

Robust microclimate control for artwork preservation in response to extreme climatic conditions: simulation of museum halls for temporary exhibitions with a validated dynamic tool

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Abstract. In museums, artworks preservation is hampered by several factors, in particular temperature and relative humidity as inappropriate values of these parameters can cause biological, mechanical, and chemical degradation. Thus, HVAC systems must be able to maintain specific suitable indoor microclimate also in critical conditions, such as variation of external climate and huge presence of visitors. In this paper, we first present the results of a monitoring campaign conducted in some rooms of an Italian museum in the 2015-2016 winter exhibition. The current HVAC system was able to maintain the required microclimate. A dynamic model (using TRNSYS for the envelope modeling and an in-house developed tool for the HVAC system) has been validated through the measured data. The dynamic model allows performing additional simulations characterized by critical boundary conditions (e.g., low external temperature and/or high relative humidity, and high number of visitors). In current conditions, these conditions would have caused unacceptable microclimate in the exhibition rooms, meaning higher risks for artworks. Through a rational rearrangement of the current HVAC system (both generators and terminal units), the microclimate was found to be suitable also in critical situations. This outcome is particularly important in exhibition rooms with temporarily borrowed artworks, since climatic conditions are basically unpredictable for the season of exhibition and so a robust HVAC system is needed.

1. Introduction

There are several factors that can hamper artworks preservation, such as temperature, relative humidity, light, and pollutants [1–3]. In particular, temperature (T) and relative humidity (RH) unsuitable values are responsible for biological, mechanical, and chemical degradation. In the last decades, conservation experts and heritage scientists have focused an increased attention to the identification of correct values of T and RH to prevent artwork deterioration. This attention led to the development of guidelines and technical standards for the correct preservation of artworks [4–8]; in some other cases, scientists have developed risk assessment methods for specific artwork typologies [9, 10]. In Italy, the technical standard UNI 10829 [4] includes, for different artwork typologies, suggested microclimate values for a correct preservation. Two ranges are identified: the “optimal range” represents the values of T and RH related to an



optimal preservation of artworks; the “tolerant range” represents a still suitable T and RH range to be applied if it is not possible to install an optimal HVAC system for the microclimate control (for example when the museum is a protected historic building).

In the light of these studies, the importance of HVAC systems in museum exhibition rooms (but also in all the rooms where artworks are stored, not exposed) is clear. The objective of HVAC system in these environments is to maintain correct values of T and RH: usually, water terminal units (e.g., fan coils, radiant panels) control temperature in the rooms, while air handling units (AHUs) control relative humidity. It is important that HVAC systems fast react to changes in the external climate or indoor systems: for example, in case of peaks of visitors, sensible and latent gains due to individuals could cause an increase in internal temperature and relative humidity. HVAC systems should be then robust, in the sense of being able to cope with abrupt and potentially dangerous changes. This feature is particularly important in the case of HVAC systems used in temporary exhibitions museums: the borrowed artworks should be maintained in optimal conditions to avoid to pay penalty fees and so HVAC system should cope with unpredictable external climate and visitors turn-out.

In this paper, we present the results of a monitoring campaign carried out in a museum in Pisa, Italy, highlighting that current HVAC system performed well in the maintenance of the correct microclimate values (Section 2). We then used a dynamic simulation to verify the response of the system to changes in the external climate and in the visitors’ presence (Section 3), showing that a rational reorganization of the current HVAC system is suitable to maintain correct indoor climate also in critical boundary conditions (Section 4). Finally, Section 5 presents the conclusions and future prospects of the work.

2. Description of the case study

2.1. Monitoring campaign

A temperature and relative humidity monitoring campaign was carried out in a museum in Pisa, Italy, for three months during a temporary exhibition of prints, posters and drawings on paper. For this artwork typology, Italian technical standard UNI 10829 suggests a temperature between 18 and 22 °C and a relative humidity between 40 and 55%. As there were several exhibition rooms, we here focus only on the most visited room, which was the one with the most famous artworks of the exhibition. This room, to which we refer as Reference Room (RR), has an area of 100 m² and a volume of 400 m³. The envelope material is rubble masonry (average total thickness: 70 cm, thermal transmittance: $0.9 \frac{W}{m^2K}$) and the roof has a typical Tuscan structure, with wood beams, bricks, and an insulating layer (thermal transmittance: $0.7 \frac{W}{m^2K}$). There is no glazed area. The RR is heated in winter through fan coils, whereas fresh air is provided by an AHU. The AHU includes a preheat coil, a cooling coil, a vaporizer and a reheat coil. A dedicated heat pump provides hot water at the AHU heating coils and fan coils. As the heat pump can operate only in heating mode in winter, the AHU cooling coil is not used. It is worth noting that the T and RH sensors that control fan coils and AHU switching on/off are not positioned in the RR, but in an adjacent room, which is less crowded. We refer to this room as the Control Room (CR). The HVAC system operates from 8 a.m. to 9 p.m. every day, as the high envelope capacitance allows to switch off the system during the night without significant variation of temperature and relative humidity.

