MULTI-OBJECTIVE OPTIMIZATION OF MICROCLIMATE IN MUSEUMS FOR CONCURRENT REDUCTION OF ENERGY NEEDS, VISITORS' DISCOMFORT AND ARTWORK PRESERVATION RISKS

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Abstract

In museums, hygrothermal conditions must be carefully controlled by HVAC system to avoid artwork degradation. Higher energy requirements are needed for the maintenance of the suitable thermal environment. Moreover, a comfortable thermal sensation is needed for a positive museum experience. In light of current policies on energy efficiency, we propose an original procedure for the concurrent achievement of three goals: artwork preservation, energy efficiency, and human thermal comfort. This procedure is based on the application of multi-objective optimization and aims at correctly choosing temperature and relative humidity setpoints, through the use of dynamic simulations and evaluation of three indexes as objectives. This strategy can be particularly effective in museums hosted in historic buildings, where envelope and HVAC refurbishment is often forbidden or discouraged due to the architectural constraints. Furthermore, the retrofit action is almost costless. A case study is presented: first, a monitoring campaign in an Italian museum has been used for the validation of dynamic simulation models of the building-HVAC system; then, the validated models have been used to show that improvements of artwork lifetime, human thermal comfort and reduction of energy requirements of the HVAC system are possible, if currently-used hygrothermal setpoints (based on technical standards and guidelines) are replaced with those identified by the optimization problem.

Keywords: energy efficiency, human thermal comfort, artwork preservation, multi-objective optimization, control strategies, hygrothermal setpoints.

1. Introduction

In Europe, a significant percentage of buildings has historic value and many of them are used as museums [1,2]. In these environments, high amounts of energy are required for the maintenance of correct microclimate for artwork preservation [3,4]. The need of strict microclimate control should be related to an effective design of all the museums subsystems, from the envelope to the HVAC system: unfortunately, especially in existing historic buildings, significant refurbishment actions for energy efficiency are not possible [5,6], as buildings are protected by local Cultural Heritage Agencies. In the last few years, research has focused on the possibility of improving indoor microclimate and reducing energy requirements. In some cases, an additional objective is a comfortable environment for visitors: as suggested by [7], thermal comfort is one of the recognized parameters that influence people in the appreciation of the museum experience. The issue of energy efficiency in museums was the topic of several researches in the last years and solutions involving the HVAC control system are often suggested. For example, three European Projects from 1994 to 2004 [8–10] used a bottom-up approach when considering existing museums and identified interventions to enhance internal microclimate. When retrofit actions on envelope or HVAC systems are not possible or convenient, the authors suggest to consider changes in the system control strategy (e.g., temperature/time/season sensitive control to reduce heating and cooling consumptions, occupancy/time sensitive system to reduce ventilation and lighting consumptions). Similar results were found for the case studies of 3ENCULT project [11] and Climate for Culture project [12–14]. In scientific literature, case studies are reported, calculating energy consumptions in real museums and evaluating best technologies and strategies to improve efficiency. For example, in [15], dynamic simulations have highlighted possibilities of energy savings through wider microclimate fluctuations. In [16], the authors have focused on the energy savings obtained with a variation of relative humidity setpoint and dead band. These two works focus on the energy issue related to museum air conditioning. Ascione [17] presents the results of a monitoring campaign and an analysis through Finite Element model of an historic building, where high thermal discomfort was identified. Among different solutions, also new setpoint definitions have been suggested as a possibility to improve thermal comfort. In a more recent work [18], Kramer presents the results of a dynamic simulation performed in a Dutch museum: the variation of temperature and relative humidity setpoints allows relevant energy savings (up to 80%) with respect to the current control strategy. However, the authors highlight that a higher attention should be given also to artwork preservation, verifying if the microclimate is still suitable to reduce risks, also after the new control strategies are implemented.

In addition, protocols and guidelines have been developed during the last five years, in the field of energy efficient preventive conservation. European Standard EN 16883 [19] proposes a detailed analysis of the building, with monitoring campaign to evaluate current indoor microclimate and dynamic simulations to evaluate the effectiveness of different energy efficiency solutions. Technical and economic aspects, energy savings and impact on the heritage value are taken into account. The technical standard suggests color-based indicators for the assessment of the effects of a retrofit actions in terms of technical compatibility, economic viability, and indoor microclimate (from red, high risk, to green, high benefit). D'Agostino [20] developed a protocol for the evaluation of microclimatic conditions in museums, where a detailed analysis of the building-HVAC system is identified as a fundamental step for the identification of criticalities in indoor microclimate; results of simulations can be used for the selection of the most useful interventions to be implemented. De Santoli [21] developed a guideline for energy efficiency in historic buildings: according to this guideline, a major focus is given to energy efficiency, but also integration in the landscape is considered, through preliminary assessment sheets. Lucchi [22] defined a simplified assessment method to evaluate both environmental and energy performance in museums. The procedure is carried out by verifying the presence or absence of a series of performance indicators on heritage conservation, human comfort, and energy efficiency.

The present research focuses on a methodology to improve microclimate in museums exhibition rooms, for both artwork preservation and visitors' comfort, and reduce energy needs when refurbishment actions on the envelope or HVAC system are not allowed by agencies for the cultural heritage. Over the past years, considerable researches have focused on multi-objective optimization applied in the building sector. However, the majority of the works concerns the multi-objective problem from an energy and economic point of view (see, for example, [23–25]). In some cases, the problem of the reduction of energy requirements is addressed together with human thermal comfort improvement [26]. In our work, we seek co-optimization of temperature and relative humidity setpoints as a strategy to reduce risks in artwork preservation, improve visitors' comfort, and decrease energy needs. Classical mathematical formulation is used to find the Pareto optimal solutions. This strategy has been defined as "promising": in [27], the authors suggest a more in-depth analysis of this methodology applied to a multi-objective optimization of energy savings and comfort in traditional buildings. The topic of our paper is exactly the application of this strategy in protected building museums, where, for the first time, the three goals of energy efficiency, visitors' comfort and artwork preservation will be concurrently optimized. Museum stakeholders can choose the best hygrothermal setpoints to set in HVAC systems, by means of the application of the proposed procedure. The results of the optimization problem will also be presented through useful maps, to highlight Pareto-optimal solutions and help in the decision-making. This original procedure would be particularly appreciated in real applications, where curators, energy managers and stakeholders can be guided in the choice of the most suitable setpoints on the basis of the chosen targets. Specifically, the multi-objective analysis will consider three target indicators, energy needs for heating/cooling of the exhibition rooms (indicator for energy efficiency), predicted percentage of dissatisfied, PPD (indicator for human thermal comfort), and equivalent lifetime multiplier, eLM (indicator for artwork preservation). These three indexes will be discussed in Section 2, where also the optimization problem formulation is discussed.

2. Methods

In this Section we present the indicators for the three chosen targets (energy efficiency, human comfort, and artwork preservation). The proposed procedure is based on the evaluation of these target indexes after carrying out dynamic simulations, which in these analyses are considered a useful approach for the identification of the optimal energy management [28,29]. The formulation of the multi-objective optimization analysis is also discussed.

2.1 Indicator for energy efficiency

The maintenance of strict thermal requirements in museums is related to the installation of HVAC systems that provide ventilation, heating, cooling, humidification, and dehumidification. Using the definition proposed in [30], these HVAC systems are classified in SL5 level. Usually, these HVAC systems consist of both hydronic systems and air handling units (in the following HS and AHU, respectively), which are used to control temperature and relative humidity within a dead band around setpoint values. Consider Figure 1, where a schematic representation of a museum exhibition room is shown. The energy balance equation of the room reads:

$$\rho c_v V \frac{dT}{dt} = \dot{m} c_p \left(T_{s,AHU} - T \right) - Q_{tr} + Q_{HS} + Q_{s,vis} \qquad \text{(Eq. 1.a)}$$

where ρ is air density, c_v and c_p are air specific heat at constant volume and pressure, V is the volume of the room, T is indoor air temperature, $\dot{m}$ is the AHU supply flow rate, $T_{s,AHU}$ is the AHU supply temperature, Q_{tr} is the total heat transfer by transmission through the envelope, depending on the envelope characteristics and external climate, Q_{HS} is the heating/cooling contribution of the HS (for example with fancoils as terminal units), and $Q_{s,vis}$ represents the internal sensible gains due to individuals. In this formulation we neglect infiltration losses. $Q_{s,vis}$ can be written as:

$$Q_{s,vis} = n \cdot q_{s,vis} \qquad \text{(Eq. 1.b)}$$

where n is the number of individuals in the room and $q_{s,vis}$ is the sensible heat rate per occupant, depending on the activity.

