppression of religious orders, in the 19th Century the convent was expropriate and in 1869 after some renovations, the monumental part of the complex was opened to public as the Royal Museum of San Marco.

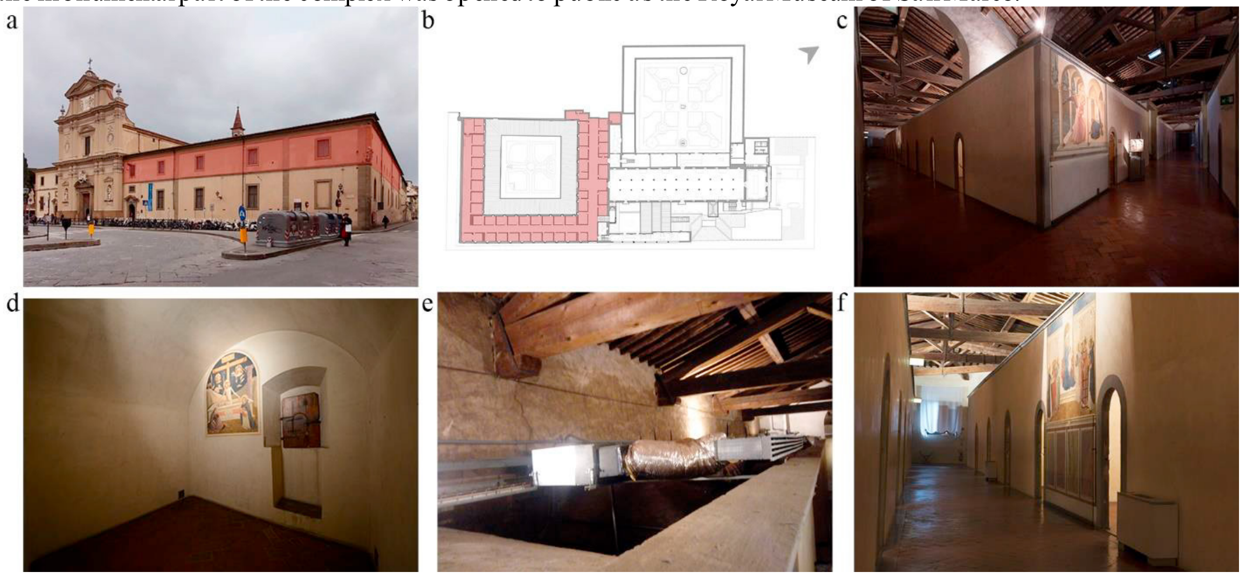

Fig. 1. (a) Photo: an external view of the San Marco Museum with the dormitory highlighted ; (b) Museum plan with the dormitory highlighted; (c) Photo: a view of the dormitory; (d) Photo: a view of the cell; (e) Photo: a view of the plant above the cells; (f) Photo: a view of the fan coil in the corridor

Our experimental investigations were carried out in the area located on the first floor that surrounds the Cloister of San'Antonino and which was the dormitories of the friars. The room still retains its original shape, is structured into three corridors on which are placed 43 cells and holds one of the most important cycles of renaissance frescoes by Fra Angelico between 1438 and 1445 (Fig. 1a-1d). The historical building conversion into a Museum, which took place in 1869, had given rise to several interventions for functional adaptation of the rooms. The room was never equipped with heating ventilation air conditioning (HVAC) system until the '90s when some fan coils were located in the corridors. Since 2013 the Dormitory was equipped by a variable refrigerant volume system (VRF). At the extrados of the vault at 3 m from the floor, eighteen indoor units are located and are equipped by a temperature control unit through a centralized system, but without humidity control (Fig. 1e-1f).

3. Microclimatic monitoring

The experimental monitoring campaign was performed from 31 July 2019 and is still in progress. The aim of the experimental investigation was the comprehension of the influence of external and internal microclimatic effects on the internal thermo-hygrometric conditions to guarantee the suggested values by UNI 10829 (1999) and MiBAC (2001) for CH preventive conservation. The cross-checking of information obtained with preliminary investigations, (i.e. bibliographic and archival study, survey and analysis of the existing status) allowed the identification of the most significant zones reducing costs and time of the experimental setup. The cell 26 and its surrounding ambient were chosen because of its central location and for its proximity to the *Madonna delle Ombre* by Fra Angelico, one of the three wall paintings located in the corridors. The second corridor is 45,5 m length, 2,50 m wide, the pitched roof is 6,97 m high at the ridge; the cells placed on both sides of the corridor are 3,70 m length, 2,75 m wide and the barrel vault is 3,35 m at the apex (Fig. 2).

