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Influence of human behavior on cool roof effect for summer cooling

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ABSTRACT

Cool roofs represent an acknowledged solution for cooling energy saving. However, the efficacy of such physical intervention can be affected by occupants' attitudes. Human behavior, in fact, is often neglected or underestimated at the design stage, e.g. while assessing the effect of physical retrofits. Accordingly, the purpose of this study is the assessment of cool roof effect with varying those occupants' attitudes having some effect on energy need for cooling and indoor Thermal Deviation Index (TDI). The analysis has been performed through calibrated dynamic simulation of a continuously monitored historic building. Innovative cool roof clay tiles, suitable for application in historic buildings, have been selected as physical retrofit. Main findings show that occupants' role can dominate the thermal-energy effect of the selected physical retrofit. For instance, cool roof tiles contribute to save 50% of primary energy for attic cooling in the hottest month, from 782 kWh to 398 kWh. If occupants' adaptation availability in adjusting temperature setups is taken into account in combination of the cool roof effect, the energy need for cooling becomes less than 100 kWh. Also, the same cool tile is able to reduce the TDI from 0.87 to 0.54. If occupants are able to implement effective natural ventilation programs, TDI decreases to 0.29. These results show the necessity to consider neither only the effect of physical retrofits, nor only the effect of human attitudes, but the combination of both of them, in order to perform reliable energy need estimation, in both ante and post-occupancy assessment.

1. Introduction

Considering the Fifth Report by Intergovernmental Panel on Climate Change (IPCC) [1] and the Energy Performance Building Directive (EPBD 2010/31/EU) [2], effective strategies for energy efficiency in the building sector represent a primary economic and environmental goal. In Italian context, buildings' energy consumption corresponds to more than 40% of the total energy requirement [3]. Therefore, an enormous potential in terms of Green House Gasses emissions reduction could result from improving energy efficiency of buildings. Given the huge growing trend of households' energy requirement for cooling [4], large energy reduction could be achieved by controlling the energy performance of buildings in summer conditions. An acknowledged effective passive strategy for reducing air conditioning requirement in buildings is represented by cool roofs [5]. In fact, their main properties consist of high solar reflectance and high thermal emittance and, therefore, they are able to absorb less solar radiation, with the subsequent reduction of roof overheating and indoor solar gain through the roof [3,6]. Accordingly, the threefold benefit of cool roofs consists of (i) reducing building energy requirement for cooling [7,8], (ii) mitigating urban heat island effect [9–11], and (iii) contributing to global warming delay [12,13]. Although cool roofs present immediate and long-term potentialities and competitive cost-benefit balance, their application is mainly limited to flat roofs of new or non-historic buildings, also for cheaper and simpler installation effort [14]. However, given the recently increased building energy demand for cooling in Italy, improving the huge amount of cultural heritage buildings in dense urban ancient centers could represent a key issue to address for the national energy use reduction. Historic buildings, in fact, are also those buildings which are considered difficult to characterize in terms of physical properties and to improve in terms of energy efficiency, due to architectural and environmental preservation measures and the lack of knowledge of technical details about the construction [15]. In this perspective, several researches aimed at elaborating new solutions for energy saving characterized by a low visual impact, in order to be suitable for application in historic buildings subject to architectural and local policy constraints. In particular, focusing on roof applications, cool coatings with similar visual appearance to the traditional ones for application in historic

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contexts were developed [16,17]. Since in Italy roof covering generally involves clay tiles, the key focus was directed toward the development of cool clay tiles with traditional visual appearance, in order to be accepted by the local regulation [15,16,18].

In the same context of energy efficiency strategies, a further direction of research investigation consisted of the development of increasingly sophisticated dynamic simulation tools, with the purpose to properly predict the efficacy of active and passive physical improvements [19]. In historic buildings particularly, the high variability of various parameters affecting the reliability of the simulation model, could cause non-negligible discrepancies between simulated and real data. Therefore, dynamic simulation models require a preliminary calibration and validation based on continuously monitored data [20]. Various calibration procedures have been proposed by previous works, based on the indications of ASHRAE's guideline 14-2002 [21], using energy consumption data as control variables [22], and indoor temperatures measures [20]. Nevertheless, sometimes large discrepancies between simulated and measured end-use energy performance of buildings occur [23]. One of the main reasons is imputable to peculiar occupants' behavior, which characterization is often neglected or underestimated in simulation models, where standard values are often the only values to be considered for describing occupancy [23]. However, human behavior and control systems are referred to be determinant of energy use in buildings [24]. In order to investigate this phenomenon, Fabi et al. [25] developed a sort of flowchart aimed at connecting physical drivers influencing occupants' attitudes and energy consumption, demonstrating the key role of (i) physical environmental factors, (ii) contextual factors, (iii) psychological factors, (iv) physiological factors and (v) social factors.