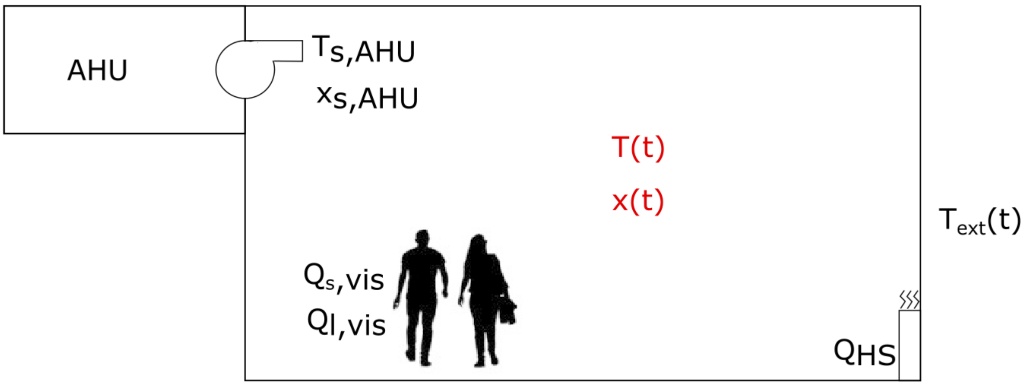


Figure 1. Schematic representation of the thermo-hygrometric balance of a museum exhibition room.

Considering again Figure 1, the mass balance of moisture in the exhibition room reads:

$$\rho k V \frac{dx_{\text{int}}}{dt} = \dot{m} \left(x_{s,AHU} - x_{\text{int}} \right) + Q_{l,vis} \qquad \text{(Eq. 2.a)}$$

where x_{int} is the specific humidity in the room, $x_{s,AHU}$ is the specific humidity of the AHU supply air, k is the effective moisture capacitance factor, which considers the effects of moisture buffering (according to the effective capacitance humidity model, as discussed in [31,32]), and $Q_{l,vis}$ represents the internal latent gains due to individuals, which can be written as ($q_{l,vis}$ is the latent heat rate per occupant, depending on the activity):

$$Q_{l,vis} = n \cdot q_{l,vis} \qquad \text{(Eq. 2.b)}$$

Technical standard ISO 7730 [33] provides values of the human heat rate per occupant, depending on the activity.

The aim of the HVAC system is to maintain indoor microclimate into specific ranges. The total thermo-hygrometric load that the HVAC system must provide is our energy efficiency indicator, given by:

$$Q_{HVAC} = Q_{HS} + Q_{AHU} \quad \text{(Eq. 3)}$$

The heating/cooling contribution of the hydronic system, Q_{HS}, is provided on the basis of a specific temperature setpoint (T*) within a corresponding dead band (ΔT*). Q_{HS} can be written as:

$$Q_{HS} = \dot{m}_w c \cdot (T_{w,s} - T_{w,r}) \quad \text{(Eq. 4)}$$

where $\dot{m}_w$ is the total water flow rate in the terminal units, c is water specific heat, and $T_{w,s}$ and $T_{w,r}$ are, respectively, the temperature of the supply and return water.

As for the energy needs at the AHU, we consider a generic AHU scheme with an economizer, heating and cooling coils, and a vaporizer, as the one shown in Figure 2. In our case, the AHU provides fresh air to meet hygienic conditions and control relative humidity in the rooms. The value of $x_{s,AHU}$ (specific humidity of the supply air) is calculated by the imposition of a fixed relative humidity inside the room (RH*) with a corresponding dead band (ΔRH*), and it is obtained through either a humidification of the supply air (for example, by means of a vaporizer), or a cooling/dehumidification of the supply air.

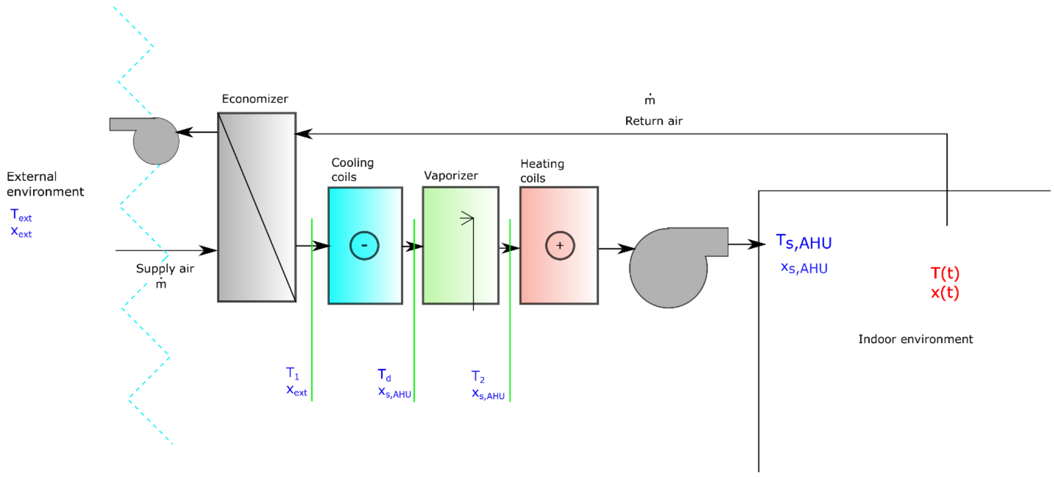


Figure 2: Schematic representation of an AHU. The represented notation for flow rate, temperature and specific humidity is used in the text.

In this AHU model, we consider the heat transfer as ideal in both heating and cooling coils. Focusing only on thermal energy (and thus neglecting electric energy at the blowers), and using the mathematical notation in Figure 2, the formulation reads:

$$Q_{AHU} = Q_{AHU,dehum} + Q_{AHU,hum} + Q_{AHU,heat} \quad \text{(Eq. 5.a)}$$

In presence of an economizer, the corresponding heat transfer is "free": the supply air is heated/cooled from T_{ext} to T_1 through a corresponding cooling/heating of the return air. In absence of the economizer, $T_1 = T_{ext}$.

The cooling coils are used to cool the supply air stream up to the dewpoint temperature T_d, which is the temperature with a specific humidity equal to $x_{s,AHU}$ and a relative humidity equal to 100%. The heat transfer at the cooling coils can be written as:

$$Q_{AHU,dehum} = \dot{m} c_p \cdot (T_1 - T_d) \quad \text{(Eq. 5.b)}$$

At the vaporizer, steam is produced through an electric resistance; the corresponding formulation reads:

$$Q_{AHU,hum} = \dot{m}\left(x_{s,AHU} - x_{ext}\right)\left[c\left(T_{boiling} - T_{aq}\right) + r\right] \qquad \text{(Eq. 5.c)}$$

This formulation means that the required moisture variation is provided by both sensible and latent heat to this water content: sensible heat is used to heat water from the aqueduct temperature (T_{aq}) to boiling temperature ($T_{boiling}$); latent heat (r in the mathematical notation) is used for the phase transition. Note that the release of steam in the air flow causes an increase of temperature of the supply air up to T_2, which can be evaluated through an enthalpy balance of the air stream entering and exiting the vaporizer. If the vaporizer is not used, $T_2 = T_d$.

At the heating coils, the supply air flow is heated up to the supply setpoint temperature, which is the same setpoint temperature of the indoor air if supply air is "neutral". The energy requirement at the heating coils is:

$$Q_{AHU,heat} = \dot{m}c_p\left(T_{s,AHU} - T_2\right) \qquad \text{(Eq. 5.d)}$$

2.2 Indicator for human thermal comfort

Human thermal comfort is influenced by the interactions of the human body and the environment, through the various heat transfer mechanisms (thermal power lost through radiation, convection, conduction and evaporation at the skin, latent and sensible heat lost by breathing). Fanger's model [34] is the most used model for the evaluation of human thermal comfort in environments where HVAC systems are present. Two indexes are provided as indicators: the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). For further details about these two indicators, see ISO 7730 [33]. The adaptive model [35,36], instead, considers the role of people in the maintenance of their own comfortable conditions (e.g., modification of clothing, control of windows opening, turning on/off the fans); this model, however, cannot be applied in thermal environments where HVAC systems are present, as common in museums.

In this work, we use PPD as indicator for human thermal comfort, as its significance is immediate in a multi-objective optimization analysis: the lower is the value, the more comfortable is the indoor environment for visitors in museum exhibition rooms. This indicator can be used for the evaluation of the visitors' comfort in museums, as several studies have shown that people are adapted to indoor conditions of a thermal environment after an adaption phase of 10-20 minutes [37,38]. In museums, this adaption period is usually finished after the passage at ticket office and cloakroom, or at most after the very first exhibition rooms.