Technical data of the used instruments are provided in Table 1. They were located in compliance with the least visibility and invasiveness. The sensor location is provided in Fig. 2. PT01 inside the cell 26 at 2,80 m from the ground; PT02 inside the cell 25 at 3,00 m from the ground; PT03 on the ledge in the corridor near the wall painting at

3,65 m from the ground; PT04 on the ledge on the other side of the corridor at 3,65 m from the ground; PT05 in the corridor at floor level. The corresponding external microclimatic data provided by "*Consorzio LAMMA. Laboratory for Meteorology and Environmental Modelling*" (located 6,4 km far from San Marco Museum) were analysed and used.

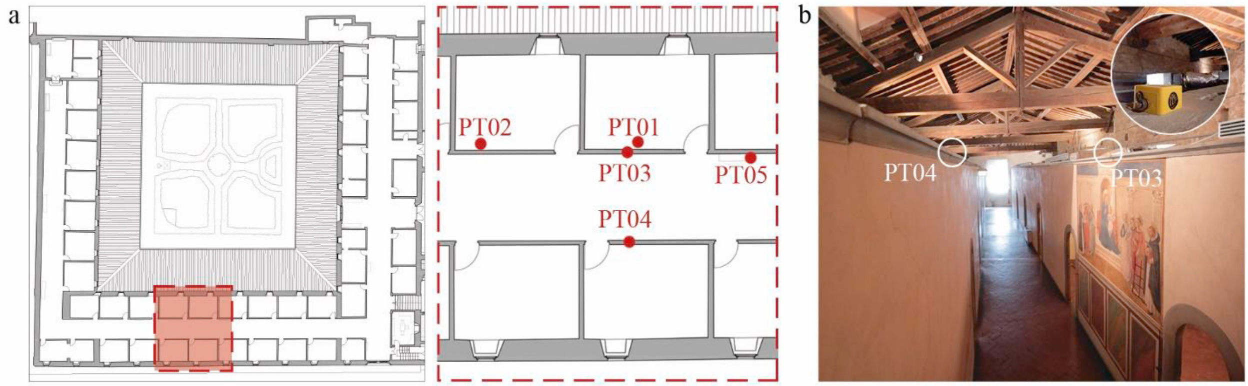

Fig. 2. (a) Dormitory plan and localization of sensors (b) Photo: localization of sensors in the corridor

Table 1. Main characteristics of the sensors.

Tinytag Plus 2 TGP-4500			Extech RHT10		
	Dimensions	34x51x80 mm		Dimensions	130 x 30 x 25mm
	Temperature Range	- 25 to + 85 °C		Temperature Range	- 40 °C to +70 °C
	Temperature Accuracy	±0.5 °C (0 to 40°C)		Temperature Accuracy	± 1 °C (-10 to 40°C)
	Temperature Resolution	0.01 °C		Temperature Resolution	0.1 °C
	RH Range	0 % to 100%		RH Range	0 % to 100%
	RH Accuracy	± 3 %		RH Accuracy	± 3 %
	RH Resolution	0.3 %		RH Resolution	0.1 %

4. Results and discussion

In this present section, experimental data analysis and post processing for the period from 31 July 2019 to 28 October 2019 are presented and discussed. In this period the centralized cooling system was on from 31 July to 17 October with a temperature set point of 23°C, without any humidity control. From 18 to 28 October the plant was off. The statistical data analysis and data error evaluation for the whole period are provided in Table 2. The mean standard deviation for T and RH is respectively 0,93 and 2,84. The mean chi-squared error is 1,45% for T and 2,55% for RH. The results showed the reliability and validity of the measurement method and obtained results.

Table 2. Statistical data analysis and error evaluation.