Therefore, the performance of sophisticated tools, such as dynamic thermal-energy simulation, and effective strategies, such as cool roofs, can be affected by a variety of occupants' actions driven by complex combined phenomena. Accordingly, several studies focused on the role of human attitudes on energy consumption and indoor environment in buildings. Considering occupants' control on natural ventilation, Iwashita and Akasaka [26] measured the ventilation rate in dwellings in Kagoshima City, in Japan, during occupied and non-occupied periods, finding an increase of 87% of the total air change rate due to occupant behavior. Roetzel et al. [23] investigated the influence of various parameters on the effectiveness of occupant controlled natural ventilation through window switching models. Fabi et al. [27], instead, presented a methodology for modelling energy-related human behavior based on medium/long-term monitoring of climate variables and occupant's control actions. The proposed procedure was then applied to simulate occupants' behavior related to window opening and closing on case study dwellings, determining probabilistic distributions of energy consumptions and air change rates for different real users' types. Another method for modelling households' behavior was presented by Johnson et al. [28] to simulate energy consumption by means of occupants' activities standardization gathered by the U.S. Census Bureau. Among several studies concerning the influence of occupancy on energy consumption, Guerra Santin et al. [29] compared the effect of occupancy and building characteristics on energy use for heating. The study showed that occupant behavior significantly affected energy use, by 4.2%, although lesser than building technical characteristics. Still studying the influence on heating consumption, Guerra Santin et al. [30] demonstrated that the number of usage hours for the heating system have a stronger effect on energy consumption than temperature settings. Yun and Steemers [31], instead, investigated the significance of behavioral parameters on cooling need, finding that occupant behavior, as a function of outdoor climate conditions, is the most significant issue. Similarly, Steemers and Yun [32] highlighted that occupancy is the second most important parameter affecting household energy consumption, after climate, which influences human behavior. Considering the achievability of what they named “human-based energy retrofits”, Pisello and Asdrubali [33], through theoretical–experimental modeling of a residential village, demonstrated that ordinary occupancy actions of energy waste reduction can produce an annual primary energy saving of 239 kWh/person in the case study village.

In this perspective, the purpose of this study is to analyze the effect of cool roof performance with varying different human attitudes, having some effects on the energy need and the efficiency of cool roof innovative solutions. Quantitative considerations about the role of each considered human-based parameter on the effectiveness of cool roofs have been carried out. Specific human behaviors have been selected based on the reviewed literature, as significant occupants' actions affecting building energy consumption.

The investigated human behavior effect has been assessed through calibrated dynamic simulation modelling. To this aim, the model of a continuously monitored case study historic building, located in the city center of Perugia, Italy, has been developed. Accordingly, a specific application of innovative cool clay tiles has been evaluated. These tiles were elaborated in previous researches [15] in order to be suitable for application in historic buildings [17].

The thermal-energy assessment of the influence of human attitudes is finally operated during summer in terms of primary energy requirement for cooling and indoor quality conditions expressed by means of Thermal Deviation Index theory [34].

2. Materials and methods

This research concerns the analysis of the correlation between effects of cool roofs and influence of human attitudes on indoor thermal conditions and energy demand for cooling. It prepares the ground from previous works concerning cool roof solutions and the effect of human behavior on the thermal-energy performance of buildings. The performance of a cool clay tile is here evaluated when compared to a traditional clay tile, with varying human attitudes. The tile has been selected based on reflectance capability, together with the possibility to apply such roof coating in historic buildings, according to the constraints imposed for the architectural preservation of the city of Perugia, Italy, where the case study building is located. A continuously monitored case study apartment with attic has been chosen, since it is mostly influenced by the roof layout. Therefore, the attic thermal-energy behavior of the case study building is studied in summer conditions, with a specific focus of the role of human behavior in determining the cool roof efficacy in the climate context of Perugia. The analysis has been carried out through calibrated dynamic simulation based on in-field continuous monitoring of indoor temperature in both the floors of the apartment. Finally, the validated model has been used to assess the effect of cool roof tiles with varying different occupants' behavior. Results have been compared in terms of Thermal Deviation Index (TDI), for *passive* behaviors, and primary energy demand for cooling, for *active* behaviors. Finally, a detailed sensitivity analysis is carried out in order to compare the effect of human behavior versus the effect of the optimization strategy.

2.1. Cool roof tiles analysis

The tiles considered in this research, which samples are depicted in Fig. 1, are two clay tiles coated with different techniques in order to vary their visual appearance and reflectance performance. Tiles were in-lab tested through spectrophotometer and emissometer and their performance was already analyzed in previous researches [15,17].