2.3 Indicator for artwork risk assessment

In literature, two approaches are used for artwork preservation: in the simplest case, guidelines suggest temperature and relative humidity setpoints for different artwork typologies (see, for example, [39,40]). This approach, even if widely used in practice, is usually based only on curators experience and not experimentally validated.

A more accurate approach is the evaluation of the risk assessment through specific correlations developed for each degradation type. Incorrect values of temperature and relative humidity can cause three types of degradation in artworks: i) biological degradation (which causes spore germination and mold growth); ii) mechanical degradation (due to cycles of compression and expansion of the layers of the artwork); iii) chemical degradation (due to the interaction of the artwork with the environment, usually strongly influenced by temperature). These three degradation mechanisms are widely used in literature and risk assessment methodologies are provided in several works (see, for example, [2,14,41,42]). In the integrated maps presented in [2], it is shown that biological degradation may not occur in HVAC-controlled environments: biological risk is, in fact, high when indoor relative humidity is high, but usually in HVAC-controlled environments, dehumidification processes help in the maintenance of correct RH values. Thus, for typical temperature and relative humidity setpoints in museum exhibition rooms, there is no biological risk. Ref. [2] also shows that damage due to mechanical degradation mechanisms can happen in case of wide relative humidity cycles, that is when a RH variation of 20% or more occurs over a short period cycle (e.g., a day). If exhibition rooms are equipped with HVAC systems, it is difficult that high RH variation occur in a short period.

In this work, lifetime multiplier (LM) is used as indicator for artwork risk assessment of chemical nature. This index is presented in [43] to compare the effects of actual microclimate with the effects of a benchmark microclimate (i.e., 20 °C and 50% for temperature and relative humidity setpoints, respectively, for several artworks of organic nature). The LM equation, at time *i* (which can represent a measurement or a result of dynamic simulation at timestep "i"), reads:

$$LM_i = \left(\frac{RH_{ref}}{RH_i}\right)^{1.3} \exp\left(\frac{E_a}{R}\left(\frac{1}{T_i + 273.15} - \frac{1}{T_{ref}}\right)\right) \qquad \text{(Eq. 8)}$$

where RH_{ref} and T_{ref} are benchmark microclimate values, respectively 50% and 293.15 K, R is the ideal gas constant (8.314 J/mol K), RH_i and T_i (respectively in [%] and [°C]) are actual values of relative humidity and temperature, and E_a is the activation energy, in J/mol, obtained by experimental works and characterizing the specific artwork typology (values of this parameter for different materials can be found in [41,43,44]). If the LM parameter is higher than 1, current microclimate reduces chemical risks with respect to benchmark microclimate.

In the case of monitoring campaigns or simulation results (N gathered values of temperature and relative humidity), a global value for the LM (called equivalent-LM, eLM) can be evaluated with the following equation [42,45]:

$$eLM = \frac{1}{\frac{1}{N}\cdot\sum_{i=1}^{N}\left(\frac{1}{LM_i}\right)} \qquad \text{(Eq. 9)}$$

This formulation gives a greater weight to LM-values lower than 1 (higher risk for conservation).

2.4 Formulation of the multi-objective analysis

The goal of this multi-objective analysis is to find temperature and relative humidity setpoint values (T*, RH*) that minimize energy requirements and PPD, while maintaining an eLM value of, at least, 1. As these objectives are conflicting, there is not a single solution that concurrently optimizes each goal. It is possible to find a set of "Pareto" optimal solutions, also called non-dominated solutions, where none of the objective functions can be improved without worsening other objective functions. All the Pareto solutions are considered equally good if the problem is not weighted-objective (that means that different weights can be attributed to the different objective functions, to favor the minimization of one of them).

In this problem, we consider a reference period, RP, [0,τ] (e.g., one month), including opening and closing periods for the museum. Furthermore, we identify also a second reference period, RP*, including only the opening periods of the museum. We choose the following three objective functions:

$$\mathbf{\Phi_A} = \int_0^{\tau} Q_{HVAC}(t)\,dt$$
$$\mathbf{\Phi_B} = mean\left(PPD^*\right)$$
$$\mathbf{\Phi_C} = eLM$$

where $\mathbf{\Phi_A}$ is the total energy needs at the HVAC system (hydronic system and air handling unit) in the RP and $\mathbf{\Phi_B}$ is the mean value of the PPD* array, where the latter is an array containing PPD values only in RP*. $\mathbf{\Phi_C}$ is simply the eLM value, evaluated in the RP. We use here the mean PPD value in the opening hours, in accordance with ISO 7730 for long-term thermal comfort evaluation. There are other indexes that are commonly used in human comfort researches, such as the PPD-weighted criterion, discussed in EN 15251, which sums the periods when PMV exceeds the chosen comfort boundaries, weighted through a weighting factor (ratio between the actual PPD and the PPD related to the chosen PMV limit) [46]. A complete discussion of the most common indicators for human thermal comfort is reported in [47].

Using the classic mathematical notation [48], the formulation of our optimization problem is:

in the $RP = \left[0, \tau\right]$, find the control vector $\mathbf{K} = \left[T^*, RH^*\right]$

which minimizes the two objective functions $\mathbf{\Phi_A}, \mathbf{\Phi_B}$ and maximizes $\mathbf{\Phi_C}$

subject to:

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{K}, \mathbf{u}, t) \qquad \text{(Eq. 10)}$$

For the purposes of the optimization problem, we have also defined the array $\mathbf{x} = [T(t), RH(t)]$, which represents the temporal evolution of the two state variables, temperature and relative humidity, in the exhibition rooms, in RP. The differential equation in Eq. 10 represents the set of equations (energy balance and moisture mass balance), reported in Section

2.1. The $\mathbf{u}$ array represents the fixed parameters in the optimization problem (e.g., heat losses through the envelope, clothing factor and metabolic rate of the occupants).

3. Application to a case study

The proposed optimization procedure has been applied to a real case study, to verify if suitable values of temperature and relative humidity setpoints can be found to achieve the chosen targets.

We have selected a reference museum in Pisa, where important temporary exhibitions take place every year. A monitoring campaign took place in the rooms where usually the most important artworks of the exhibition are exposed. In these rooms, air relative humidity is controlled through an air handling unit (AHU), with the traditional components (heating coils, cooling coils, humidifier, and reheat coils). The air supply temperature is set equal to room setpoint. Air temperature in the rooms is instead controlled through fancoils. Both air handling unit and fancoils are served by heat pumps, providing warm or cool water. Temperature and relative humidity setpoints are chosen to reduce artwork risks only. In fact, the monitoring campaign highlighted that current microclimate is suitable for preservation purposes. Furthermore, the monitoring campaign data were used to validate a model of the reference rooms, where the characteristics of the envelope and HVAC system were implemented. The envelope is modeled in TRNSYS 17 [49], which evaluates the hygrothermal values (array $\mathbf{x} = [T(t), RH(t)]$) in the exhibition room and the total heat transfer by transmission through the envelope (see Eqs. 1a-2a). Monitored values of the external climate are used for the validation. An in-house model, developed in MATLAB, is used for the HVAC system, implementing Eqs- 3-5. Using the technical data provided by manufacturers for the various HVAC system components, the comprehensive building-HVAC model provides the hygrothermal profile in the room. The 15-minutes indoor hygrothermal profiles are compared with the measured profiles, showing a good agreement (deviation less than 5%). Figure 3 shows a schematic representation of the validation procedure. More details on the monitoring campaign can be found in [50], while further details on the models for the dynamic simulation can be found in [51].

