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Statistical analysis of the ranking capability of long-term thermal discomfort indices and their adoption in optimization processes to support building design

Salvatore Carlucci*, Lorenzo Pagliano, Andrea Sangalli

end-use Efficiency Research Group, Dipartimento di Energia, Politecnico di Milano, Via Lambruschini 4, 20156 Milano, Italy

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ABSTRACT

The scientific literature and some standards offer a number of long-term thermal discomfort indices and methods for predicting the likelihood of summer overheating in buildings. Such metrics can be useful tools for driving the optimization process of the design of new buildings, for the operational assessment of thermal comfort in existing buildings, or for optimizing the operation of building systems. Recently long-term discomfort indices are employed more and more often in mathematical optimization methods to support the design of buildings where thermal comfort is used as an objective function.

Focusing on the summer period, 16 long-term discomfort indices are applied for assessing a sample of different variants of a large office building. Such building variants are obtained by varying in discreet steps some key design parameters of the building envelope, such as steady-state transmittance of components, air permeability, solar factor of glazed units, thermal mass, and the natural ventilation strategy. The values of the 16 indices are compared and contrasted in subsets to identify similarities and differences in assessing the whole sample of building variants. The indices deliver significantly different results with deviations up to 70% with respect to the same building variant and identify diverse optimal-building variants. Accordingly, the choice of the long-term discomfort index has a strong impact on the outcome, and, therefore, this paper is intended to provide clarification on how to employ them in a reliable and conscious manner.

Finally, some of the analyzed indices have shown the capability to deliver a similar ranking even based on different comfort models.

1. Introduction

The scientific literature and the standards ISO 7730 [1] and EN 15251 [2] offer a few methods for the long-term evaluation of the general thermal comfort conditions and for predicting the likelihood of the summer overheating occurrences in a building. Such methods – generally indices that cumulate over time and space, in a variety of ways, a chosen hourly and local discomfort metric – are also used for comparing the effect on the indoor environment of alternative design strategies. Several authors have used long-term thermal discomfort metrics to assess and compare the thermal comfort performance of different design options without discussing the influence of the used metric on the outcomes, and whether the adoption of a different metric might have provided a different result. Thus, the first objective of this paper consists in comparing and contrasting the ranking capability of the long-term thermal discomfort indices identified in literature in order to ascertain if the differences in their values are due to the different design options or to an inherently different manner to estimate long-term discomfort. Moreover, EN 15251 guides designers towards a two-step optimization procedure, which is based on the sequential use of two long-term discomfort indices. The first is based on the European adaptive model [3] and should be used for the dimensioning of passive means in summer conditions. The second is based on the Fanger comfort model [4] and has to be used if the adaptive limits proposed in EN 15251 cannot be guaranteed by adopting only

Acronyms: ASHRAE, American Society of Heating Refrigerating and Air Conditioning Engineers; CEN, European Committee for Standardization; CIBSE, Chartered Institution of Building Services Engineers; DhC, Degree hour criterion; EN, European Standards; EU, European Union; ISO, International Organization for Standardization; IWEC, International Weather for Energy Calculations; LPD, Long-term percentage of dissatisfied; NaOR, Nicol et al.'s overheating risk; PMV, Predicted mean vote; POR, Percentage outside range; PPD, predicted percentage of dissatisfied; PPDwC, PPD-weighted criterion; RHOR, Robinson and Haldi's overheating risk; SCATs, European Project Smart Controls and Thermal Comfort; Sum_PPD, Accumulated PPD.

* Corresponding author. Tel.: +39 02 2399 3918; fax: +39 02 2399 3913.
E-mail address: salvatore.carlucci@polimi.it (S. Carlucci).

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passive means, and, hence, the installation of a mechanical cooling system is unavoidable for providing thermal comfort [2]. However, Pagliano and Zangheri [5] show that employing the indices proposed by EN 15251 in such two-step optimization procedure brings to discontinuities when switching from the index based on the adaptive model to the one based on the Fanger model, since the indices identify different optimal building variants. Thus, the second objective of this paper is to identify, at least, a suitable pair of long-term discomfort indices that provide a similar ranking (even with different values) of building variants using an adaptive model and the Fanger comfort model.

The analyses are numerically carried out by using a dynamic energy simulation engine, EnergyPlus [6], guided by a parameterization engine, JePlus [7]. The case study, on which the analyses are carried out, is a large office building. Four design variables regarding the building envelope and passive strategies, such as (i) envelope quality (expressed through the steady-state transmittance of envelope components and air permeability), (ii) solar factor of glazed units, (iii) thermal mass and (iv) type of natural ventilation strategy, are identified; two options are proposed for the envelope resistance to heat flows and air infiltration and three options for the remaining design parameters. By combining the above design options, 54 building variants have been derived. Focusing on the summer period, the 16 long-term discomfort indices reported in Ref. [8] are employed for assessing the comfort performance of the 54 different building variants.