In accordance to technical standard UNI 10829 [4], EN 15758 [11], and EN 16242 [12], T and RH sensors were positioned in points representative of an area where the thermal environment is substantially homogeneous, avoiding AHU dampers and fan coils. Table 1 shows the position and the characteristics of the sensors. Sensors gathered T and RH at a 1.5 m height in proximity of the artworks every 6 minutes. Additional sensors gathered data of the external climate and of the HVAC system (e.g., AHU dampers, heat pump supply and return water temperature). Finally, for two reference days, we performed 15-minute observation of visitors’ presence in RR.

Table 1: Specifics of the sensors used in the monitoring campaign.

Model	Position	Monitored parameter	Measuring range	Accuracy	Acquisition period
Siemens QAA24	RR and CR	T	-50...+80 °C	±0.6 K	15 min.
SEMITEC NTC	RR and CR	T	-50...+110 °C	±0.2 K	6 min.
4-noks THL-M	RR and CR	T RH	-40 ... +120 °C 0 ... 100 %	±0.2 K ±3 %	6 min.
Siemens QFM21160	AHU dampers	T RH	0 ... 50 °C 0 ... 100 %	±0.7 K ±3 %	15 min.
DICKSON TM325	AHU entrance	T RH	-20 ... +70 °C 0 ... 95 %	±0.5 K ±3 %	15 min.

Further details on the case study can be found in [13].

The suitability of the indoor thermal environment has been assessed through the evaluation of specific indexes, discussed in [13] and [14]. In particular, we used PI and PI* indexes, where:

- PI is the percentage of time in which T and RH values are within the optimal range;
- PI* identifies the percentage of time in which T and RH occurs within the tolerant range in the monitored environment.

These indexes were evaluated considering December month, which was a central month of the exhibition. The results of the monitoring campaign showed that the current HVAC system (heat pump, AHU, and fan coils) was able to maintain the correct microclimate inside the RR in December. For this exhibition, PI and PI* are, respectively, 87% and 100%, highlighting that the indoor climate is suitable for artwork preservation.

2.2. Dynamic simulation of the RR

We developed a detailed dynamic model of the RR in TRNSYS 17 [15], using the characteristics of the envelope and of the HVAC system. In particular, we simulated the entire zone of the museum that includes the RR and the CR, to more realistically represent the control of the HVAC system. The outputs of the simulation were the profiles of T and RH in the RR during December.

The whole model was validated using a one-to-one approach: single models (e.g., envelope, visitors' presence, AHU, heat pump) were validated through a comparison of the simulation results with monitoring data. In particular:

- the TRNSYS envelope model was validated comparing internal T and specific humidity in the RR with monitored data, using as inputs monitored external climate, visitors' profile, AHU T and RH of the supply air, supply and return water T of the heat pump;
- the visitors' profile model in the RR, based on the sold tickets at the box office, was validated comparing specific humidity from simulation and from monitoring, using as inputs monitored external climate, AHU T and RH of the supply air, supply and return water T of the heat pump [16];
- the AHU model, based on the ϵ -NTU method [17] of the heat exchangers, was validated comparing the inlet specific humidity and the return water T at the heat pump from

simulation and monitoring, using as inputs monitored external climate and supply water T of the heat pump [18] .