	Mean		Median		Maximum		Minimum		Standard Deviation		Chi-squared %	
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
PT01	24,2	55,1	24,2	55,3	28,1	64,9	21,2	40,0	1,57	4,01	1,90	3,05
PT02	23,1	57,1	23,1	57,2	25,6	63,4	20,9	47,1	0,88	2,60	1,43	2,45
PT03	23,1	57,2	23,2	57,5	25,1	63,9	21,1	48,3	0,71	2,41	1,28	2,36
PT04	23,4	57,6	23,6	57,6	25,2	64,8	21,5	49,0	0,79	2,47	1,36	2,39
PT05	22,9	58,1	23,0	58,2	24,2	65,3	21,0	45,3	0,70	2,72	1,28	2,51

T and RH trends for each measurement point during the entire monitored period are shown in Fig. 3. It can be noted the stability of the indoor microclimate parameters: the maximum daily range of T is 3,4°C and of RH is 16% in PT01 inside the cell, and 1,6°C and 10,3% in PT03 in the corridor. T and RH range values during the entire monitoring campaign, calculated both for the period with plant on (from 31 July 2019 to 17 October 2019) and with plant off (from 18 October to 28 October 2019), are always low due to thermo-physical behavior of the building (i.e. high thermal inertia and capacity). In particular, the mean daily T range in the period with the plant on is lower than that one of the period with plant off, while the daily RH range in the period with the system on is greater than that one of the period with the plant off. This is due to temperature control system that does not provide the contemporary relative humidity regulation. The experimental data were analysed and discussed referring to the UNI 10829 (1999) and MiBAC (2001) recommendations. The cycle of painting inside the cell and the *Annunciazione* in the first corridor were painted with the frescos technique, while the *Madonna delle Ombre* in the second corridor was painted by "dry", a rare technique in the Fra Angelico' art. Restoration works and investigations carried out before the installation of the HVAC system show that the decorative and structural elements of great value did not have serious decay and instability phenomena due to the indoor environment. The famous restorer Dino Dini, who restored the wall paintings between 1975 and 1983 reported as primary causes of the decay phenomena on the frescoes the passage of time, dirt, scratches, abrasions, blackening of candle fumes, damage due to the many repainting that were cause of the bad readability of the frescoes and of the proliferation of mould.

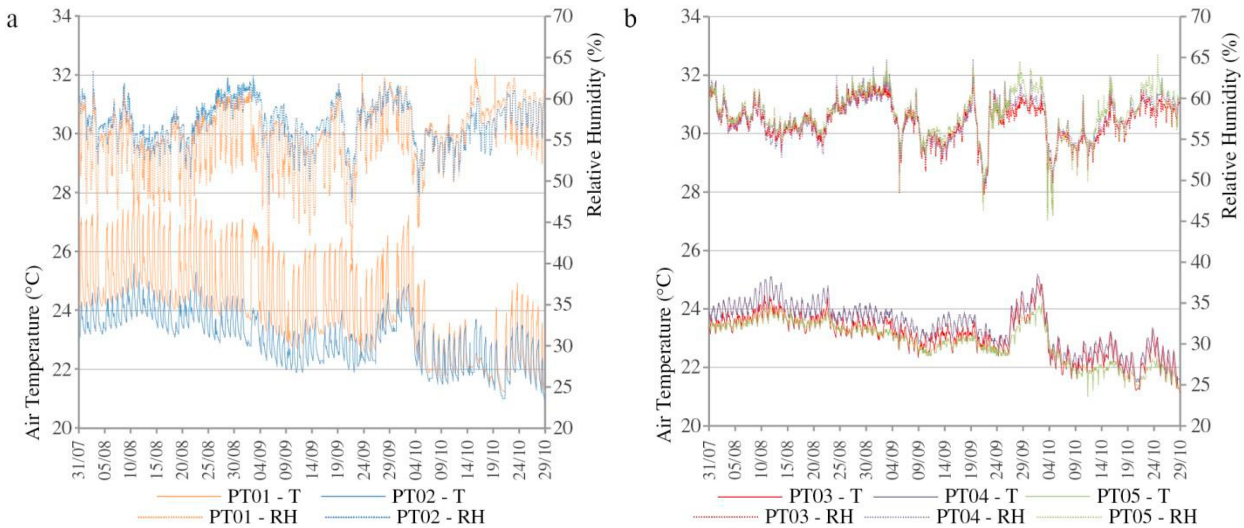

Fig. 3. (a) Air Temperature trend and (b) Relative Humidity trend for the entire period

The EN 1575 (2010) standard introduces the concept of "historical climate" and defines as suitable for conservation those values related to the environmental history of the object. Unless there are no degradation phenomena, the standard suggests not to alter this climatic condition. In our case due to the introduction of the HVAC system was not possible to trace the microclimatic conditions in which the artworks acclimatized and preserved for centuries before, so we referred to the ranges of T and RH as suggested in UNI 10829 (1999) and to MiBAC (2001). These limits are given in Table 3.

Table 3. Limits suggested by the current standards for wall paintings conservation.

