Application of different methodologies for artwork risk assessment and reduction: simulation of a museum room with a validated dynamic model

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Abstract. Temperature and relative humidity are two parameters that can hugely hamper artwork preservation, leading to different types of degradation. In scientific literature and regulatory guidelines, two methodologies are used to assess suitable conditions for artifacts and potential risks. These two methods are generally alternatively applied, missing a comprehensive evaluation of indoor suitability of artwork preservation. The concurrent application of both approaches can help in the choice of the best strategy or design of HVAC systems to improve microclimate to artwork preservation. In this work, a validated dynamic model of a room in an Italian museum is presented as a case study. The analysis of indoor temperature and relative humidity profiles for a typical winter and summer period shows the importance of the application of both methodologies to identify potential risks for artworks. Thus, for both periods, new strategies improving indoor microclimate and leading to a most suitable environment for artwork are tested and successfully identified.

1. Introduction
In the choice of heating, ventilation and air-conditioning (HVAC) system operation and management, in museum environments, the microclimate setpoints are chosen considering the exposed artifacts, which need the maintenance of specific values to avoid damage. Temperature and relative humidity, in fact, have been found to be two of the most sensitive variables that can interfere with artworks integrity [1, 2, 3]. Several works report the cases of artworks being damaged by incorrect values of temperature or relative humidity, or huge variations of these parameters on daily or seasonal scale [4, 5].

To verify if indoor microclimate is suitable, two methodologies can be applied: the first one assesses microclimate impact on artworks on the basis of specific models (e.g.,
biological or chemical mechanisms), involving particular mechanisms, and is typical of scientific literature [6, 7], whereas the second, more common in regulatory approach (for example, the Italian Standard UNI 10829 [8]), suggests the maintenance of constant and homogeneous microclimate inside museum rooms to reduce risks, as confirmed by [9, 10].

Nevertheless, in literature, these two methods are alternatively applied, and a comprehensive evaluation of the microclimate suitability, based on both analyses, is missing. In a recent study on historic libraries, the importance of the harmonization of both methods has been highlighted, showing that only the analysis of the microclimate through both approaches provides a thorough outline of risks for books [11, 12]. The present work shows that, also in the case of museums, the application of both methods provides an improved identification of possible criticalities. Thus, the most suitable HVAC system control can be chosen after a complete analysis of the indoor microclimate, verifying if current setpoints are suitable for preservation and eventually seeking new strategies to improve the indoor conditions.

The work is structured as follows: in Section 2, the two methodologies are discussed. In Section 3, a case study is presented: a museum in Pisa, Italy, where important artworks are periodically exposed. The case study is simulated through a validated dynamic model to obtain indoor hygrothermal values in current conditions. The analysis of those microclimate data for a typical winter and summer period permits to check if possible risks for artworks are present (Section 4). The current HVAC control and management is then changed in the dynamic simulation to verify the improvement of performance indexes, in Section 5. Section 6 presents the concluding remarks.

2. Methodology

Literature reports two methods for the assessment of temperature and relative humidity suitability in museum rooms. On one hand, the analysis of microclimate through the risk assessment method highlights possible biological and chemical damages. On the other hand, the microclimate method provides typical range of temperature and relative humidity variation to be maintained inside museum environment, considering that also temporal microclimate span can cause damage; thus, only low variation of the two hygrothermal parameters are allowed.

2.1. Risk assessment method: biological damage

Biological degradation is due to high values of relative humidity, causing microbial and mold growth on the superficial layers of the artwork [13]. Spore growth is responsible for the embrittlement and destruction of the materials and substrates where they are reproducing [1]. Isopleth curves are proposed in literature as a graphical way to check if indoor conditions can potentially leading to spore germination or can be associated to specific mold growth rates. This model is known as Sedlbauer model [14] and is reported in several guidelines and scientific works [15, 16]. To verify if, in a certain period of experimental measurement or dynamic simulation, indoor conditions leading to spore germination can occur, biological risk index \((BRI)\) is defined [11], as the percentage of time in which the lowest isopleth curve for the spore germination is overpassed. As museum rooms indoor conditions are usually controlled through HVAC system, the probability of having mold growth conditions should be very low.
2.2. Risk assessment method: chemical damage
A model to assess the risks of chemical damage is provided by Michalski [17], which correlates the indoor microclimate values (in terms of temperature and relative humidity) with a multiplier of the artwork lifetime. Typical values for the lifetime of paper are, for example, 500 years [18]. A resulting multiplier lower than 1 hints a reduced lifetime of the artwork, so chemical risks are possible. The Michalski model provides, for each timestep $i$ of the monitoring campaign or of a dynamic simulation of the museum, a value of the lifetime multiplier, $LM_i$:

$$LM_i = \left(\frac{50\%}{RH_i}\right)^{1.3} e^{\frac{E_a}{R}\left(\frac{3}{T_i + 273.15} - \frac{1}{293.15}\right)}$$

where $RH_i$ and $T_i$ represent the indoor conditions of relative humidity and temperature, $E_a$ the activation energy, and $R$ the gas constant ($8.314\text{ J mol}^{-1}\text{K}^{-1}$). The typical value for the activation energy for paper is $100\text{ kJ mol}^{-1}$.

