An Evaluation Model for Indoor Light Environment

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Abstract Indoor luminous quality affects occupants' health a lot, but no mature solution exists to assess the quality. The objective of this paper was to develop a practical fuzzy evaluation model for light environment. Based on previous studies and a series of luminous experiments, illuminance, correlated color temperature and illuminance uniformity were chosen as evaluation indicators and a fuzzy synthetical evaluation model with five grades was developed.

Keywords Indoor light environment · Model · Fuzzy evaluation

1 Introduction

Indoor light environment is of great importance to human health and well-being, especially in residential buildings where people spend most of their time [1–3]. There are many standards and guides which provide instructions on how to design the light environment of residential buildings in a qualified way. However, how to assess the light design remains a problem for building designers and users.

Assessment of luminous quality can be classified into the following ways, concluded from literature review. User survey, usually called 'POE' (post-occupant evaluation), is the most direct way to achieve evaluation from subjects, while the process is time-consuming, and pre-evaluation is not allowed [4–6]. The second tool is empirical models identified by performing regression analysis based on a large amount of luminous satisfaction experimental data [7]. However, the accuracy of empirical model is limited mainly by sample size which is relatively small in present luminous studies (e.g. Iwata used 147 subjects) compared with the database (covering tens of thousands observations) used in thermal comfort model establishment. To obtain an

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integrated judgment of luminous environment, synthetical evaluation is offered as an alternative in some research [8]. When applying synthetical evaluation, factors are evaluated, respectively, and then weighted to make an overall assessment. There are several studies discussing about this method but in a theoretical or hypothetical manner, which means it cannot be used in practice due to the lack of experimental support.

This paper attempted to work out a reliable and comprehensive model which is operative in practical engineering, based on a series of luminous experiments together with extensive investigations. In this work, fuzzy synthetical evaluation was adopted to address the uncertainty of occupants' satisfaction with light conditions.

2 Model Construction

Luminous quality is influenced by factors such as illuminance and color temperature. The first problem in this study is how to deal with the integration of multiple factors. Besides, the luminous assessment ought to base on occupant satisfaction, which is exactly a fuzzy feeling, while assessment usually needs to be presented in a quantified form. If the measured illuminance of a room is 250 lx while the recommendation value given by standards is 300 lx, does that mean the measured environment performs badly? The precise threshold makes it clear that if a design meets the standards, however, it is hard to judge the light quality because it depends on situations and differs largely between occupants. Consequently, fuzzy synthetical evaluation is used in this paper to solve the above problems.

In the classical set theory, there are only two kinds of ownership between an element x and a set A: x belongs to A and x does not belong to A. No intermediate states exist. It is reasonable to apply classical theory in judging if a light design is up to the standards, while the light quality based on human satisfaction is difficult to describe using this theory. Fuzzy mathematics is adopted to describe the intermediate state. For example, for a given illuminance value, it belongs to both satisfying interval and dissatisfying interval in different degrees (called membership degree in fuzzy mathematics). Fuzzy synthetical evaluation integrates multiple factors using weight factors and fuzzy evaluation [9].

2.1 Evaluation Indicator Set

Evaluation indicator set covers major influencing factors of luminous environment quality. The visual quality aspects of light environment are divided into two parts: light intensity (and its distribution) and light color. As a result, the light environment evaluation should include quality parameters for each aspect. GB/T 50033 [10] lists some luminous indices covering these aspects in residential buildings; accordingly, the illuminance (u_1), correlated color temperature (CCT, u_2) and illuminance uniformity (u_3, which was defined as the ratio of the minimum illuminance to the average illuminance) were selected as the evaluation indices. The indicator set is expressed as: $U = \{u_1, u_2, u_3\}$.

2.2 Grades and Benchmarks

Though precise threshold is not suitable for judging a light environment, it is still necessary to establish a grade set because the evaluation result of light quality should be presented in grades or levels. The simplest grade set is {good, bad} or {qualified, unqualified}.

What is the benchmark for being qualified? Standards [10, 11] give the qualification limits of various factors. For example, the minimum illuminance of dining room should reach 150 lx [10], in other words, 150 lx is the lower limit of the qualified interval. Illuminance is not the higher the better, but there are different opinions about the upper limit of illumination. Considering the upper limit, the highest value 2500 lx [12] was selected. Then, 150–2500 lx is the qualified range for illumination in dining room. The benchmark determination processes of other factors are similar. The results are summarized in Table 1.

In the zones like living room, bedroom and kitchen where different activities may occur, the luminous requirements for visual activities (expressed as '*V*' in Table 1) including reading and cutting work are stricter than those for non-visual activities (expressed as '*N*' in Table 1), so the corresponding benchmark should also be differentiated.

However, such a grade set cannot specifically evaluate the luminous quality. To this end, on the basis of {qualified, unqualified}, the grade set was refined into five levels: $V = \{v_1, v_2, v_3, v_4, v_5\}$ (see Table 2).