3. Analysis of the system in critical conditions

3.1. Sensitivity analysis: discussion

Changes in external climate or visitors' number in RR can cause a variation of risk assessment. Through the validated model of the building-HVAC system, variation of PI and PI* can be estimated when varying boundary conditions. The main criticality in the analyzed museum is the absence of dehumidification in winter, so we verified the current system performance varying the parameters that are responsible for an internal relative humidity increase. Three parameters are identified: a lower external T, a higher external RH, and a higher number of visitors. Also synergistic effects have been considered. External temperature, relative humidity and visitors' number were modified using three parameters:

- a_T , varying in the range [0.8; 1.0], in the expression:

$$T_{ext,new} = T_{ext} - abs[(T_{ext} - T_{ext,ref})(1 - a_T)]$$

where $T_{ext,new}$ is the new value of external temperature used in the simulation, T_{ext} the actual monitored value of external temperature, and $T_{ext,ref}$ is a reference temperature, namely 0 °C;

- b_{RH} , varying in the range [1.0; 1.1] in the expression:

$$RH_{ext,new} = RH_{ext} + [(RH_{ext,ref} - RH_{ext})(b_{RH} - 1)]$$

where $RH_{ext,new}$ is the new value of external RH used in the simulation, RH_{ext} the actual monitored value of external RH, and $RH_{ext,ref}$ is a reference RH, namely 100%.

- c_{vis} , varying in the range [1;2], in the expression:

$$n_{vis,new} = n_{vis}c_{vis}$$

where $n_{vis,new}$ is the new number of visitors in the RR, used in the simulation, while n_{vis} is the number of visitors in the RR as evaluated through the dynamic model in [16].

Accordingly to the paper aim, the chosen ranges of a_T , b_{RH} , and c_{vis} include the most critical conditions, as expected for the museum location and analysis period. The performed simulations considered also synergistic effects, as in some cases a_T , b_{RH} , and c_{vis} concurrently vary. Simulations were performed for the December month, using the 2015 monitored external climate data as reference.

3.2. Results and discussion

The simulations results show that the variation of external T and RH and visitors' number are responsible for a worse microclimate in the RR.

Figure 1 shows the simulation results, in terms of PI, varying the three parameters a_T , b_{RH} , and c_{vis} . The figure shows that PI rapidly decreases when more critical conditions occur. In particular, the most critical parameter is the number of visitors in the room, which causes a significant reduction of PI: when $c_{vis} = 2$, $a_T = 1$ and $b_{RH} = 1$, PI value is about 66%, and decreases up to 44% in the worst condition ($a_T = 0.8$, $b_{RH} = 1.1$, and $c_{vis} = 2$). Visitors are in fact responsible for high internal gains, particularly latent ones: this causes a high increase of relative humidity in the RR. Also the external temperature decrease causes a reduction of suitability parameters: a lower external temperature increases heat exchange through the