The global value of the lifetime multiplier on a period of measurement or simulation is evaluated considering the several values of $LM_i$, depending on the instantaneous values of temperature and relative humidity, and giving more importance to the indoor conditions resulting harmful for artworks [6]:

$$eLM = \frac{1}{N\sum_{i=1}^{N} \frac{1}{LM_i(T_i, RH_i)}}$$

where $N$ is the total gathered values of climatic conditions. A suitable value of $eLM$ should be equal to 1.

2.3. Microclimate method: daily variation of indoor microclimate
In addition to biological and chemical damage, some artworks result sensitive to short-term and long-term variation of indoor conditions, leading to cycles of shrinkage and expansions, causing weakening of the materials and even cracks. The reduction of the artwork damage risk due to hygrothermal variations, in scientific literature and guidelines, is usually addressed through the suggestion of maximum values for daily span of temperature and relative humidity. For example, ASHRAE museums classification [19] suggests a daily temperature variation of $2K$ and a relative humidity variation between 5 and 10%, to reduce risks. In [20], a daily span index ($DSI$) is proposed, which represents the percentage of days, in a period of measurement or simulation, where microclimate conditions do not exceed the threshold limits. Thus, a $DSI$ equal to 1 hints a suitable indoor environment for artworks preservation purposes. In the present work, a maximum relative humidity variation of 8% is considered.

3. Description of the case study
A case study is presented to show the potential of the harmonization of the two approaches presented in Section 2. The analyzed museum is located in Pisa, Italy, periodically hosting prints, drawings and paper artworks exhibitions. Hereafter, one of the museum rooms is considered, where the most important artworks are exposed, as already studied in [21]. The characteristics of this room, in terms of envelope materials
and HVAC system, are reported in Table 1. In particular, the HVAC system includes fancoils, which heat and cool the room, and an air handling unit (AHU), providing fresh air (at the same setpoint temperature of the room) and controlling indoor humidity. Both fancoils and AHU are connected to a single reversible heat pump. Thus, during winter, the AHU cooling coils cannot be used, as the heat pump is operated in heating mode. During summer, instead, both cooling and reheat coils can be used, as the heat pump is operated in cooling mode and can recover heat at the desuperheater.

Table 1: Characteristics of the museum room used as case study.

| Characteristic                                      | Value                              |
|----------------------------------------------------|------------------------------------|
| Area                                               | 100 m²                             |
| Volume                                             | 400 m³                             |
| Average thermal transmittance of external vertical walls | 0.9 W/m²K                          |
| Average thermal transmittance of roof              | 0.7 W/m²K                          |
| HVAC system operation hours                        | 8 a.m.-9 p.m., every day           |
| Temperature setpoint & deadband (winter)           | 20 ± 1 ºC                          |
| Temperature setpoint & deadband (summer)           | 24 ± 1 ºC                          |
| Relative humidity setpoint & deadband (winter)     | 45 ± 5%                            |
| Relative humidity setpoint & deadband (summer)     | 50 ± 5%                            |
| Air flow rate at air handling unit (constant value) | 5 m³/h                             |

The museum room was modeled in TRNSYS 17 (for the envelope modeling [22]), and MATLAB (for the HVAC system). The dynamic model was validated comparing the simulated temperature and relative humidity profiles with those resulting from a monitoring campaign [20]. Also the MATLAB model of the air handling unit was validated, using the supply specific humidity and return water temperature as validating parameters [23].

In this work, the dynamic model of the building is used to simulated two reference periods: two weeks of January (from January, 9th to January, 23rd) and two weeks of July (from July, 7th to July, 21st). External climate for the two periods is taken from [24], which reports the typical meteorological year for the city of Pisa. Visitors’ profile inside the room are taken from [25].

4. Analysis of the microclimate results in the current conditions
The results of the dynamic simulation are profiles of temperature and relative humidity for the two reference periods. In Figure 1a, the output profiles of temperature (blue line) and relative humidity (red line) for the two winter reference weeks are shown: it is highlighted that, during nighttime, the intermittent HVAC operation causes temperature decrease and relative humidity increase; in some cases, relative humidity increase is found also around midday, in correspondence of visitors’ presence peaks. Figure 1b represents
the profiles of temperature and relative humidity for the two summer reference weeks. In this case, both microclimate parameters are found to be more constant during day, and their profiles are not particularly influenced by the HVAC turning off on nights.

The application of the two approaches in the analysis of the dynamic simulation results for the two reference periods reveals that possible risky situations could occur. In particular, the HVAC system, turning daily on and off, causes huge short-term variation of temperature and relative humidity. Even if, during HVAC operation, temperature and relative humidity are allowed to vary in narrow ranges (see Table 1), microclimate undergoes strong variations during nights. Furthermore, as the air handling unit cannot provide dehumidified air in winter, values of relative humidity higher of the allowed setpoint are reached also during opening hours. The corresponding DSI value represents thus a criticality in winter. In summer, instead, the possibility of cooling and dehumidifying air allows to maintain more constant values of temperature and relative humidity also in case of huge presence of visitors. The higher value of the temperature setpoint, however, represents a possible risk for chemical damage of artworks, as eLM is found equal to 0.55. In both the analyzed periods, no biological risks were found. In Table 2, the results of the microclimate analysis for the two periods are reported, in terms of maximum and minimum indoor temperature and relative humidity and performance indexes.