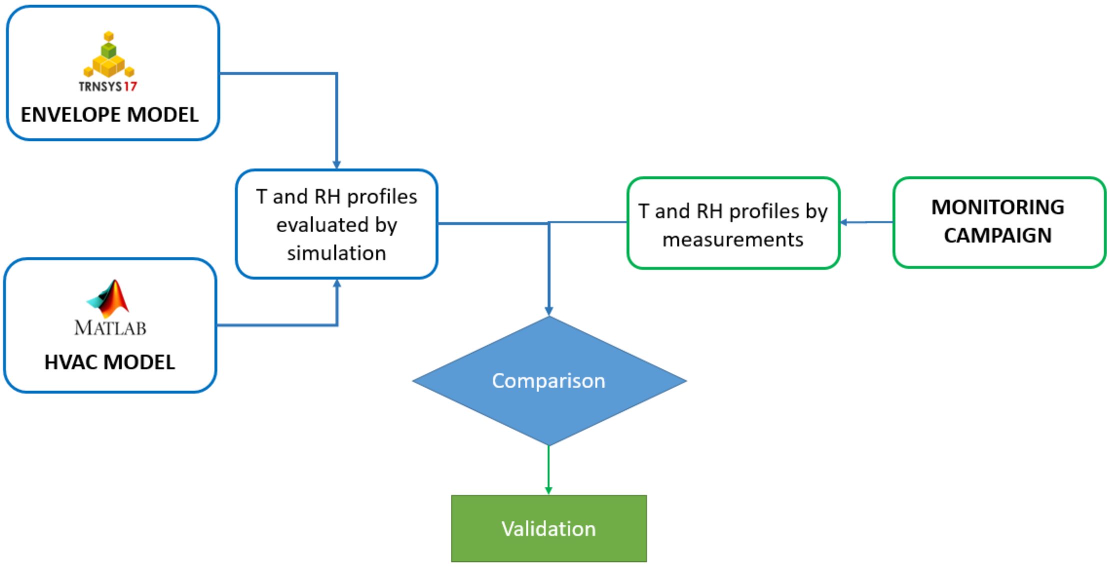


Figure 3. Simplified scheme of the validation of the building-HVAC system.

3.1 Description of the case study

The validated model, using TRNSYS, MATLAB and the reference climatic data for Pisa (provided by Italian CTI [52]) was used to perform a dynamic simulation of the reference rooms, considering a temporary exhibition of panel paintings artworks in two different periods: July and January, in both cases with a time step of 15 minutes. The envelope of the chosen rooms is characterized by opaque heavy uninsulated walls (thickness: 0.7 m, U-value 0.9 W/m^{2}K, total area of vertical walls facing external: 160 m^2), and no glazed area. Floor is considered adiabatic, while the roof has a typical Tuscan structure and an insulating layer (U-value: 0.7 W/m^{2}K, total area facing external: 101 m^2). As for the moisture capacitance model, a "k" factor equal to 10 was used. The HVAC system was modeled in MATLAB, with an in-house tool where actual characteristics of the AHU and fancoils were implemented. Currently, the HVAC system is used from 8 a.m. to 9 p.m., every day, while during closing hours temperature is let free floating. Note that the HVAC operating period is different from the museum opening hours (which is from 10 a.m. to 7 p.m. from Monday to Friday and from 10 a.m. to 8 p.m. on Saturday and Sunday). As for the fancoils, Table 1 reports the characteristics of the terminal unit given by manufacturers. There are five operation modes, varying fan speed. In the simulation, the energy requirement to maintain the chosen temperature setpoint is evaluated and then compared with the possible heating/cooling loads: the closest value to the ideal heating/cooling load is then applied in the room simulation. The AHU provides fresh air, with the correct specific humidity to maintain relative humidity setpoint in the rooms. It includes a cooling coil (for air cooling and dehumidification purposes), a vaporizer (which provides steam using an electric resistance), and a reheat coil (for air heating purposes), while there is not the economizer. Each AHU heat exchanger can accurately control the water flow rate to have the desired supply air temperature and specific humidity at the exit. The temperature setpoint of the supply air is the same as the exhibition rooms setpoint. Table 2 shows the characteristics of the AHU.

Table 1. Specifics of the fancoils, with supply/return water temperatures equal to 7 °C and 12 °C (cooling mode) or 55 °C and 50 °C (heating mode). $Q_{c,tot}$ and $Q_{c,L}$ represent the total cooling capacity and latent cooling capacity, respectively, while Q_H represents the heating capacity. $T_{e,a}$ is the temperature of the air exiting the fancoils in cooling mode.

Fan speed [%]	Heating mode	Cooling mode			Electrical power [W]	Air flow rate [m^3/h]
	Q_H [W]	$Q_{c,tot}$ [W]	$Q_{c,L}$ [W]	$T_{e,a}$ [°C]		
100	3989	3100	2188	15.0	21.0	545
80	3316	2842	1979	12.7	15.5	415
60	2652	2182	1475	12.0	10.3	295
40	1676	998	663	16.5	5.5	185
20	987	523	342	17.2	5.1	105

Table 2: Characteristics of the AHU.

	Nominal parameter	Value
Cooling coils	Air mass flow [m^3/h]	3200
	Max. heat transfer capacity [kW]	40
Reheat coils	Air mass flow [m^3/h]	3200
	Max. heat transfer capacity [kW]	13

3.1.1 Details on the July simulation

July was chosen as indoor thermal environment characteristics should be different if either artwork preservation or energy savings would be chosen as targets. In summer months, in fact, typical rules of thumb [39] suggest a temperature setpoint of 23 °C for artwork preservation and relative humidity setpoint of 50%. However, major energy savings can be reached if higher temperature and relative humidity values are allowed. Climatic data, in terms of external temperature, relative humidity and solar irradiation have been provided by CTI [52], on an hourly basis. Table 3 reports mean, minimum and maximum values of temperature and relative humidity in July. An interpolation between the hourly data provides data every 15 minutes, which are used as thermal characteristics of the supply air at the inlet of the AHU.

Table 3. Characteristics of Pisa climatic data in July.

	External temperature [°C]	External relative humidity [%]
Mean value	21.7	75.4
Minimum value	11.2	30.0
Maximum value	31.9	100.0

Visitors are considered internal gains in the rooms, providing sensible and latent heat. The profile of visitors in the rooms has been calculated on the basis of the sold tickets at the box office. The model was discussed in depth in [51]. The clothing insulation factor was chosen equal to 0.5, a value provided by EN ISO 7730 [33] and EN 15251 [53] for a typical summer clothing. As for the metabolic rate, we used typical values for a person standing provided by TRNSYS software (185 W per person: 90 W sensible heat, and 95 W latent heat). For the evaluation of human thermal comfort index, also the relative air velocity is needed: we used a value of 0.1 m/s, in accordance with spot measurements in the rooms.

3.1.2 Details on the January simulation

Opposed to the previous case, January is a period where artwork preservation and human thermal comfort are in contrast. For their correct preservation, artworks would require low temperature and relative humidity values, thus reducing also energy requirements. Typical reference values are provided by Italian technical standard UNI 10829 [39], which suggests 20 °C and 50% as setpoints for temperature and relative humidity. However, human thermal comfort is instead associated with higher values of temperature. Table 4 reports mean, minimum and maximum values for external temperature and relative humidity, according to CTI database [52]. As for visitors, the same profile used in the July simulation has been used also for the January simulation. The clothing insulation factor was chosen equal to 1.0, in accordance to EN 15251 [53]. The metabolic rate has been chosen equal to that of the previous case.

Table 4. Characteristics of Pisa climatic data in January.

	External temperature [°C]	**External relative humidity [%]**
Mean value	8.0	82.0
Minimum value	-3.4	15.0
Maximum value	16.3	100.0

3.2 Setpoint strategies (July)

Several setpoint strategies were considered, varying temperature and relative humidity setpoints. In particular, five different air temperature setpoints and four different relative humidity setpoints were evaluated, identifying 20 different simulations. Typical dead band for the hygrothermal parameters were used (±1 K for temperature, ±5 % for relative humidity). Table 5 shows the setpoints identifying each simulation.

The outputs of the simulation for each timestep are: air temperature, air relative humidity, mean radiant temperature of the walls, human thermal comfort indexes (PMV and PPD), energy requirements at the AHU and cooling loads at the fancoils.

3.3 Setpoint strategies (January)

Twenty additional simulations have been considered for January simulation, varying temperature and relative humidity setpoints as in Table 5. Typical dead band for the hygrothermal parameters were used (±1 K for temperature, ±5 % for relative humidity). The outputs of the simulations are: air temperature, air relative humidity, mean radiant temperature of the walls, human thermal comfort indexes (PMV and PPD), energy requirements at the AHU and heating loads at the fancoils. We have verified if all the hygrothermal setpoints in Table 5 would lead to condensation and possible mold growth on wall surface, using the methodology reported in ISO 13788 [54]. Also for the less favorable setpoints (high values of indoor humidity), the calculated indoor surface temperature is higher than the dew-point temperature. Furthermore, the ratio between the internal water vapor pressure and the saturated vapor pressure (using the indoor surface temperature) is always lower than 80%, which is the threshold limit given by the standard, above which mold growth on the wall surface is possible. Thus, all the considered setpoints are acceptable.

Table 5. Hygrothermal setpoints for July and January simulations. For each set of simulations, the first row identifies the ID number and the second row the setpoint values (first number: temperature setpoint, in °C, second number: relative humidity setpoint, in %).

