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Impact of adaptive thermal comfort criteria on building energy use and cooling equipment size using a multi-objective optimization scheme

Mohamed Hamdy*, Ala Hasan, Kai Siren

Aalto University, School of Engineering, Department of Energy Technology, P.O. Box 14400, FI-00076 Aalto, Finland

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ABSTRACT

Recently adaptive thermal-comfort criteria have been introduced in the international indoor-climate standards to reduce the heating/cooling energy requirements. In 2008, the *Finnish Society of Indoor Air Quality* (FiSIAQ) developed the national adaptive thermal-comfort criteria of Finland. The current study evaluates the impact of the Finnish Criteria on energy performance in an office building. Two fully mechanically air-conditioned single offices are taken as representative zones. A simulation-based optimization scheme (a combination of IDA-ICE 4.0 and a multi-objective genetic-algorithm from MATLAB-2008a) is employed to determine the minimum primary energy use and the minimum room cooling-equipment size required for different thermal comfort levels. The applicability of implementing energy-saving measures such as night ventilation, night set-back temperature, day lighting as well as optimal building envelope and optimal HVAC settings are addressed by investigating 24 design variables. The results show that, on average, an additional 10 kWh/(m^2 a) primary energy demand and a larger 10 W/m^2 room cooling-equipment size are required to improve the thermal comfort from medium (*S*2) to high-quality (*S*1) class; higher thermal comfort levels limit the use of night ventilation and water radiator night-set back options. Compared with the ISO EN 7730-2005 standard, the Finnish criterion could slightly decrease the heating/cooling equipment size. However, it significantly increases both the heating and cooling energy demand; the results show 32.8% increase in the primary energy demand. It is concluded that the Finnish criterion-2008 is strict and does not allow for energy-efficient solutions in standard office buildings.

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1. Introduction

The energy demand of buildings depends significantly on the criteria used for indoor environment (temperature, ventilation and lighting) and building (including systems) design and operation [1]. The maintenance of a particular thermo-hygrometric comfort level is linked to energy demand and consequent energy cost [2]. Based on field studies [3], de Dear and Brager [4–7] have pointed out that, in not fully mechanically controlled buildings, the expectations of the users concerning the thermal environment allow the interval of acceptable temperatures to be wider than that obtained from Fanger's theory, which is based on the PMV index [8] and centred on slightly different values. Centnerova and Hensen [9] showed that using adaptive comfort criterion [5] for buildings with natural ventilation in moderate climates (such as in the Netherlands and the Czech Republic) would result in considerably lower energy demands for heating in comparison to standard criteria [10,11]. Corgnati et al. [12] showed that, as far as not fully mechanically controlled buildings where an adaptive comfort theory [13] can be applied are concerned (with the same percentage (10%) of dissatisfied people), the energy demand can be reduced to 50%.

The adaptive approach allows wide intervals of indoor temperature (e.g., 30 °C in summer and 18 °C in winter) in naturally ventilated buildings. This allows good energy saving opportunities. However, how realistically these intervals are acceptable and how the adaptive opportunities can achieve these intervals is debatable. Thermal comfort studies [14,15] show a decrease in productivity at higher ambient temperatures. Some studies [9,16,17] indicate that the adaptive criteria lead to a very low indoor temperature when the outside temperature is cold. Barlow and Fiala [18] concluded that both passive and active adaptive opportunities such as controlling solar glare, turning lights off locally, and controlling solar gain are important in future low-energy office refurbishment strategies. Pfafferott et al. [19] analyzed room temperatures in 12 passively cooled low-energy office buildings in Germany. The analysis indicates that buildings that use only natural heat sinks for cooling provide good thermal comfort during typically warm summer periods. However, long heat waves, such as during the extreme European summer of 2003, overstrain passively cooled buildings with air-driven cooling concepts in terms of thermal comfort.

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* Corresponding author. Tel.: +358 452757982; fax: +358 947023418.
E-mail address: Mohamed.Hassan@tkk.fi (M. Hamdy).

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To guarantee high thermal comfort levels, most probably an air-conditioning system is required. In air-conditioned buildings, the clothing of occupants changes according to the weather [20]. Other adaptive comfort opportunities such as an adjusting control and/or location might be available. This leads to proposing adaptive thermal comfort criteria in *fully mechanically controlled* buildings [21–23]. In such buildings, few studies have investigated the adaptive approach. One criticism of the adaptive comfort approach is its inherent complexity, which makes it difficult to apply to building designs (i.e., a special controller is needed for the air-conditioning systems). In response to this criticism, the adaptive control algorithm (ACA) was developed and applied to two air-conditioned buildings [17]. The ACA showed potential for energy-saving. However, since the time schedule of the test was limited, it was noted that the ACA must be extensively tested over a long term with a wider range of building types before it can be fully marketed as an alternative solution to fixed set-point temperature controls. Dynamic simulation is used to evaluate the impact of the comfort approach on the energy demand in *fully mechanically controlled* and *not fully mechanically controlled* typical office rooms [12]. The evaluation addressed a 1-year period, assuming the operative temperature set points of the HVAC system control as a function of the mean monthly outdoor temperature.