The comprehensive analysis reports that: (i) current HVAC operation is suitable to avoid biological degradation; (ii) during winter, possible risks can occur, caused by short-term variation in temperature and relative humidity, due to HVAC turning off on nights and lacking of cooled and dehumidified air; and (iii) during summer, possible chemical risks can occur, due to high temperature setpoint.

### Table 2: Microclimate analysis results in the current state. Optimal value for BRI: 0%; optimal value for DSI: 100%; optimal value for eLM: ≥ 1.

|       | T set [°C] | RH set [%] | Min. Min. | Max. Max. | BRI [%] | DSI [%] | eLM [-] |
|-------|------------|------------|-----------|-----------|---------|---------|--------|
| Winter| 20         | 45         | 17.4 21.0 | 66.4 43.8 | 0       | 0       | 1.06   |
| Summer| 24         | 55         | 23.1 24.6 | 56.3 49.4 | 0       | 100     | 0.55   |

5. **Change of the HVAC system management and design**

In this Section, the findings of the previous analysis are used to simulate different HVAC system controls and design and then reduce risks.

5.1. **Winter analysis**

The main criticality found in winter analysis is the short-term variations of indoor temperature and relative humidity. Four possible solutions are analyzed to improve this...
Figure 1: Profiles of indoor air temperature and relative humidity in two reference weeks (museum in current state).

5.2. Summer analysis
To improve the chemical index in summer, two solutions are analyzed: (i) maintain HVAC turned on also during nights, with a temperature setpoint of 22°C, and a relative humidity setpoint of 50% (deadband: ±5%); and (ii) HVAC turned on during nights, a reduced temperature setpoint (22°C) and a reduced relative humidity setpoint equal to 45% (deadband: ±5%). The case (ii) has been tested as solution (i) does not reach sufficient high values of $eLM$, and lower temperature setpoints are discouraged for
Table 3: Microclimate analysis results for winter period, considering four possible improving solutions. Optimal value for BRI: 0%; optimal value for DSI: 100%; optimal value for eLM: ≥ 1

| Solution | Min. obt. T [°C] | Max. obt. T [°C] | Min. obt. RH [%] | Max. obt. RH [%] | BRI [%] | DSI [%] | eLM [-] |
|----------|------------------|------------------|------------------|------------------|---------|---------|--------|
| current  | 17.4             | 21.0             | 43.8             | 66.4             | 0       | 0       | 1.06   |
| (i)      | 18.8             | 20.5             | 44.7             | 60.0             | 0       | 79      | 1.18   |
| (ii)     | 18.9             | 21.2             | 44.7             | 58.2             | 0       | 71      | 1.11   |
| (iii)    | 18.8             | 20.1             | 44.7             | 61.6             | 0       | 79      | 1.19   |
| (iv)     | 19.3             | 21.6             | 45.0             | 49.7             | 0       | 93      | 1.06   |

visitors’ comfort. Thus, to further increase the $eLM$ parameter, the effect of a further reduction of relative humidity has been tested. Results are presented in Table 4 and show that only reducing both relative humidity and temperature allows to have an $eLM$ approximately equal to 1. Figure 2b shows the profiles of temperature and relative humidity resulting as output of simulating solution (ii).

Table 4: Microclimate analysis results for summer period, considering two possible improving solutions. Optimal value for BRI: 0%; optimal value for DSI: 100%; optimal value for eLM: ≥ 1

| Solution | Min. obt. T [°C] | Max. obt. T [°C] | Min. obt. RH [%] | Max. obt. RH [%] | BRI [%] | DSI [%] | eLM [-] |
|----------|------------------|------------------|------------------|------------------|---------|---------|--------|
| current  | 23.1             | 24.6             | 49.4             | 56.3             | 0       | 100     | 0.55   |
| (i)      | 21.9             | 23.3             | 45.9             | 55.1             | 0       | 100     | 0.73   |
| (ii)     | 21.9             | 23.3             | 40.0             | 48.3             | 0       | 100     | 0.96   |

6. Conclusions

In this paper, the importance of a concurrent application of both microclimate approach and risk assessment method is discussed as a way to provide a complete evaluation of current microclimate suitability in museum rooms and propose most suitable HVAC system control and/or design. The application of both procedures in the analyzed case study has highlighted possible criticalities in the two periods, which can be solved through a tailored HVAC system management. In this way, the performance indexes are improved. Possible future works will focus on the concurrent optimization of microclimate suitability for artworks and energy efficiency.
Figure 2: Profiles of indoor air temperature and relative humidity after the change of HVAC system management and design.

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