2. Background

2.1. Current use of the long-term discomfort indices in literature

A long-term thermal discomfort index is a metric that summarizes in one value the thermal comfort performance inside a building, evaluated over a long period. A number of authors use methods and indices for assessing thermal comfort for comparing the performance of different design strategies or for improving the overall design of a new building.

Pane [9] measures the frequency of exceedance of the threshold temperatures of 25 °C and 27 °C for studying the relationship between thermal mass and summer overheating. Schnieders [10] uses the frequency of the overheating events for comparing several options of glazing units and for assessing summertime climate in a passive house; to support designers against summer overheating, the frequency of exceedance of the temperatures of 25 °C and 26 °C has been included in the software 'Passive house planning package' (PHPP), which is used for the design and validation of the German Passivhauses [11]. Grignon-Massé, Marchio [12] use one of the long-term discomfort indices introduced by ISO 7730 and called 'Percentage outside range' (POR) to assess the cooling performance of several building-envelope-retrofitting techniques and ventilation strategies in offices and commercial buildings. Also Rohdin, Molin [13] use POR, and represent it using the foot-print proposed in EN 15251, for assessing thermal comfort conditions in nine passive houses in Sweden as a consequence of the change of the set-point temperature. Hwang and Shu [14] use the PPD weighted criterion derived by ISO 7730 to quantify discomfort due to overheating between May 1 and September 30. Cappelletti, Prada [15] also adopted the PPD weighted criterion to assess long-term thermal discomfort conditions due to different glazing units in an open-space office under controlled indoor thermal conditions. Yao [16] assesses the effect of movable solar shading calculated in two scenarios with the building in free-floating mode by comparing the distribution of PMV votes. Borgeson and Brager [17] propose two long-term discomfort indices called $\text{Exceedance}_{\text{PPD}}$ and $\text{Exceedance}_{\text{Adaptive}}$ and use them to assess, through simulations, summer thermal discomfort caused in a reference free-floating building simulated in the 16 different climatic zones of California. Di Perna, Stazi [18] use the version of POR based on the European adaptive comfort model and introduced by EN 15251 to assess the summer reduction of thermal discomfort offered by an increase of thermal mass.

In the last years, long-term discomfort metrics have been used more and more often in mathematical optimization of buildings where thermal comfort is employed as an objective function of the optimization problem, or as a constraint or penalty function. Wang and Jin [19] use a sum weighted method to solve a multi-objective optimization problem and one of the objective functions is thermal discomfort defined as the square of the hourly simulated 'Predicted mean vote' (PMV), which was introduced in Ref. [4]. Kolokotsa, Stavrakakis [20] and Mossolly, Ghali [21] use the square of the difference between a threshold PMV set by the user and the hourly simulated PMV. Angelotti, Pagliano [22] use PMV to optimize the design of ground exchangers and night ventilation strategies. Nassif, Kajl [23], and Kummert and André [24] minimize the hourly simulated index called 'Predicted percentage of dissatisfied' (PPD), which was introduced in Refs. [4], for optimizing a HVAC control system strategy. Magnier and Haghighat [25] build an objective function multiplying the average PMV over the whole year and over all occupied zones by a function directly proportional to the number of hours when the absolute value of PMV is higher than 0.5. Corbin, Henze [26] use as an objective function the deviation from the actual PMV with respect to the PMV thresholds of ± 0.5, weighted by the floor area of every zone of the building. Emmerich, Hopfe [27] assess long-term thermal discomfort conditions in building counting the frequency of hourly exceedance of a threshold temperature fixed at 28 °C, and optimize a building by minimizing such long-term discomfort metric. Loonen, Trčka [28] use the same strategy but choose a temperature threshold fixed at 25 °C. Hoes, Hensen [29] minimize summer overheating and winter overcooling hours and, in order to ensure a minimal thermal comfort level, they set a constraint on the maximum number of discomfort hours fixed at 200 h. Stephan, Bastide [30] used POR and the 'Degree-hour criterion' (DhC) expressed in the EN 15251 version to optimize openings for night natural ventilation in order to activate the thermal mass and, hence, reduce diurnal thermal discomfort. An optimization procedure that adopts the 'Long-term Percentage of Dissatisfied' (LPD) to support the design of a net zero energy building located in a warm climate is proposed in Refs. [31,32]. Finally, besides energy and cost, a long-term metric based on thermal comfort has been used as the objective function in an optimization process [33,34]. Due to the large number of indices based on different assumptions found in the literature, Carlucci and Pagliano [8] collected and reviewed 16 long-term discomfort indices and grouped them into four families according to common features. This paper analyzes these 16 long-term discomfort indices and draws conclusions from their use for evaluating the long-term thermal comfort condition in a building model.

2.2. Comfort models and their applicability ranges

2.2.1. The Fanger model

The Fanger model was developed starting from studies carried out in controlled climate chambers [4]. The idea at the base of this comfort model is that thermal sensation felt by a person can be correlated to the heat balance of the human body under steady-state condition. According to this assumption, if total thermal power leaving the human body compensates the summation of power generated by and entering into it, a person is in a neutral state which corresponds to a theoretical comfort condition and is