The Balance Between Occupants' Living Comfort and Energy Conservation of Intelligent Buildings

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Abstract. This paper established an occupants' living comfort evaluation model of different intelligent buildings based on the linguistic assessment information. A multi-objective optimization model for improving living comfort and reducing energy consumption is constructed and Pareto optimal frontiers are obtained to achieve a comprehensive balance. Results show that, the occupants' living comfort has been significantly improved under the same energy consumption level. Pareto optimal frontier results show that the building energy consumption of shopping malls and office buildings is optimized by 7.53% and 18.06%, and the occupants' living comfort level is improved by 3.19% and 3.53%, respectively.

Keywords: Intelligent building · living comfort · linguistic assessment · triangular fuzzy number

1 Introduction

The carbon neutralization and carbon peaking plan are the important strategic goals in the near future. The balance between building energy conservation and occupants' comfort has become a hot topic in recent years. According to the 2021 Global Status Report for Buildings and Construction, the construction and operation of the building sector accounted for 36% of global final energy consumption and 37% of energy-related CO_2 emissions in 2020 [1]. However, the emissions from building operations accounted for approximately 28% of total global energy-related CO_2 emissions in 2020. The building sector accounts for a large part of energy demands and can play a major role in mitigating the climate change threat, especially in the building operation process. In that case, energy conservation and emission reduction in the building sector will play a crucial role in promoting the realization of the "3060" goals.

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2 Literature Review

One of the most promising approaches to intelligent building energy efficiency is to make offices, commercial and residential buildings intelligent, by performing intelligent control of building facilities and establishing continuous communication with occupants [2]. The literature survey study found that the building sector comprised 40% of office buildings, 31% of residential buildings, and 29% of commercial buildings [3]. Further data collection and analysis were performed on six mosques of different sizes in Turkey to assess temple comfort, energy consumption, and air quality [4]. Cui et al. proposed a new method to optimize energy utilization in intelligent buildings to solve the problem of multi-objective optimization and improve the efficiency of regulation [5].

According to the literature survey, it is of great significance to find a balance between energy conservation and occupants' living comfort. The gaps lie in that the characteristics of intelligent buildings for different purposes were not reflected in the study. Different types of buildings have different functions, occupants will have different comfort requirements for the functions they provide. Moreover, occupants' comfort is not valued in the existing studies. Directly measurable environmental data are always used to represent the occupants' comfort feeling. However, the occupants' comfort is a subjective expression, which cannot be obtained objectively by quantitative data only.

3 Methodology and Data Source

Firstly, this paper collected the linguistic assessment information given by different types of intelligent building occupants on the thermal, visual, sound, and air quality. Then, this paper converted the assessment information of 5-granularity phrases into triangular fuzzy numbers to calculate the evaluation value and the non-fuzzy value. Then the occupants' overall living comfort functions of different building types will be concluded. After that, a multi-objective optimization model for improving living comfort and reducing energy consumption is constructed. Finally, the Pareto optimal frontier is obtained to achieve a comprehensive balance.

3.1 Comfort Index Evaluation System

Shaikh et al. summarized 121 relevant literature and found that thermal comfort (48%), visual comfort (21%), air quality (18%), humidity effects (6%), and personal preference (7%) are mentioned in evaluating the building comfort. Recent researches expand the span of building comfort, such as a sound environment [6]. Caniato et al. studied the impact of indoor environmental health on autistic patients from four comfort zones, using noise level as a descriptive indicator of sound environment comfort [7]. According to the existing research, thermal, visual, sound, and air comfort are selected to represent the evaluate the comfort of an intelligent building. Finally, the factors of occupants' living comfort including temperature, humidity, dress heat resistance, metabolism, natural lighting, illumination intensity, color temperature, noise, sound insulation, dust-free, smell, ventilation, green plants.

3.2 Triangular Fuzzy Evaluation Method

Occupants' evaluations will be collected in the form of a questionnaire, which adopts the form of the 5-granularity phrase. The triangular fuzzy number is designed as $M_\theta = (M_\theta^1, M_\theta^2, M_\theta^3), \theta = 0, 1, 2, 3, 4$.