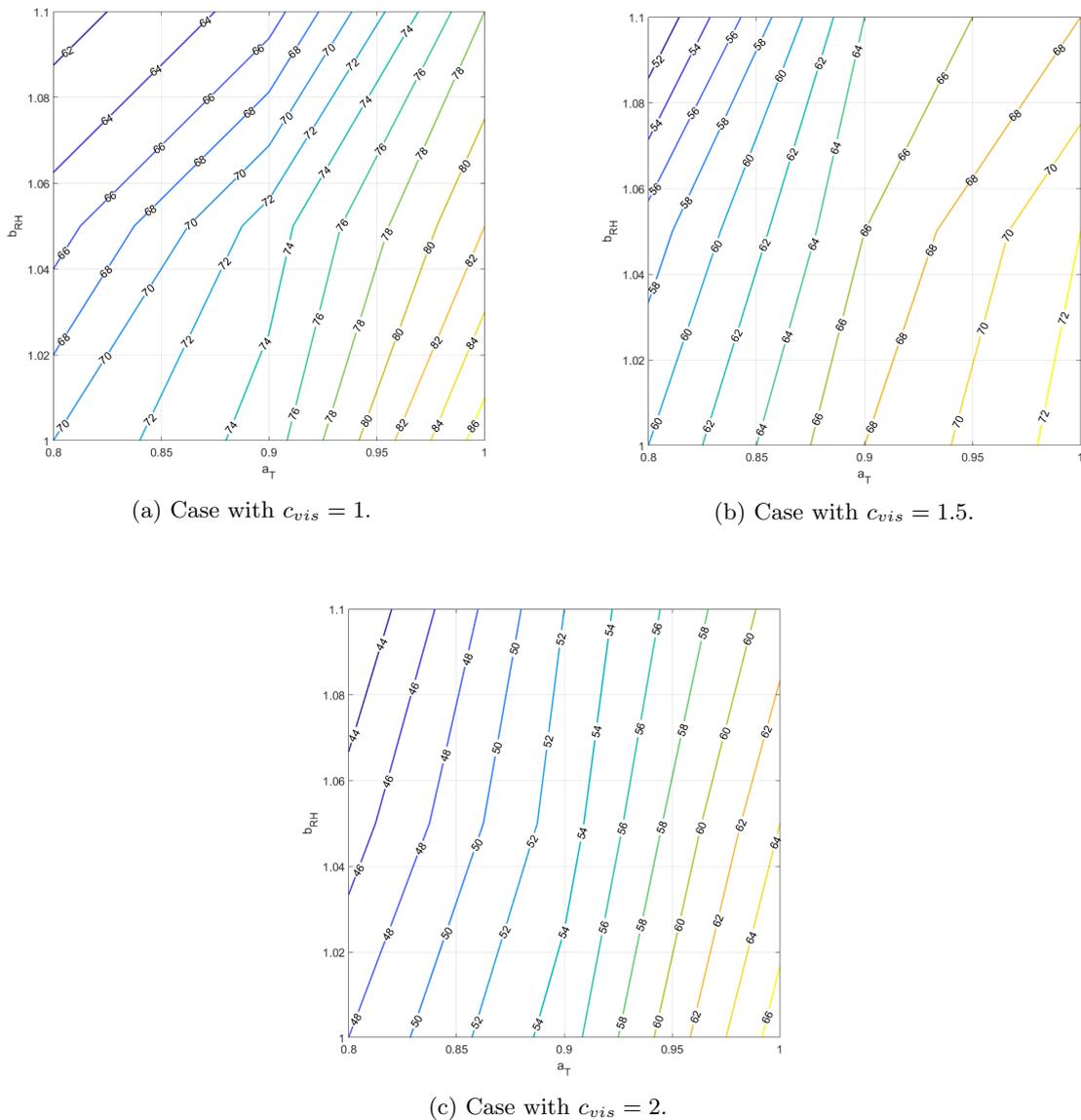


Figure 1: PI indexes as results of the sensitivity analysis in the current HVAC configuration.

building envelope, so the reduction of internal microclimate suitability is due to the reduction of internal temperature during nights, when HVAC system is switched off. RH is high in the RR due to visitors’ presence and lack of dehumidification and it even increases during night, as T decreases: thus, it exceeds the threshold limit. Also PI* decreases when worse conditions occur: the 100%-value of PI* is found when the three sensitivity parameters are equal to 1, but lower values (around 70-75%) are reached when visitors’ number increase or external temperature decreases. These results clearly highlights that current HVAC system is potentially unable to cope with critical boundary conditions, hampering artworks preservation: so a variation of the HVAC system is needed.

4. Reorganization of the HVAC system and application of the sensitivity analysis parameters

4.1. Implementation of the new HVAC system: discussion

Usually, the refurbishment of a museum hosted in a historic building is difficult, as several classical solutions for optimal HVAC system design cannot be used because of the constraints for the protection of the envelope. The most recommended solutions are identified after an in-depth analysis of the whole building-HVAC system. In the analyzed case study, we considered the whole building-HVAC system, which includes also other rooms and generators. We found that another temporary exhibition area is heated through a condensing boiler, which is largely oversized (nominal power: 500 kW). In fact, the analysis of this adjacent zone showed that it needs the 50% of the condensing boiler power for heating purposes. This condensing boiler is positioned near to the RR generation system. Then, we considered the possibility of a rearrangement of the HVAC system: the condensing boiler can be used for the generation of heated water for fan coils and heating coils of the AHU, while the current heat pump can be used only for cooling water of AHU cooling coils in winter and for fan coils and AHU cooling coils in summer. In the decision of the HVAC system rearrangement, we considered the following aspects:

- the solution respects the constraints due to the museum protection by the local agency for the historic building protection (i.e. Soprintendenza), as it does not affect the envelope;
- it allows the modification of the microclimate in the RR without modifying it in the other rooms of the temporary exhibition area;
- as the condensing boiler, heat pump and AHU are in adjacent equipment rooms, it should be easy to connect the generators, the terminal units and the AHU.

The current dynamic model of the HVAC system in RR was modified, implementing the use of AHU cooling coils: the cooled water is provided by the currently-used heat pump, while the heated water (at both AHU and fan coils) is provided by the condensing boiler. The HVAC system is considered switched off during night, as in the current case. The sensitivity analysis is then applied, to verify if the new system is more suitable in maintaining correct microclimate in the RR. The sensitivity parameters a_T , b_{RH} and c_{vis} are supposed to vary in the same ranges as discussed in previous section. The simulation is performed for the same reference month as above.

