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Comfort metrics for an integrated evaluation of buildings performance

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ABSTRACT

The capability of expressing all the different aspects of the building's performance, besides and beyond the mere energy behavior is becoming more and more important, because of the increased expectations related to either new construction or the renovation of existing buildings.

Even though building energy performance is one of the main aims of an appropriate design process or of a suitable management strategy during the operation phase, it can be strongly undermined by the underestimation of the role of the indoor environmental quality. Poor thermal or visual comfort not only *affects occupant satisfaction, well-being and productivity, but also induces actions and operations that* ultimately compromise the energy efficiency targets.

In order to support the design approach, including, since the very beginning, the comfort conditions among the design requisites, a set of metrics is proposed in this work, considering either time constancy or spatial uniformity of a single comfort aspect –or of different aspects at the same time. These metrics have been applied to a simulated reference environment, in order to test their ability to represent the performance of the envelope components when comparing building configurations characterized by high solar and daylighting gains and different window and shading configurations.

1. Introduction

The current trend towards high performance buildings, either new or renovated, driven by the energy efficiency policies entered into force in several countries and fostered by international institutions, such as the European Union through the Directives on the Energy Performance of Building [1,2], has strongly emphasized the building energy efficiency. Improved energy performance is pursued through enhanced insulation and air tightness levels of the opaque envelope, improved glazing and framing systems for windows components, and increased use of renewable energy sources and energetic materials. In combination with the larger transparent surfaces that characterize the current architecture tendencies, in response to the increasing request of daylighting and external view by the occupants, these actions have strongly raised the ratio between gains and losses, and put to the test the capability of ensuring an adequate level of thermal and visual comfort. In turn, the level of comfort plays a crucial role in determining the amount of energy needed to operate the building [3], since unsatisfactory indoor conditions induce occupants to react in order to restore or preserve their comfort [4].

Not only energy and comfort goals are mutually competing, but also different energy and comfort aspects have to be balanced to optimize the overall building performance, such as thermal and lighting energy needs, and visual and thermal comfort.

Building simulation techniques can help reach this target, as they allow the prediction the building behavior from the early design steps, and the detailed assessment of the contribution of all the different components (opaque envelope, glazing and shading systems, HVAC systems, control strategies, etc.). Even with various levels of complexity and uncertainty, they can provide information about the global performance, including thermal energy, lighting and daylighting, thermal and visual comfort aspects. They allow the detailed analysis of the solar radiation (visible and thermal) through the window components and its distribution in the indoor environment, which is crucial to evaluate the global performance of the building correctly.

Moreover, when comparing different configurations, contrasting strengths and weaknesses and trying to optimize the building

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design and/or operation require the interpretation of the outcomes of the integrated performance analysis, which may come in different terms. While annual or seasonal primary energy needs are the preferred option, sometimes distinguishing among different uses (heating, cooling or lighting), there is a wide choice of comfort metrics, different by quantity, time reference (short or long term metrics) and space reference (local/point or zonal/global metrics) [5].

Quite a few examples in literature are devoted to the integrated assessment of the different energy and non-energy aspects related to the interaction of opaque and transparent envelope components. Almost all the works focus on office buildings, assessing the impact of different design parameters (geometrical, thermal and optical properties of glazing systems, and/or shading and lighting systems control strategies) on the different energy performance and/or indoor environmental conditions.

The most significant among the works adopting building simulation to assess simultaneously multiple aspects in building performance, can be divided into three principal groups according to the specific comfort sensation analyzed: visual comfort and energy needs (i), thermal comfort and energy needs (ii), visual and thermal comfort and energy needs (iii).