July																				
ID	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***
SP	22 40	22 45	22 50	22 55	23 40	23 45	23 50	23 55	24 40	24 45	24 50	24 55	25 40	25 45	25 50	25 55	26 40	26 45	26 50	26 55
January																				
ID	***1w***	***2w***	***3w***	***4w***	***5w***	***6w***	***7w***	***8w***	***9w***	***10w***	***11w***	***12w***	***13w***	***14w***	***15w***	***16w***	***17w***	***18w***	***19w***	***20w***
SP	18 40	18 45	18 50	18 55	19 40	19 45	19 50	19 55	20 40	20 45	20 50	20 55	21 40	21 45	21 50	21 55	22 40	22 45	22 50	22 55

4. Discussion and results

4.1 July simulations

The results of the 20 July simulations show that current HVAC system is able to maintain the desired hygrothermal conditions in the room. Figure 3 shows the profile of temperature and relative humidity in typical graphical representation used in [55,56] for simulations #1, #4, #17, and #20. These simulations have been chosen to verify the actual hygrothermal conditions when the minimum and maximum setpoints for temperature and relative humidity are applied (in other words, if the HVAC system can maintain microclimate in the exhibition rooms when setpoints are challenging).

Figure 4 shows that the current HVAC system allows a perfect control of the relative humidity in the rooms, while, when the lowest temperature setpoint is applied (22 °C), a perfect control of the temperature is not achieved: HS is not able to maintain temperature in the dead band (see Figures 3.a and 3.b). In any case, the maximum value of air temperature in these simulations is around 24 °C, only 1°C higher than the dead band maximum value.

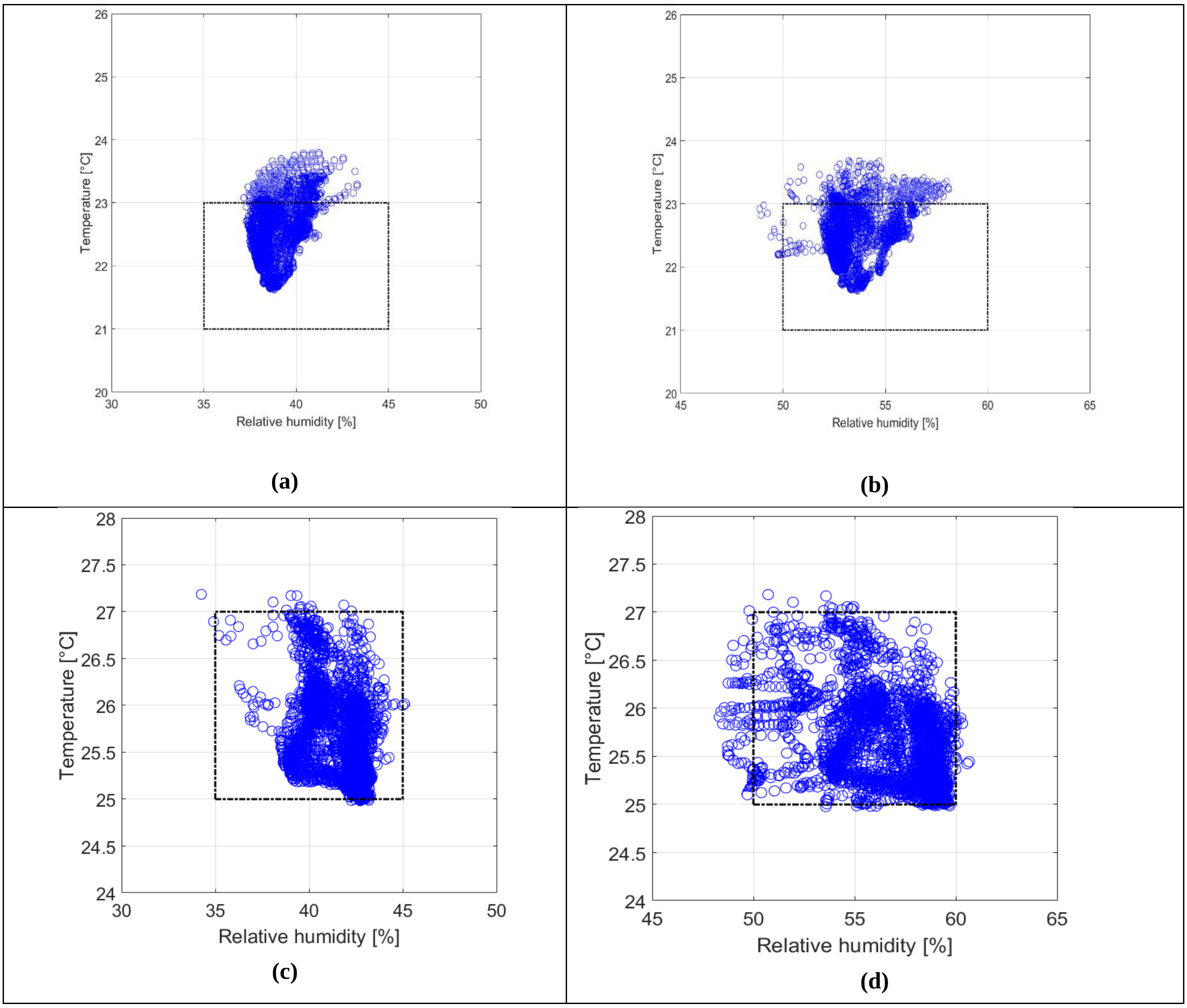


Figure 4. Hygrothermal conditions in the exhibition rooms for four reference simulations. In particular, (a), (b), (c), and (d) show results of simulation #1, #4, #17, and #20, respectively.

From the 20 simulations results, integrated maps can be created where iso-curves for the three parameters (energy requirements, PPD and eLM) are represented. Figure 5 shows iso-eLM and iso-energy curves, where the values of iso-energy curves are in kWh. This Figure shows that the two indicators are in contrast: for higher eLM values, highest energy consumptions are needed. Figure 6 shows how temperature and relative humidity setpoints are related to human thermal comfort. The magenta solid lines represent the number of dissatisfied people. It is worth noting that relative humidity does not play an important role in human thermal comfort in these temperature and relative humidity ranges. However, relative humidity value is an important parameter for the artwork preservation.

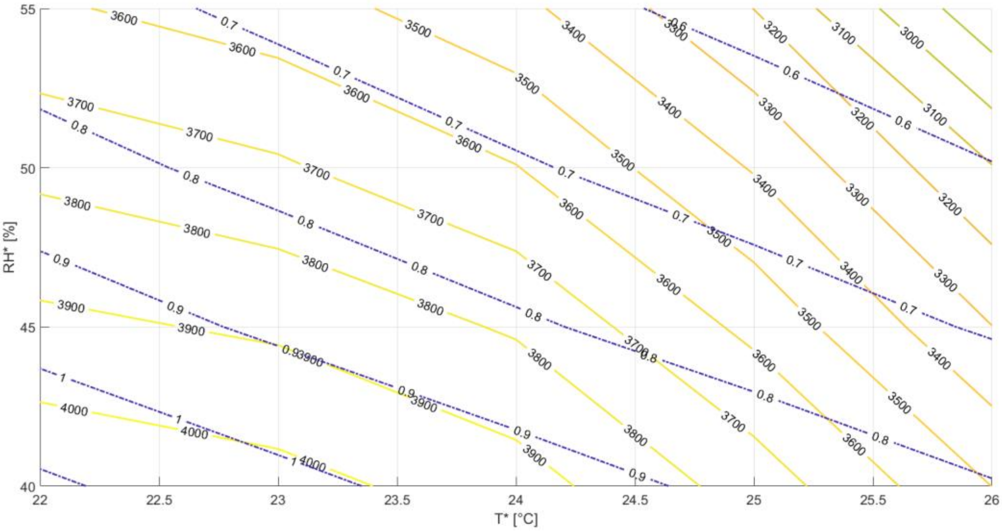


Figure 5. Integrated maps representing iso-eLM (violet dash-dotted) and iso-energy (yellow solid) curves (July simulation). Values for the iso-energy curves are in kWh.