Step1: The average weight (A_{ik}) and average evaluation value (B_{ik}) of occupants' living comfort factor x_{ik} are calculated as shown in (1) and (2):

$$\mathrm{A}_{ik} = \frac{\sum_{j=1}^{t} A_{ik}^{j}}{t} \tag{1}$$

$$\mathrm{B}_{ik} = \frac{\sum_{j=1}^{t} B_{ik}^{j}}{t} \tag{2}$$

Step2: Calculation of the triangular fuzzy evaluation value of category f_i. f_i is denoted as $f_i = (f_{i1}, f_{i2}, f_{i3})$. If $f_{ik} > 1$, , it should be standardized as (3).

$$f_i = \sum_{i=1}^{n} \overline{\mathrm{A}}_{ik} \cdot \frac{\mathrm{B}_{ik}}{\sum_{i}^{n} \mathrm{A}_{ik}} \tag{3}$$

Step3: Defuzzification of f_i^*. After obtain the triangular fuzzy evaluation value of category f_i^*, the non-fuzzy value of each category $\varepsilon_i\left(f_i^*\right)$ can be calculated as (4) and (5):

$$\varepsilon_i\left(f_i^*\right) = \frac{f_{i1}^* + f_{i2}^* + f_{i3}^*}{3} \tag{4}$$

$$\omega_i = \varepsilon_i / \sum_{i=1}^{4} \varepsilon_i (i = 1, 2, 3, 4) \tag{5}$$

3.3 Multi-objective Optimization Design

When designing the multi-objective process, there are two goals to be pursued: the maximum occupants' living comfort and the minimum economic cost. The two objectives can be expressed below.

the occupants' living comfort objective here can be expressed as (6):

$$\begin{aligned} Maximize F_1(t) = \omega_1\left[1 - \left(\tfrac{p_{at}(t) - P_{ct}}{P_{ct}}\right)^2\right] + \omega_2\left[1 - \left(\tfrac{p_{av}(t) - P_{cv}}{P_{cv}}\right)^2\right] \\ + \omega_3\left[1 - \left(\tfrac{p_{as}(t) - P_{cs}}{P_{cs}}\right)^2\right] + \omega_4\left[1 - \left(\tfrac{p_{aa}(t) - P_{ca}}{P_{ca}}\right)^2\right] \end{aligned} \tag{6}$$

in which $p_{at}(t), p_{av}(t), p_{as}(t), p_{aa}(t)$ represent the actual electricity consumed by the thermal, visual, sound, and air quality. $P_{ct}, P_{cv}, P_{cs}, P_{ca}$ are constants.

The objective function of energy consumption costs is expressed as (7):

$$Minimize F_2(t) = \sum_{t=1}^{T} c_e\left[p_{at}(t) + p_{av}(t) + p_{as}(t) + p_{aa}(t)\right] \tag{7}$$

The energy consumption cost is uniformly expressed as the electricity cost to serve its thermal, visual, sound, and air quality. c_e is the electricity price.

The comfort constraint functions of thermal, visual, sound, and air quality all range from 0 to 1. The constraints of this study are obtained as shown in (8).

$$s.t.\begin{cases} 0 < p_{at}(t) \le 2P_{ct} \\ 0 < p_{av}(t) \le 2P_{cv} \\ 0 < p_{as}(t) \le 2P_{cs} \\ 0 < p_{aa}(t) \le 2P_{ca} \\ 0 < p_{at}(t) + p_{al}(t) + p_{as}(t) + p_{aa}(t) \le p_{max}(t) \end{cases} \tag{8}$$

3.4 Survey Data Collection

There are two parts designed to the questionnaire: the importance of the comfort index (expressed as extremely unimportant, unimportant, general, important, and very important) and the feeling of the comfort index (very bad, bad, medium, good, very good). 228 questionnaires were recovered in shopping mall and office.

SPSS is used to verify the reliability and validity of the data. The results show that the overall Cronbach's alpha coefficient of the sample is 0.688 (>0.6), and the Cronbach's alpha value of each index in the evaluation model exceeds 0.7. On the other hand, the KMO test and Bartlett test were performed. The KMO of this test was 0.610 (>0.6), and the significance level of the Bartlett sphere test was 0.000, indicating that the obtained data obeyed a normal distribution.

4 Analysis of Results

4.1 Occupants' Living Comfort Evaluation

The process of evaluation of occupants' living comfort assessment is carried out in Table 1. Due to space limitations, shopping malls are used as an example for calculation.

Occupants have different emphasis on the comfort feeling of different intelligent buildings. The thermal, visual, sound and air quality comfort in shopping mall is 0.288, 0.110, 0.210,0.392, 0.201, office is 0.133, 0.378, 0.289. The occupants' comprehensive evaluation value of air quality comfort ranks first in the shopping mall, but in office buildings, occupants pay more attention to the comfort of the sound environment. Different buildings focus on different ways to improve the comfort of occupants, which directly leads to the different requirements in energy consumption. Facing such personalized characteristics, the cost of energy consumption and occupants' specific comfort demands should be closely balanced.