Madhavi and Dervishi [6], compared the performance of a predictive simulation-supported lighting and shading control system, with four conventional approaches, optimizing the electrical power for lighting, the mean workstation horizontal illuminance (HI), and the unified glare ratio (UGR) for a reference position in the room, combined in an aggregate utility function. Tzempelikos and Shen [7] analyzed four different dynamic shading controls in order to quantify their influence on total source energy consumption for space lighting, heating and cooling. The daylighting performance was described using dynamic daylight performance metrics such as Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), Maximum Daylight Autonomy (mDA), and Useful Daylight Illuminance (UDI). Chan and Tzempelikos [8] conducted a detailed study on dynamic control strategies for venetian blinds, quantifying the impact on lighting energy use, dynamic daylight metrics and Daylight Glare Probability. Also Nielsen et al. [3] analyzed the potential of automated dynamic solar shading in office buildings, quantifying the annual energy demand for heating, cooling (temperature set-point was used according to the thermal comfort categories as prescribed in the technical standards) and lighting, considering the Daylight Factor (DF) and the usable area on the work plane. Ochoa et al. [9] proposed energy and visual criteria suitable for multi-optimization analysis techniques. Total energy consumption related to heating consumption, cooling consumption, lighting consumption and artificial ventilation had to be minimized, with window's size able to ensure a minimum illuminance value, a Daylight Glare Index (DGI) of 22, a minimum illuminance uniformity for at least 50% of the total working hours. Oh et al. [10] considered the total energy consumption and DGI to define the optimum automatic control strategy for slat-type blinds. Shen and Tzempelikos [11] conducted a sensitivity analysis to identify the most influencing factors on daylighting and energy performance of perimeter offices with automated shading. Again annual lighting, heating and cooling demand and annual source energy consumption, as well as UDI, were used as performance indicators. Singh et al. [12] performed a parametrical analysis on different glazing and internal woven roller shades comparing their effects on energy consumptions, DA, UDI and DGI. DA and glare-free annual time have been used as long term metrics at two reference positions. Fasi and Budaiwi [13] analyzed the impact of daylight integration and visual comfort on building energy consumption for office buildings in hot climates, using DF and DGI.

Buratti et al. [14], in order to evaluate different glazing types in a classroom, analyzed the heating and cooling annual energy demand and used the average Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) in the occupation period as long-term metrics for thermal discomfort. Wang et al. [15] developed and validated the energy model of a school and evaluated the influence of several factors (indoor set-point temperatures, pre-ventilation, sun shading system, efficiency of the heat recovery facility) on energy consumption and thermal comfort, assessed as internal air temperature frequency distribution. Bessoudo et al. [16] evaluated the impact of shading systems on thermal comfort near facades with large glazing areas using experimental measurements. The hourly evolution of the Mean Radiant Temperature (MRT), corrected for the effect of the solar radiation on the person, was analyzed for representative days. Tzempelikos et al. [17] evaluated the effect of different glazing and shading properties on dynamic thermal sensation using the two-node thermal comfort model. Hwang and Shu [18] assessed the effect of building envelope regulations on thermal comfort and on cooling consumption. Through a parametric analysis, they evaluated the effect of glazing types, Window to Wall Ratio (WWR) and overhangs on the occurrence of discomfort and severity of overheating. In this case, the direct contribution of solar radiation to the body thermal balance was included in the PMV and PPD calculation. The same was done by Cappelletti et al. [19], in order to compare heating and cooling energy needs for different glazing systems maintaining equivalent nominal comfort conditions in an office building, with PMV and PPD used to assess long term performance in terms of Weighted Discomfort Time (WDT), mapping the performance on 9 position in the room. Kolarik et al. [20] used the percentage of working hours with PPD larger than 10% and the annual primary energy use for cooling and heating, in order to evaluate the performance of conventional all-air VAV ventilation system and thermo-active building system (TABS) supplemented with CAV ventilation.

In Liu et al. [21], different control strategies for intelligent facades have been evaluated looking for the optimization of comfort performance and the minimization of thermal energy demand for an office building. Long-term thermal comfort has been evaluated thorugh the time frequency of the comfort classes suggested by EN 15251:2007 [22]. Visual comfort is imposed cutting all direct solar radiation. David et al. [23] proposed simple indices to compare thermal and visual efficacy of different solar shading systems, balancing solar protection and natural light. Thermal efficacy is expressed through the fraction of the beam solar irradiation that impacts the glazing with and without the use of solar shadings, and thermal comfort is analyzed as a consequence of the cooling demand. Visual efficacy is assessed by means of DA, UDI, and the ratio of the working plane where the illuminance exceeds 8000 lx. Vanhoutteghem et al. [24] proposed a method to choose different window properties to ensure the requested performance for a Danish nearly Zero Energy Building (nZEB). A long-term index, the time percentage in which the Operative Temperature (OT) exceeds a specific range, and an enhanced DF, which considers the median exterior diffuse illuminance in specific locations, have been used, together with the heating demand, to analyze the influence of window size, orientation and properties. Mainini et al. [25] proposed different strategies to improve the transparent part of the envelope in order to obtain low HVAC primary energy consumption and improve comfort conditions. The hourly thermal comfort was evaluated though the PMV and PPD in accordance with ISO 7730 [26] and expressed as a monthly average. The DGI, calculated for a single point in the room, and the luminance distribution on the glazing surface, have been used as visual comfort parameters. Roetzel et al. [27] compared the impact of building design and occupancy behavior on comfort and energy performance in offices. Besides analyzing the global energy consumption (heating, lighting, office equipment and cooling), they evaluated the DA, the percentage of working time when shading is activated, and the long-term thermal