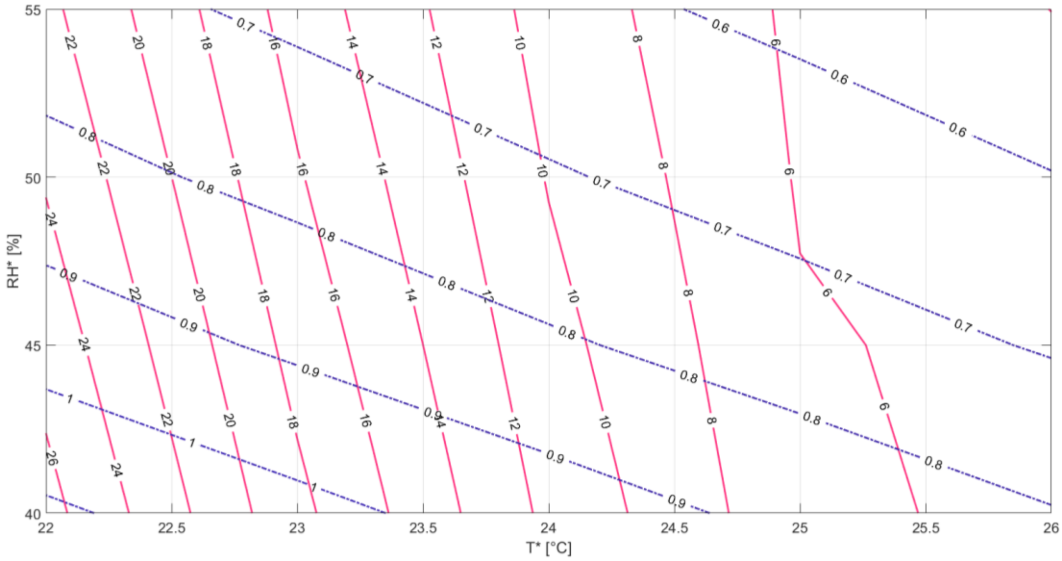


Figure 6. Integrated maps representing iso-eLM (violet dash-dotted) and iso-PPD (magenta solid) curves (July simulation).*

In Figure 7, the results of the 20 dynamic simulations, in terms of the three objective functions, are presented. In particular, artwork preservation index and energy savings index (Φ_C and Φ_A) are represented on the x- and y-axis, respectively. Each round marker represents the results of a dynamic simulation. The filling color of each marker represents the value of the human thermal comfort index, i.e. Φ_B, where the corresponding color bar is shown on the right: the whiter the filling color, the lower is the dissatisfied people percentage value. Using the PPD-weighted criterion, the found Φ_B values correspond in an almost linear correlation to a range going from a minimum of 0 to a maximum of 1100. The label of each marker shows the PPD* value, and in brackets the temperature and relative humidity setpoints for the simulation. The black solid line connects all the markers lying on the Pareto front. The unconnected points are dominated solutions. All the Pareto points (with the exception of point #19, with temperature and relative humidity respectively 26 °C and 50%) optimize the problem minimizing Φ_A and maximizing Φ_C. Point #19, instead, represents an additional Pareto point which minimizes the Φ_B-objective.

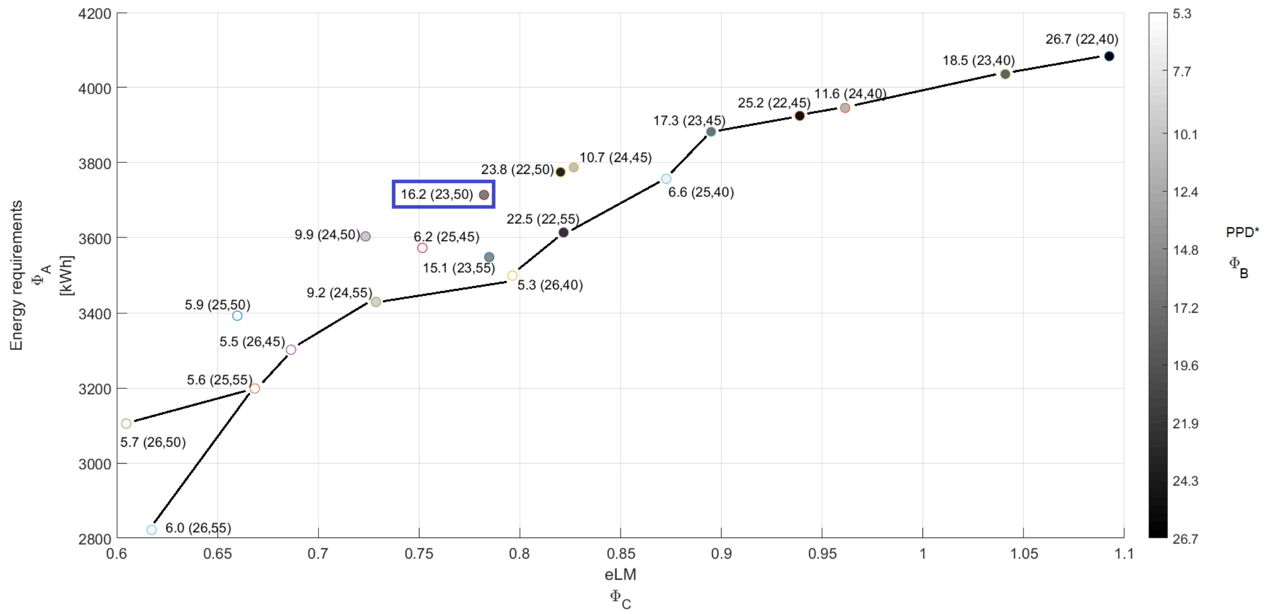


Figure 7: Representation of the multi-objective analysis results for July, varying temperature and relative humidity setpoints (in brackets for each marker). The number outside brackets represents the PPD value. The black solid line represents the Pareto front. The blue rectangle highlights the currently used hygrothermal setpoints* [39].

The results of the simulations show that it is not possible to achieve concurrently an improvement of the three objective functions: in particular, human thermal comfort and energy savings can be achieved with higher temperature setpoints, while artwork preservation needs lower indoor temperature and relative humidity values. In this case, museum stakeholders and energy managers should decide which objective is more important to optimize. For example, Figure 7 highlights that, if energy saving is the main focus, higher savings can be obtained with higher hygrothermal setpoints. In summer, a temperature setpoint of 23 °C and a relative humidity of 50% are often used, according to technical standard UNI 10829 [39]: this point is highlighted in Figure 7 with a blue rectangle. In this case, energy savings up to 24% are possible using a temperature setpoint equal to 26 °C and a relative humidity equal to 55%, with a reduction of energy requirements from 3.7 MWh to 2.8 MWh. With these setpoints, PPD* is also improved, but eLM decreases.

Applying the proposed methodology, appropriate setpoints can be identified even for concurrently improving all the three objective indexes with respect to the existing conditions. The latter are commonly chosen according to “rules of thumb” or technical standards. As mentioned, we consider, as reference case for the summer period, point #7 of Table 5, with setpoints 23 °C and 50% for temperature and relative humidity, respectively. The maintenance of these setpoints in the analyzed rooms leads to: i) a PPD* index (named PPD^*_{ref}) of 16.2 % (PPD-weighted criterion: 677), ii) an eLM index (named eLM_{ref}) of 0.78; iii) an energy requirement (named Q_{ref}) of 3.7 MWh. We consider the possibility of changing these setpoints, verifying if there is room for concurrent improvement of the three objectives. Three comparison indexes are evaluated (*i* is the simulation ID in Table 5):

$$\delta_{PPD^*}(i) = \frac{PPD^*_{ref} - PPD^*(i)}{PPD^*_{ref}} \text{ [\%]} \qquad \text{(Eq. 11.a)}$$

$$\delta_{eLM}(i) = \frac{eLM(i) - eLM_{ref}}{eLM_{ref}} \text{ [\%]} \qquad \text{(Eq. 11.b)}$$

$$\delta_{en}(i) = \frac{Q_{ref} - Q(i)}{Q_{ref}} \text{ [\%]} \qquad \text{(Eq. 11.c)}$$

For all the three comparison indexes, a positive value means an improvement of the corresponding objective, hence a higher thermal comfort, a higher equivalent lifetime, and a higher energy saving with respect to the reference case.

Figure 8 shows the iso-lines for the three comparison indexes, varying temperature and relative humidity setpoints. The black solid lines represent the energy savings with respect to the reference case ($iso-\delta_{en}$). The red dotted lines represent the microclimate improvement for artwork preservation ($iso-\delta_{eLM}$); the blue dash-dot line represent the human thermal comfort improvement ($iso-\delta_{PPD^*}$). Reference point at 23°C/50% setpoints is also highlighted.

In Figure 8, the yellow area highlights the setpoints range which leads to an improvement of all the indexes:

- an improvement between 40 and 60% of the human thermal comfort;
- an improvement of the equivalent lifetime multiplier between 0 and 10%;
- an improvement of energy efficiency between 0 and 5%.

In terms of the PPD-weighted criterion, the use of the new setpoints are related to the minimum values of this indicator (from 0 to 150).