	UR (%)	Δ(UR)max (%)	T (°C)	Δ(T)max (°C)
UNI 10829: 1999	55-65	-	10-24	
MiBAC 2001	45-60	-	6 -25	± 1,5/h

Experimental data were analyzed according to UNI 10829 (1999). This standard provides for each climatic parameters the calculation method of the deviation index, defined as the percentage of time in which the parameter is found to be outside the range of values suggested for the conservation of a category of artwork. Cumulative frequency was plotted to calculate the Performance Index (PI) as an indicator of the conservation quality of the indoor environment in relation to the type of goods preserved. PI represents the percentage of time in which the parameter remains within the range suggested. The calculation of cumulative frequency and PI of T and RH given in Table 4, allowed the assessment of the suitability of the values for the preservation of wall paintings. Fig. 4 shows the comparison of the limits suggested by UNI 10829 (1999) and MiBAC (2001) and the T and RH values distribution during the entire monitoring campaign. Even if the individual values of PI are good, Fig. 4 shows how the values are not contemporarily verified for T and RH. In particular, the PI for the measuring point PT01 inside the cell is very low due to the significant influence of the lighting system who affects the indoor environment conditions.

Table 4. Performance Index (PI) values for T and RH.

Position of the sensors	Performance Index (PI)					
	UNI 10829: 1999		MiBAC 2001		UNI 10829: 1999 e MiBACT 2001	
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
PT01	43,89%	55,79%	69,28%	88,87%	43,89%	55,32%
PT02	86,78%	78,63%	99,61%	85,95%	86,78%	72,94%
PT03	93,06%	82,15%	99,95%	87,82%	93,06%	78,47%
PT04	78,43%	83,29%	99,35%	83,24%	78,43%	75,58%
PT05	99,79%	87,80%	100,00%	72,78%	99,79%	66,06%

After checking T and RH values stability for the artworks conservation, potential variations in the interaction between building and environment were assessed. The impact of the outdoor and indoor environmental variables (e.g. HVAC plant, lighting system, visitor and staff) were analyzed and discussed. Comparison of outdoor and indoor T trend in the period with plant off, from 18 to 28 of October, shows how the thermal inertia and capacity of the building significantly reduce fluctuations. E.g., Fig. 5 shows the outdoor and indoor T trend in PT04, the mean value of T is 22,2 °C, the maximum is 23,3 °C and minimum is 21,5 °C with a mean daily range of 0,8 °C. In particular, the phase shift of thermal wave is evident: e.g. at 6:00 of the 18 of October the external T is 11,4 °C and the internal T is 21,8

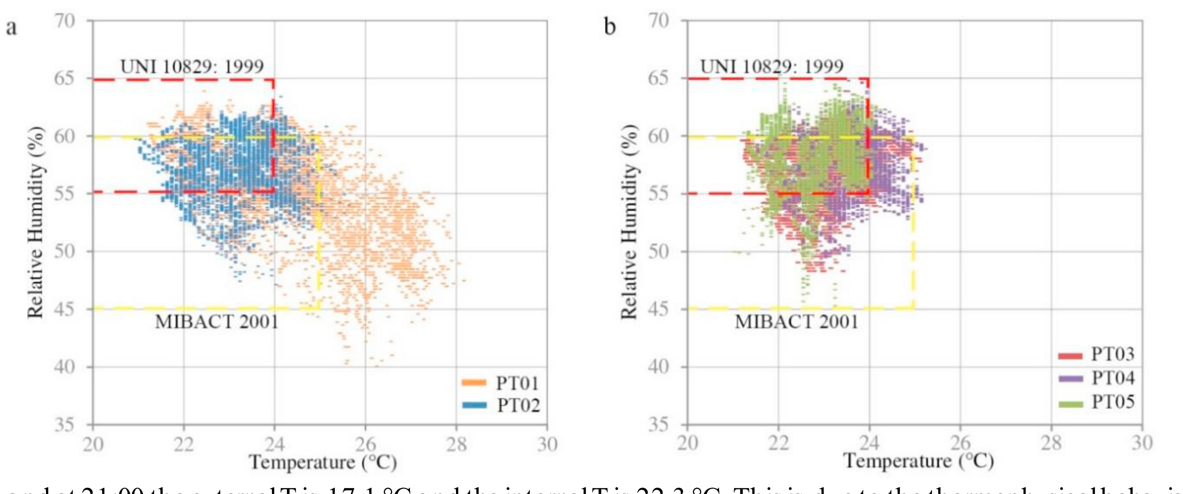

Fig. 4. Distribution of T and RH for the entire monitored period compared with the limits suggested by UNI 10829 (1999) e MIBAC (2001) in (a) PT01 e PT02 in the cells and (b) PT03, PT04 and PT05 in the corridor.