4.2. Results of the sensitivity analysis with the new HVAC system

The results of the new simulations show that the retrofit solution allow a good control of internal microclimate also when both external climate and visitors profile significantly change. Figure 2 shows the simulation results when the three sensitivity parameters vary.

The results show a small PI decrease when a_T decreases and when c_{vis} increases (the T and RH control sensors are positioned in a less crowded room, not in the RR):

- when a_T decreases, the external temperature is lower also during night, when the HVAC system is turned off; the night heat losses through the envelope are higher and the indoor temperature decreases, thus resulting in a lower PI than in $a_T = 1$ case;
- PI decreases when c_{vis} increases because the values of AHU supply specific humidity are chosen to meet the hygrothermal setpoints on the basis of microclimate in the CR, which is less crowded than the RR; then, higher values of RH are found in the RR, resulting in a worse microclimate when the visitors' number is high.

In any case, high values of PI are reached in almost all the analyzed cases: when $a_T = 1$, $b_{RH} = 1$, and $c_{vis} = 1$, PI value is about 90%, while in the current HVAC configuration PI is about 84%. The improvement of PI value is clearly visible in the results of the simulations where $c_{vis} = 2$, which were the most critical cases. In fact, in the current HVAC configuration, PI value

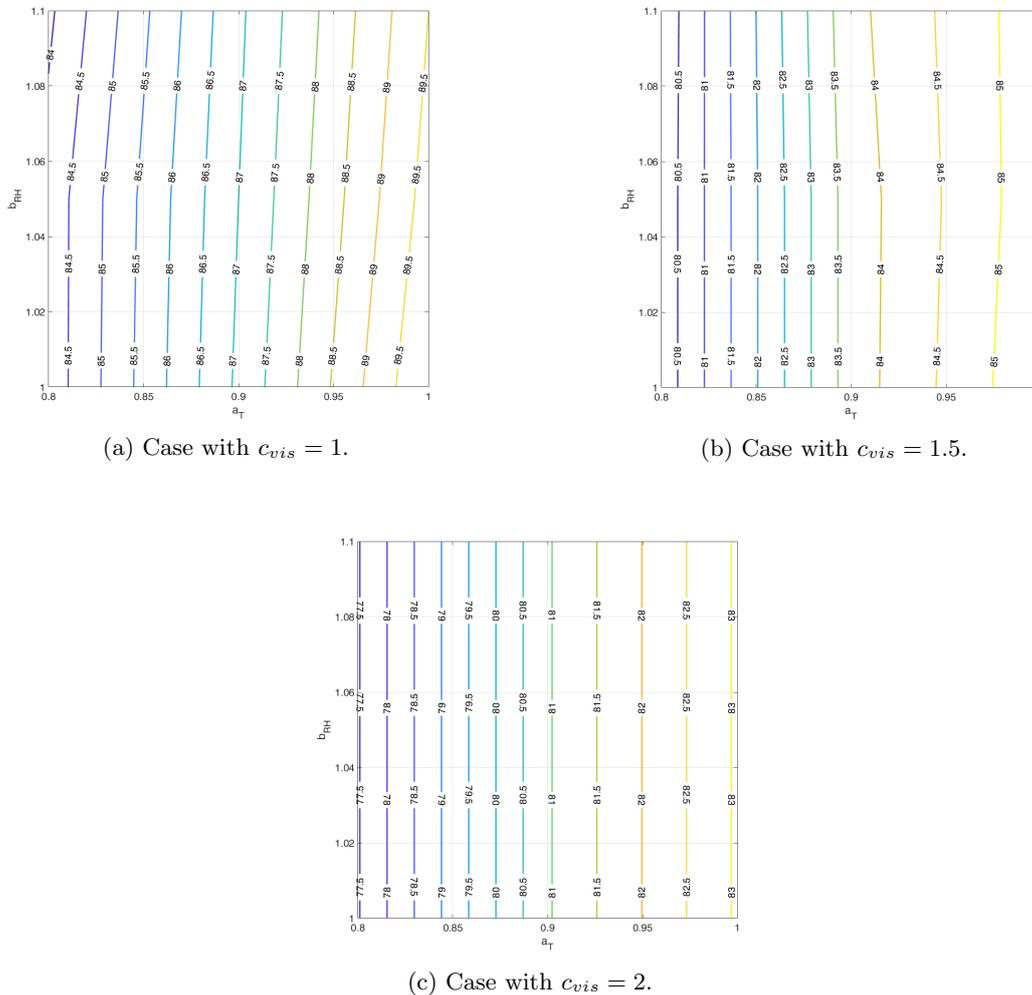


Figure 2: PI indexes as results of the sensitivity analysis in the new HVAC configuration.

ranges between 44 and 66%, while, with the new HVAC configuration, PI ranges between 77 and 83%. Also PI* value has improved, being equal to 100% in all the simulations.