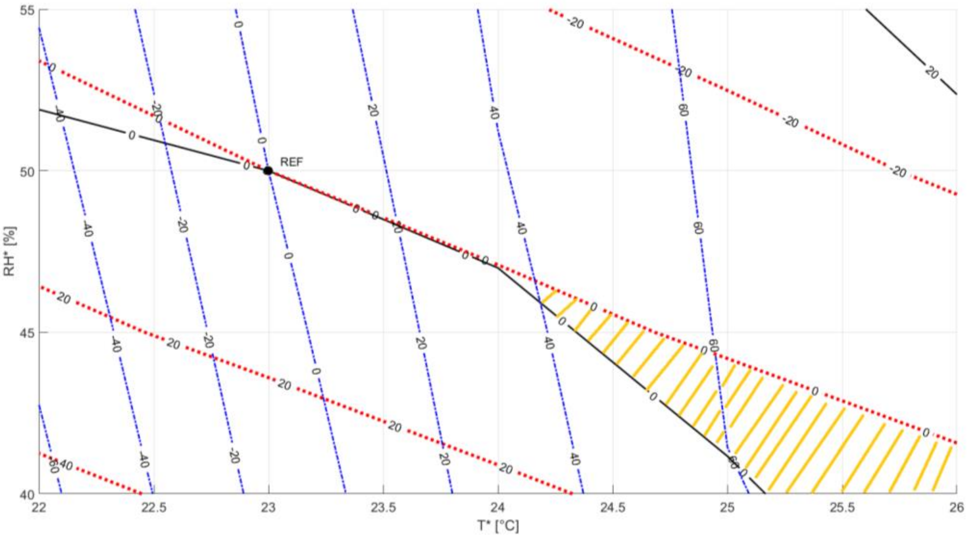
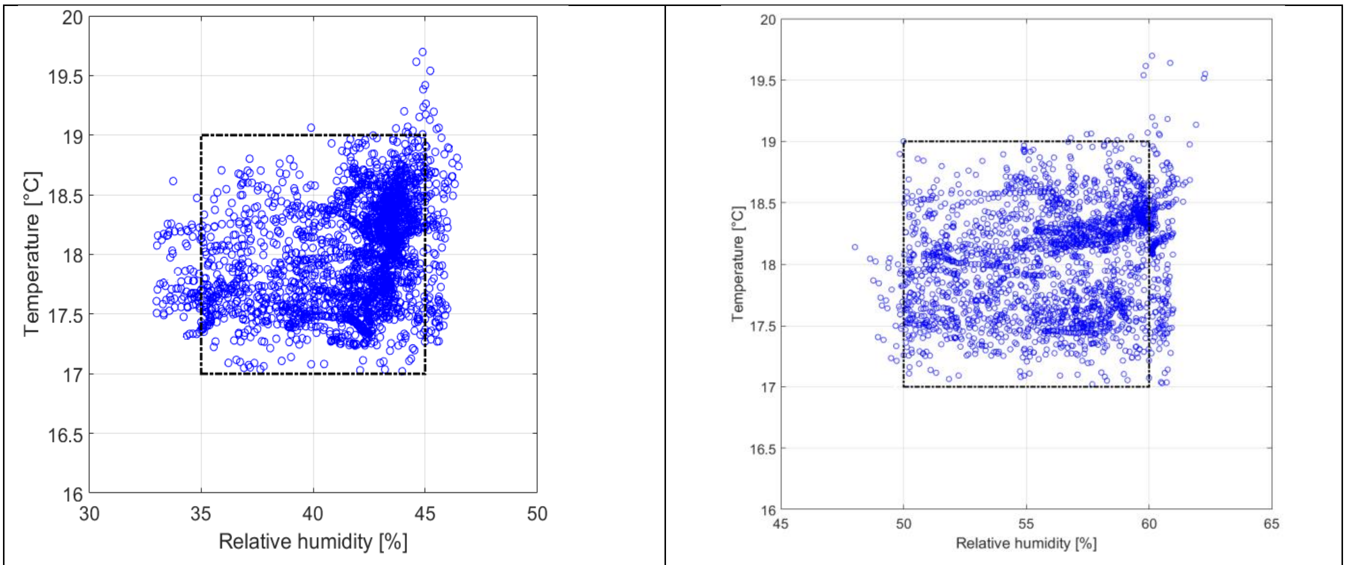


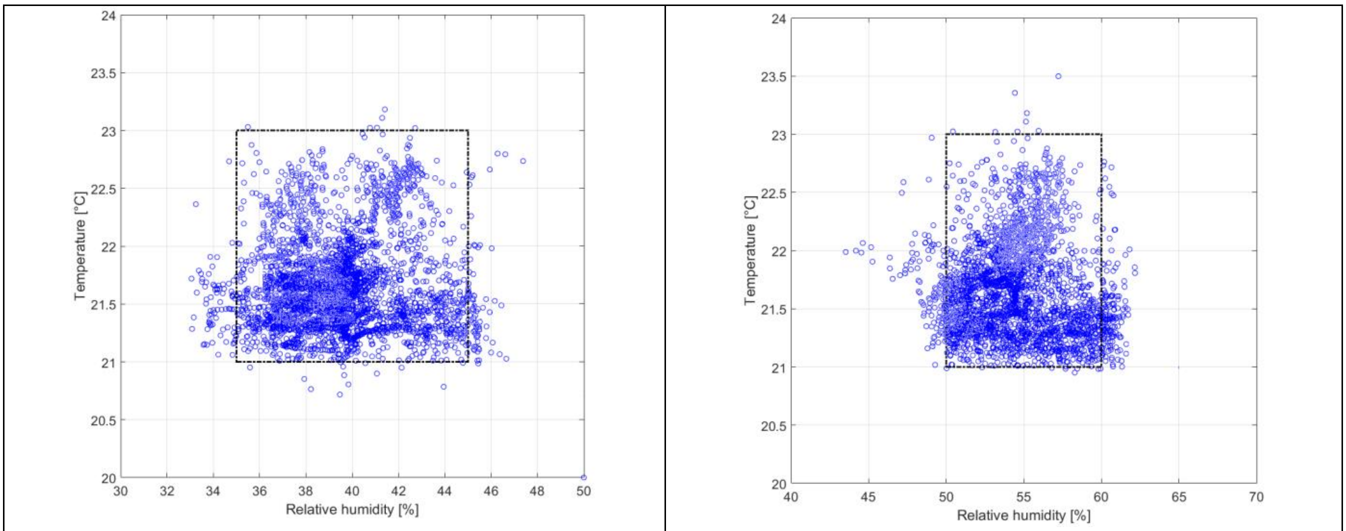
Figure 8: Possibility of improvement of three objectives with respect to a reference case, in July. The "REF" point represents the current used setpoint in summer. Red dotted lines refer to eLM improvements, blue dash-dotted lines refer to PPD improvements, and black solid lines refer to energy improvements.*

4.2 January simulations

For each of the 20 winter simulations, results show an accurate maintenance of the chosen setpoints in the rooms. Figure 9 reports the hygrothermal conditions for the four most challenging simulations, i.e. #1-w, #4-w, #17-w, #20-w.



(a) **(b)**



(c) (d)

Figure 9: Hygrothermal conditions in the exhibition rooms for four reference simulations in January. In particular, (a), (b), (c), and (d) show results of simulation #1-w, #4-w, #17-w, and #20-w, respectively.

This second set of simulations shows that microclimate for artwork preservation is in contrast with human thermal comfort. In fact, artworks would prefer low temperature and relative humidity to increase lifetime; energy requirements would decrease if temperature setpoint decreases. On the contrary, people would prefer higher air temperature setpoints, as wall mean radiant temperature is low (the envelope is not insulated, due to architectural constraints). Figure 10 shows the results of the 20 simulations in terms of eLM (x-axis) and PPD* (y-axis). Using the PPD-weighted criterion, the found Φ_B values correspond, again in an almost linear correlation, to a range going from a minimum of 0 to a maximum of 800. The markers color identifies the energy requirements: the whiter the filling color, the lower the energy requirements. Figure 9 shows that simulations with the lowest PPD are those with the highest energy requirements (more than 3,300 kWh in January). Furthermore, the representation of a Pareto front in this Figure is graphically complicated, as eLM improves from left to right, PPD* from top to bottom, and energy savings increase moving towards the upper central part of the Figure. There is only a point which is not a Pareto solution: it is highlighted in the figure with a dashed red line and a rhomboidal marker. All the other solutions are included in the 3D Pareto frontier.