°C and at 21:00 the external T is 17,1 °C and the internal T is 22,3 °C. This is due to the thermophysical behavior of massive building. It can be noted that the plant working conditions produce a damping effect on the outdoor environmental load, combined with the appreciable thermal properties of the building. Results show the plant system efficacy for guaranteeing preventive conservation conditions but also it important adaptivity and acclimatization due to its thermal peaks damping effect, and microclimatic extreme variations reduction, that are the most damaging for artworks and building. Building thermo-physics combined with plant working conditions, assure stability requirements of microclimate that play a key role in the deterioration processes. Variations in thermo-physical parameters that ate as damaging as their absolute values, are reduced. The humidity ratio (x; i.e. the ratio between mass of water vapour and dry air, g_r/kg) was calculated using the saturation pressure evaluated as function of T and RH.

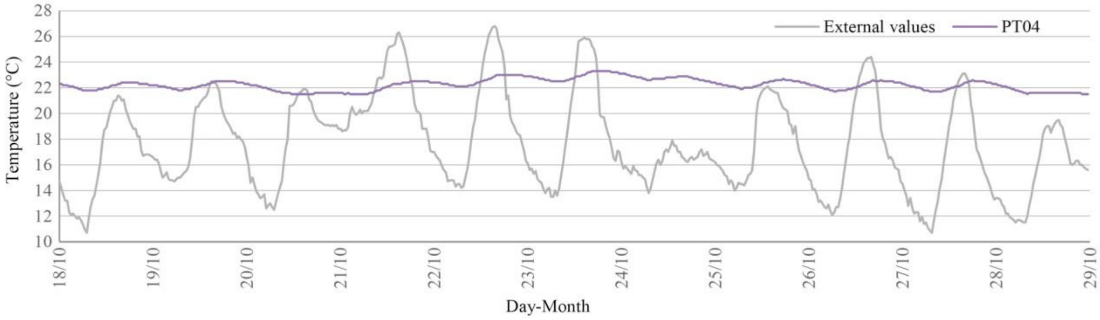

Fig. 5. Air Temperature trend for the period with plant off (from 18 October to 28 October 2019)