The higher values of microclimate suitability indexes are due to the improved RH control. During the opening hours, in fact, AHU maintains indoor RH around the 45%-setpoint; only in the cases with high visitors' crowd, the indoor RH increases, with values around 55%. In these cases, the HVAC turning off during nights causes the microclimate to go beyond the optimal limits, thus decreasing PI. In any case, the variation of microclimate between opening and closing hours is limited, with a maximum T daily span of 2 °C and a maximum RH daily span of 5%. According to [19], for artwork preservation, suitable daily variation is 2 °C for T and 8% for RH. Hence, the indoor microclimate variation due to the nocturnal HVAC turning off does not hamper artwork integrity.

It is worth noting that these good outcomes are reached without additional costs except the ones for the new connections between generators and distribution system.

5. Conclusions

In this paper, we verified that current HVAC system of our case study maintained correct microclimate during a temporary exhibition in 2015-2016, but, in presence of more critical

conditions (lower external T, higher external RH and higher visitors' number), it would be unable to maintain suitable microclimate due to the current working technical equipment. Through an analysis of the whole museum, we have identified a new configuration of the HVAC system using only the currently-present components, so without additional installation costs. The new configuration has been tested through dynamic simulations, verifying the improvement of all the suitability indexes, which indicates a better control of internal microclimate also in critical conditions. Further research will investigate also the microclimate improvements due to change in the HVAC control system (e.g., setpoints, operating periods, setback temperature).

This study highlights the importance of a flexible HVAC system to maintain T and RH in the correct ranges for artwork preservation. In museums hosted in historic buildings, it is not always possible to have an optimal envelope-HVAC system, because of the constraints due to the building protection. Furthermore, the HVAC should be also "resilient", that is being effective when boundary conditions become critical. This is particularly important for HVAC systems in temporary exhibition museums, where HVAC systems should be able to maintain different setpoints depending on the exposed artworks, regardless of unpredictable external conditions and internal gains. In this perspective, an accurate analysis of the building-HVAC system and dynamic simulation support stakeholders and experts for correct design and management.

Indoor conditions are also important to ensure visitors' comfort, though different T and RH values are generally required. The efficiency of energy production has to be considered as well. The same implemented models of the building and generators can be used to investigate this three-multi-objective problem: we will deal with this additional analysis in future works.

References

- [1] Camuffo D 1998 *Microclimate for Cultural Heritage* (Amsterdam: Elsevier).
- [2] Bernardi A 2003 *Conservare opere d'arte. Il microclima negli ambienti museali* (Saonara, IT: Il Prato).
- [3] Pavlogeorgatos G 2003 *Build. Environ.* **38** 1457–62.
- [4] UNI 1999 UNI 10829
- [5] CEN 2010 EN 15757
- [6] Italian Cultural Heritage Ministry 2001 D.M. 10/05/2001
- [7] National Museum Directors' Conference 2009
- [8] Publicly Available Specifications 2012 PAS 198
- [9] Schito E and Testi D 2017 *Build. Environ.* **123** 585–600.
- [10] Silva H E, Henriques F M A, Henriques T A S and Coelho G 2016 *Build. Environ.* **104** 21–34.
- [11] CEN 2010 EN 15758
- [12] CEN 2012 EN 16242
- [13] Schito E, Testi D and Grassi W 2016 *Buildings* **6** 41.
- [14] Corgnati S P, Fabi V and Filippi M 2009 *Build. Environ.* **44** 1253–60.
- [15] Klein S A et al 2017 *TRNSYS 17: A Transient System Simulation Program* (Madison, USA).
- [16] Schito E and Testi D 2017 *Build. Simul* **10** 977–87.
- [17] Incropera F P, DeWitt D P, Bergman T L and Lavine A s 2007 *Fundamentals of Heat and Mass Transfer* (Hoboken, USA: John Wiley & Sons).
- [18] Schito E 2017 *Methods and tools for a rational and efficient use of energy in museum environments* (PhD Thesis, University of Pisa, Pisa, IT).
- [19] Thomson G 1978 *The museum environment* (Amsterdam: Elsevier).