In analogy with the previous case, we have considered a reference case, with setpoints suggested by UNI 10829. In the winter period, the reference setpoints are 20 °C and 50% for temperature and relative humidity, respectively: this point is highlighted with a blue rectangle in Figure 10. These setpoints correspond to: i) a PPD* index (named PPD^*_{ref}) of 19.0 % (PPD-weighted criterion: 487), ii) an eLM index (named eLM_{ref}) of 1.24; iii) an energy requirement (named Q_{ref}) of 2,490 kWh. As in the July simulation, Figure 10 helps in the identification of the setpoints for the improvement of a single parameter: for example, if the main objective is the energy saving, one can use 18 °C and 45% as setpoints, with a reduction of about 28% of energy requirements (from 2.5 MWh to 1.8 MWh). However, here we want to verify, as in the previous case, if there is room for improvement for all the three objectives, using the same indexes of Equations 11.a, 11.b and 11.c (a positive value of each index means an improvement of the corresponding objective). Figure 11 shows the iso-lines of the three comparative indexes (red dotted lines refer to eLM objective, blue dash-dotted lines refer to PPD* objective, and black solid lines refer to energy objective). The Figure shows that it is possible to improve the three objectives only if microclimate setpoints are chosen in the orange-highlighted area: in this case, eLM can improve up to 30%, while human thermal comfort and energy requirements can improve up to 5%. A lower improvement percentage (2%) is found in terms of the PPD-weighted criterion.

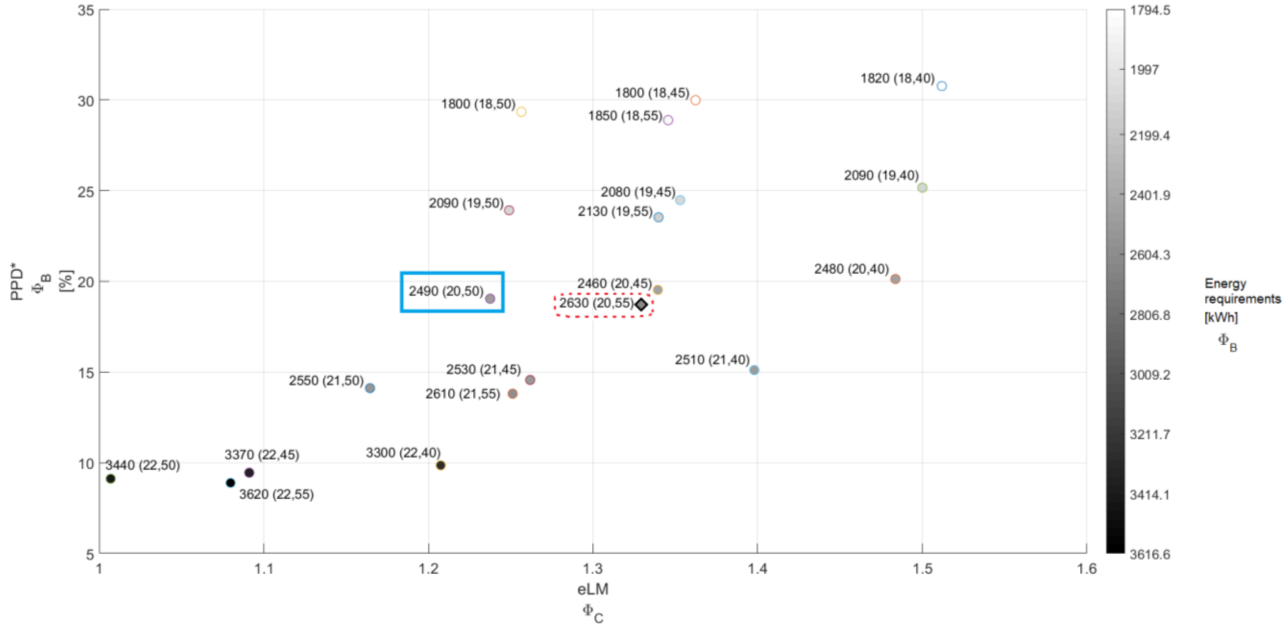


Figure 10: Representation of the multi-objective analysis results for January, varying temperature and relative humidity setpoints (in brackets for each marker). The number outside brackets represents the monthly energy requirements. The blue rectangle highlights the currently used hygrothermal setpoints, according to [39].

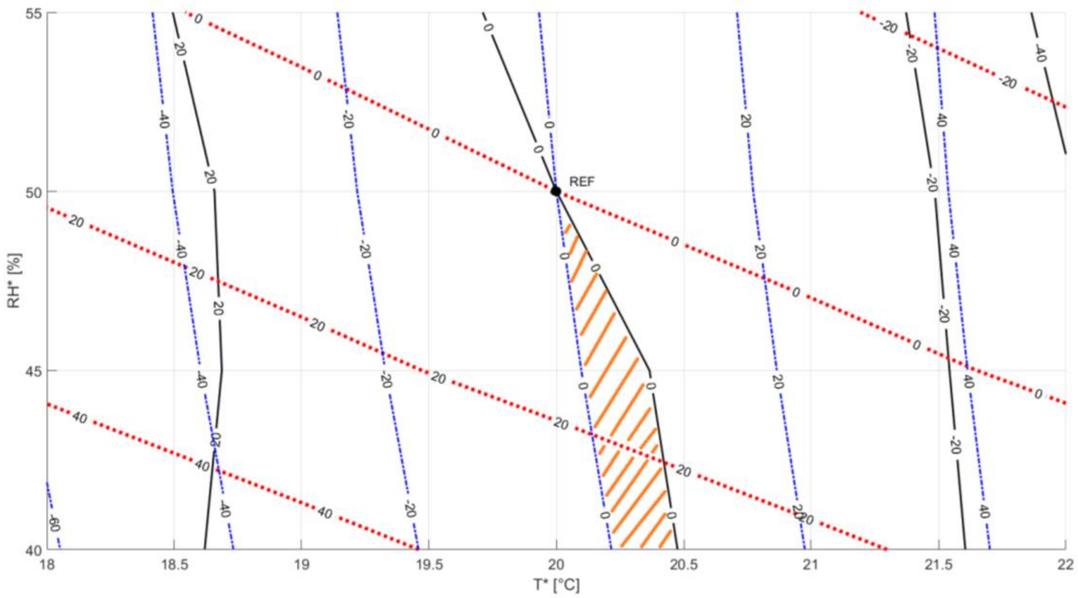


Figure 11: Possibility of improvement of three objectives with respect to a reference case, in January. The "REF" point represents the current used setpoint in winter. Red dotted lines refer to eLM improvements, blue dash-dotted lines refer to PPD improvements, and black solid lines refer to energy improvements.*

5. Conclusions

Museums are typical environments where a multi-objective optimization approach can be applied: the heritage significance and the artistic and cultural importance of artworks drive the attention on preservation issues, while climate change makes the matter of energy efficiency particularly urgent; furthermore, museum stakeholders are interested in the maintenance of a comfortable environment for their visitors, for a positive experience in the museum. The challenge is to find the most efficient strategy to optimize all these three targets under specific constraints.

In this paper, we have studied the choice of hygrothermal setpoints as an effective and costless way to solve the multi-objective optimization problem in museums hosted in historic buildings, where typical refurbishment actions (e.g., envelope insulation, use of renewable energy sources) are not allowed due to architectural constraints or economical unfeasibility. The choice of setpoints influences artwork preservation, human thermal comfort, and energy requirements. These goals are often contrasting, so it is necessary to analyze in depth each case, using dynamic simulations. To the best of the authors' knowledge, the concurrent optimization of these three major objectives was never tackled in literature by means of a comprehensive mathematical formulation. Besides, handy maps and simple indexes are provided, easy to use by curators and HVAC system managers, to identify the most appropriate setpoints, based on their specific requests.

More specifically, in the proposed case study, the simulation of 20 different hygrothermal setpoints for summer and other 20 simulations for winter have highlighted that it is possible to find a Pareto-front of optimal solutions, which reduce conservation risks (maximization of equivalent life time multiplier), human discomfort (minimization of predicted percentage of dissatisfied) or energy requirements. Decision makers can choose among the Pareto-optimal setpoints.

Using, as a reference, typical setpoints used in exhibition rooms with panel paintings (i.e. 23°C/50% in summer, 20°C/50% in winter for temperature and relative humidity, respectively), we have shown that all the three objectives can be improved with appropriate setpoints. In particular, in summer, higher temperatures and lower relative humidity are preferable, while in winter, the temperature setpoint is almost adequate, but the relative humidity setpoint should be decreased. The application of the procedure to a case study has also highlighted its handiness in a real application.

Future works will focus on the application of this procedure also in new energy-efficient museums, where the control strategies can be optimized together with the design of hybrid HVAC systems, also using renewable energy sources.

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