4.2 Multi-objective Optimization of Intelligent Buildings

Figure 1 and Fig. 2 show the original and optimized Pareto frontiers of multi-objective optimization of the two kinds of intelligent buildings. The X-axis represents the comfort

Table 1. The triangular fuzzy results (Take shopping mall for example)

Factor	Average weight	Average evaluation value
Temperature	(0.572, 0.822, 0.951)	(0.472, 0.713, 0.896)
Humidity	(0.525, 0.775, 0.914)	(0.382, 0.623, 0.843)
Dress heat resistance	(0.498, 0.748, 0.910)	(0.359, 0.602, 0.829)
Metabolism	(0.421, 0.671, 0.875)	(0.486, 0.729, 0.924)
Natural lighting	(0.347, 0.574, 0.778)	(0.113, 0.264, 0.507)
Illumination intensity	(0.479, 0.720, 0.859)	(0.097, 0.234, 0.475)
Color temperature	(0.495, 0.745, 0.965)	(0.051, 0.146, 0.394)
Noise	(0.699, 0.949, 0.998)	(0.257, 0.461, 0.681)
Sound insulation	(0.597, 0.847, 0.970)	(0.273, 0.479, 0.706)
Dust-free	(0.468, 0.699, 0.847)	(0.725, 0.975, 1.000)
Smell	(0.442, 0.674, 0.838)	(0.701, 0.951, 0.995)
Ventilation	(0.394, 0.620, 0.808)	(0.729, 0.979, 1.000)
Green plants	(0.532, 0.782, 0.963)	(0.697, 0.947, 0.993)

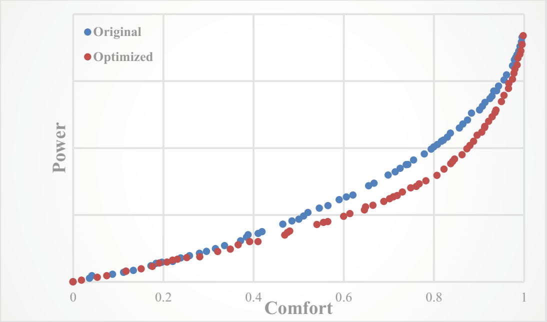

Fig. 1. Pareto frontier of Shopping mall

degree of occupants, and the Y-axis represents the amount of energy consumption of the intelligent building. It can be seen that there is a significant right shift in the optimized results. This means that, on the premise of ensuring the comfort of occupants, the energy consumption of the intelligent building is reduced. Or when the energy consumption of the intelligent building is comparable, the occupants' comfort is improved.

From the comparison of the two types of intelligent buildings, shopping malls and office buildings both have obvious optimization effects. After the optimization, the occupants' comfort in an office building has increased by 3.53%, and the energy consumption has been reduced by 18.06%. These data are 3.19% and 7.53% in a shopping mall. There's

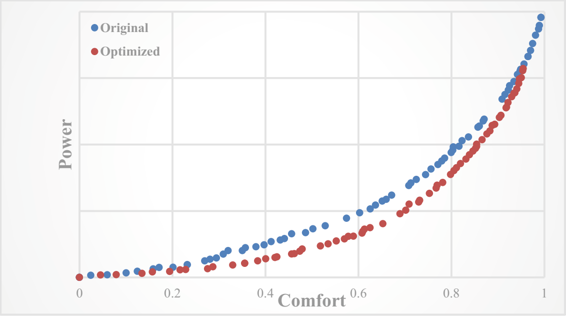

Fig. 2. Pareto frontier of Office building

no need to sacrifice the occupants' living comfort to achieve the purpose of energy conservation. On the contrary, fully considering the occupants' living comfort can save the energy consumption level to a certain extent.

5 Conclusions

The aim of this paper is to find a balance between occupants' living comfort and building energy-saving. Intelligent building energy consumption and occupants' comfort seem to be inherently opposed. However, the hypothetical approach adopted by most studies ignores the intuition of occupants' comfort. Most of the studies used measurable data, ignoring the intuitive feeling that environmental data brings to occupants, which isolates the relationship between occupants' real feelings and the building environment. This paper established an occupants' living comfort evaluation model of different intelligent buildings based on the linguistic assessment information. The Pareto optimal frontiers are obtained to achieve a comprehensive balance.

Results show that after the optimization, the occupants' living comfort has been significantly improved under the same energy consumption, and when the occupants' comfort is determined, the energy consumption of both buildings shows a downward trend.

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