The exponentially weighted mean outside temperature has been found to be a more accurate outdoor temperature index than the monthly mean outdoor temperature [16,24]. In 2008, the *Finnish Classification of Indoor Climate* [25] has introduced adaptive thermal comfort criteria for naturally ventilated and mechanically air-conditioned environments. The criteria use the 24-h average outdoor temperature as the outdoor temperature index, see Section 2. The current study evaluates the impact of the Finnish criterion not only on the energy demand but also on the room cooling-equipment size. The study addresses two fully mechanically air-conditioned single offices as representative zones (Section 3). A simulation-based optimization scheme is used to find an optimal relation between the energy demand and thermal comfort level. Section 4 presents the simulation-based optimization scheme and its objectives, constraints, and design variables. The results are presented in Section 5 and discussed in Section 6. Section 7 compares the Finnish criterion and EN ISO 7730:2005 in terms of primary energy demand and applicability of using energy saving measures such as night ventilation and night-setback. The conclusion of the study is in Section 8.

2. The Finnish adaptive thermal comfort criterion

The significance of indoor climate for health, comfort and productivity has been well recognized in Finland in recent decades. Kurnitski and Seppänen [26] briefly summarized the development of the indoor climate classifications in Finland. In late 2008, the Finnish Society of Indoor Air Quality (FiSIAQ) released a new *Classification* [25]. The classification includes three thermal comfort classes. The first class (*S*1) corresponds to the best quality, meaning higher satisfaction with indoor environment. The second class (*S*2) corresponds to a normal level of expectation. *S*1 and *S*2 are proposed for fully mechanically air-conditioned environments. While *S*3 is stipulated for naturally ventilated buildings, it is out of the scope of the current study.

The classification defines the indoor operative temperature set points as a function of the 24-h mean average outdoor air temperature ($\mathrm{ODT}_{24\,\mathrm{h\,average}}$). Fig. 1 shows the set-point profiles, the allowable set-point deviation bands, and the maximum/minimum temperature limitations of the *S*1 and *S*2 classes. It is important to mark that *S*1 and *S*2 classes have the same set-point temperature profile. The *S*1 class stipulates that the operative temperature (T_{op}) should be kept at the set-point with acceptable deviations of ±0.5 for 95% of the occupied hours. However, *S*2 class requires keeping the operative temperature at the set-point with acceptable deviation ±1 °C, 90% of the occupied hours. The criterion proposes 20 °C and 23 °C as the minimum and maximum temperature limits in the cold season. For summer, the maximum temperature limits (26 °C and 27 °C) are proposed by *S*1 and *S*2, respectively. The cold season's limitations come in line with the *B* and *A* categories of the ISO EN 7730:2005 standard [27]. The summer limitations are consistent with the *B* and *C* categories of the standard. Table 1 shows the design conditions of EN ISO 7730:2005, which are calculated based on Fanger's theory [8] assuming sedentary persons (1.2 met) in typical summer (0.5 clo) and winter (1.0 clo) clothing. These assumptions are adequate to the situation in office rooms, which is the subject of the current study.

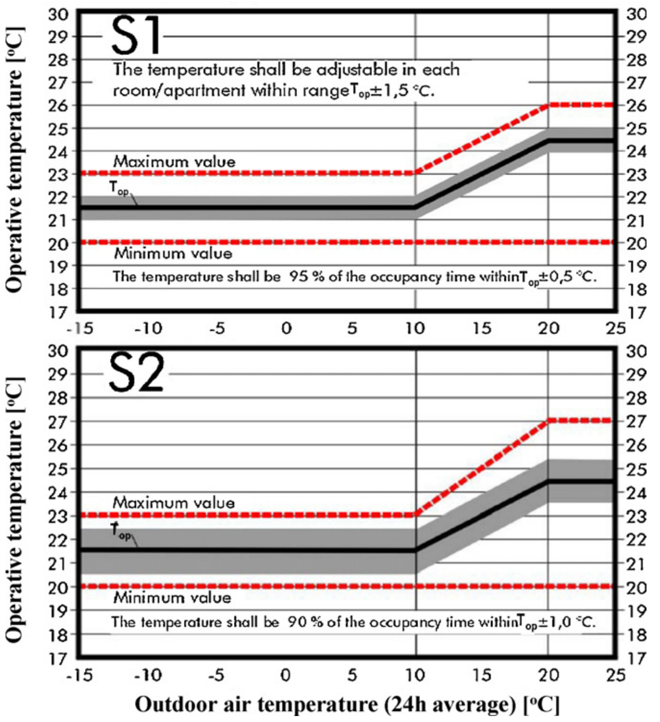

Fig. 1. The set-point profile, minimum and maximum limits according to the Finnish Classification of Indoor Climate 2008 [25].

3. Case study

3.1. Representative zones

The main purpose of most installed heating and air-conditioning systems in buildings is to provide an environment that is acceptable and does not impair health and performance of the occupants. The evidence shows that thermal conditions within the thermal comfort zone can reduce performance (productivity) by 5–15% [28]. High thermal comfort level is usually a target in work places (e.g., office cellular). The present study evaluates the impact of the higher thermal comfort Finnish classes (*S*1 and *S*2) on the energy demand and the room cooling-equipment size in an existing office building in Helsinki, Finland. The office building consists of eight floors (1490 m^2 per floor). The current study takes only two single offices with different orientations (north and south) as representative zones. The two zones have the same area (12 m^2) and are located on the same storey (the 7th floor). The whole storey is simulated and represented by nine zones: LN zone, machine room, RN zone, interior zone, RS zone, LS zone, and machine room, in addition to the

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