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Multi-objective optimization of microclimate in museums for concurrent reduction of energy needs, visitors' discomfort and artwork preservation risks

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HIGHLIGHTS

- A methodology for a multi-objective optimization in museums is presented.
- Artwork preservation, energy efficiency, and human comfort are considered as goals.
- The optimization provides hygrothermal setpoints for HVAC systems.
- This strategy is useful in historic building museums and it is costless.
- New setpoints can replace currently-used ones and improve all the targets.

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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.

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

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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 Fig. 1, where a schematic representation of a museum exhibition room is shown. The energy balance equation of the room reads:

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

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

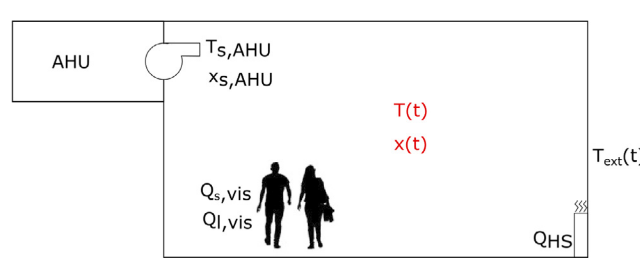

Fig. 1. Schematic representation of the thermo-hygrometric balance of a museum exhibition room.