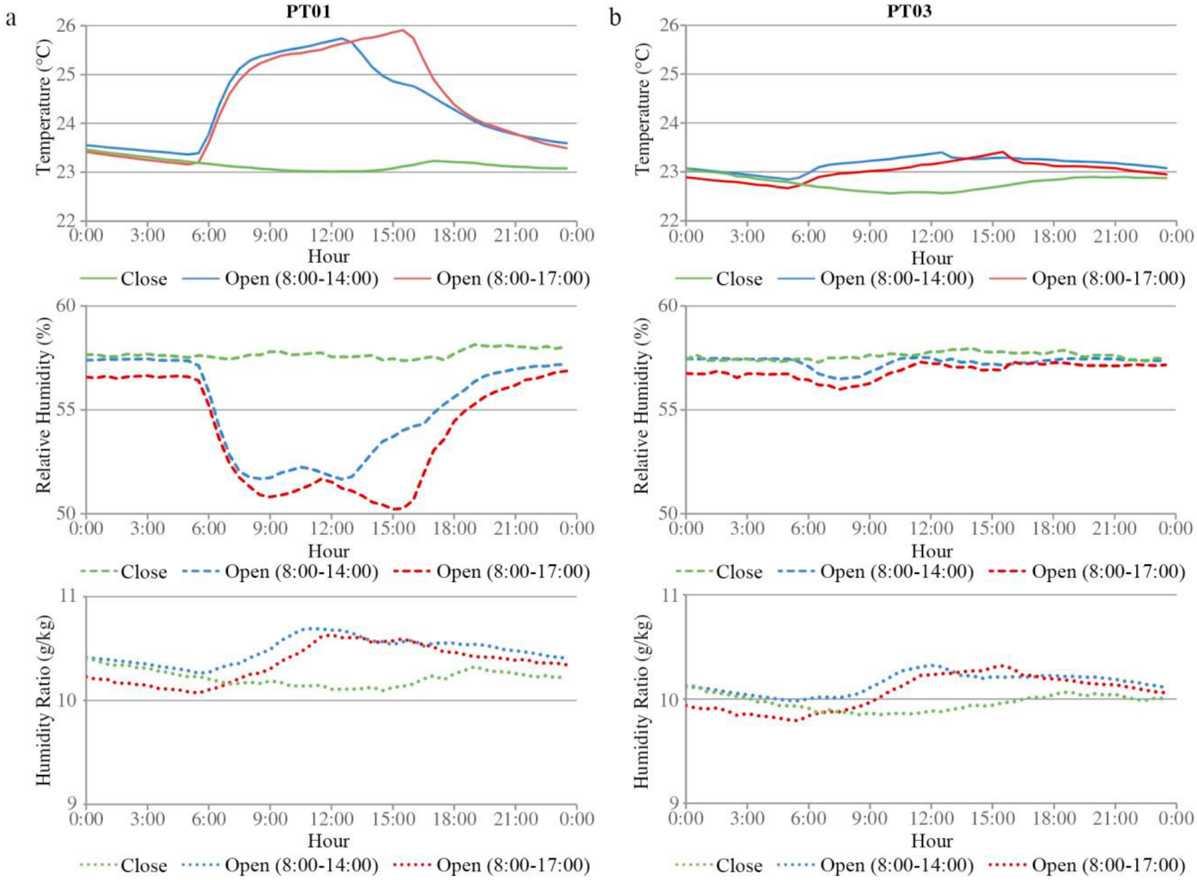

Fig. 6. Mean hourly value of T, RH an x during closing and opening hours of the museum for the entire period in (a) PT01 and (b) PT04

The influence of indoor thermal loads was identified by calculation of mean hourly value of the thermo-hygrometric parameters referring to three user profiles: closing days, opening days from 8:00 to 14:00 and opening days from 8:00 to 17:00. E.g., graphs for T, RH and x in PT01 and PT03 are shown in Fig. 6. It can be observed that during the closing days, the values of T, RH and x remain stable with minimal variations, while during the closing days there is a rise in T and a decrease in RH during the opening hours. The switching on the ligh ting system is the main cause of the T rise in PT01. This rise is also in PT03 although lower.

Analyzing the x value variations during the entire monitored period for both indoor and outdoor environment, it can be noted that the amount of internal vapor and consequently the latent heat loads are not very appreciable because are only due to the low visitors presence. Therefore the efficacy of VRF system for the control of the microclimatic conditions stability is guaranteed. As a matter of fact, the VRF solution is the best for museums and exhibitions inside massive historic buildings, characterized by large volumes, without appreciable and impulsive latent loads. Only in the farther zones from the HVAC units and luminaires (i.e. PT04, PT05) and where the highest concentration of visitors was checked. It can be noted a rise in T and RH with a x value increase. From data analysis it can be observed a non-homogeneous distribution of temperature values with a vertical gradient of about 1°C between the PT05 located on the floor, and the PT04 located on the ledge, and with a horizontal gradient of about 1°C between points PT03 and PT04 both located on the ledge, PT03 located closer to the indoor air units.

5. Conclusions

Results showed that the proposed experimental approach can be a useful tool for a methodological study of CH *sustainable adaptive reuse* with a view to conservation and preventive protection, based on a deep knowledge of the building physics and its indoor environment connected to plant system thermodynamics and control/regulation system presence. It can be extended, by means of specific adjustment, to all similar cases, but also non-listed buildings and current designs. The proposed method is also an operative and practical tool for assessing the sustainability, feasibility and effectiveness of non-invasive, reversible system solutions based on the concept of *plants acclimatization*. It allows *sustainable*, a*daptive* and *acclimatization* concepts quantification aimed at identifying the degradation risk. It provides also the fundamental approach for the analysis of the plant system working by a view of its slowly and progressively adaptation to thermo-physical building behaviour. Only in the long term, it should lead to the internal microclimate and air quality for the *optimal* conditions of artwork and building conservation and people health and well-being. The practical application of the method can provide a useful support in decision making about the choice of the most compatible and sustainable environmental control strategies such as passive control, ventilation solutions, movable and reversible local plant equipment.

Acknowledgements

The authors thank: Dr. Stefano Casciu, Director of the *Polo Museale della Toscana*; Dr. Marilena Tamassia, Director of the *Museo di San Marco*; Ms. Stefania and the staff of the Museum; Dr. Luca Fibbi of the *Consorzio LAMMA*; the Technical Director and the staff of *Tecnoengineering S.r.l.;* Luigi Puglioli of the *Agenzia Benvenuti*.

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