Since there is no unified statement about the comfort ranges of each luminous factor, it is difficult to find basis for grade refinement. In this context, the qualified range was divided equally into four grades as an attempt: excellent v_1, good v_2,

Table 1 Qualified ranges for evaluation indicators

Zone	u_1 (lx)	u_2 (K)	u_3
Living room	100–2500 (N); 300–2500 (V)	3000–6500	0.5–1 (N); 0.7–1 (V)
Bedroom	75–2500 (N); 150–2500 (V)	3000–6500	0.5–1 (N); 0.7–1 (V)
Dining room	150–2500	3000–6500	0.5–1
Kitchen	100–2500 (N); 150–2500 (V)	3000–6500	0.5–1 (N); 0.7–1 (V)
Bathroom	100–2500	3000–6500	0.5–1

Table 2 Grade refinement

Grade	Excellent (v_1)	Good (v_2)	Ordinary (v_3)	Passable (v_4)	Failed (v_5)
Proportion in qualified range	25%	25%	25%	25%	–
e.g. u_3 (dining room)	(0.875, 1]	(0.75, 0.875]	(0.625, 0.75]	(0.5, 0.625]	<0.5

ordinary v_3 and passable v_4 (see Table 2, range division of u_3 in dining room is given as an example).

As for optimal values, illuminance and correlated color temperature should be neither too high nor too low, so the closer to the center of the qualified range the better. Illuminance uniformity is the ratio of the minimum illuminance to the average illuminance; thus, the value of illuminance uniformity is in the range of 0–1 and 1 is the optimal value.

2.3 *Membership Function Set*

In order to obtain the membership function set, we conducted a series of experiments in a light laboratory where luminous parameters are under control. The subjects were asked to fill out the subjective evaluation surveys under different light conditions. A total of 18 healthy students, half male and half female, participated as subjects in the experiments for up to 158 times in total. All protocols were approved by the university's ethics committee. Verbal and written informed consents were obtained from each subject prior to participation. Based on the experiment results, the membership functions of each indicator could be obtained by fuzzy statistics. Referring to the commonly used membership function distribution forms: rectangular distribution, trapezoidal distribution, parabolic distribution, Gaussian distribution, Cauchy distribution, appropriate forms were selected, and functions were determined using regression method.

The membership functions are listed in Table 3. Membership degree is represented by 'm', the subscript 'x' indicates the measured parameters to be evaluated, and the subscript 'c' indicates the center value of grade range. The input parameter means the parameter required for the membership degree calculation. For the convenience of calculation, the illuminance I_x and the correlated color temperature T_x to be evaluated are converted into relative values I_r and T_r (the degree of deviation from the optimal values I_0, T_0 whose explanations were given above), while the illuminance uniformity U_x is directly used as input parameters.

According to the regression analysis, the value of the coefficient 'k' in the membership function varies in different rooms and visual situations.

For an input value of a certain indicator, the membership degrees to five grades can be obtained, respectively, by substituting the center values (subscript c) of each grade. The membership degree set is represented as $M = \{m_1, m_2, m_3, m_4, m_5\}$. The

Table 3 Membership functions

Indicator	Input	Membership function
u_1	$I_r = 1 - \frac{\lvert I_x - I_0 \rvert}{I_0}$	$m(I_{\mathrm{rc}}) = \begin{cases} 1, & I_{\mathrm{r}} \in \text{grade range of } I_{\mathrm{rc}} \\ e^{-\pi[k_{\mathrm{I}}(I_{\mathrm{r}} - I_{\mathrm{rc}})]^2}, & I_{\mathrm{r}} \notin \text{grade range of } I_{\mathrm{rc}} \end{cases}$
u_2	$T_{\mathrm{r}} = 1 - \frac{\lvert T_x - T_0 \rvert}{T_0}$	$m(T_{\mathrm{rc}}) = \begin{cases} 1, & T_{\mathrm{r}} \in \text{grade range of } T_{\mathrm{rc}} \\ e^{-\pi[k_{\mathrm{T}}(T_{\mathrm{r}} - T_{\mathrm{rc}})]^2}, & T_{\mathrm{r}} \notin \text{grade range of } T_{\mathrm{rc}} \end{cases}$
u_3	U_x	$m(U_{\mathrm{c}}) = \begin{cases} 1, & U_x \in \text{grade range of } U_{\mathrm{c}} \\ \left[1 + \left(\frac{U_x - U_{\mathrm{c}}}{k_U}\right)^2\right]^{-1}, & U_x \notin \text{grade range of } U_{\mathrm{c}} \end{cases}$

evaluation the single factor can be achieved by the above steps, and the result is the corresponding grade of the maximum value in membership degree set.

2.4 Indicator Weight Set

The integration of all indicators depends on not only the membership degree sets, but also factor weights which can be acquired via Delphi method, expert investigation method, judgment matrix method, etc. In this work, expert investigation was adopted.

The indicator importance sequence questionnaire was used to conduct weight investigation [13]. As shown in Table 4, the importance of indicators was compared in pairs, and corresponding weight values were assigned to each indicator according to the relationship that the expert chose. The final weight is the accumulated value of all comparisons. After the calculation of 51 valid surveys collected, the weight set (weights are expressed in the sum of 1) was obtained: $W = \{w_{u_1}, w_{u_2}, w_{u_3}\} = \{0.47, 0.25, 0.28\}$.

Table 4 Paired comparison

Relationship	Description	Assigned values
$u_a(3)$	u_a is much more important than u_b	Weight value of $u_a + 3$
$u_a(2)$	u_a is a little more important than u_b	Weight value of $u_a + 2$
u_a/u_b	u_a is equally important as u_b	weight values of both $+1$
$u_b(2)$	u_b is a little more important than u_a	Weight value of $u_b + 2$
$u_b(3)$	u_b is much more important than u_a	Weight value of $u_b + 3$

2.5 Integrated Evaluation

Integrated evaluation can be achieved by the combination of weight set together with membership degree sets. Before the weighted calculation, membership degree set M should be normalized so that the total membership degree in the set is 1, and the processed membership degree set is represented by M'. The comprehensive membership set is:

$$E = \{e_1, e_2, e_3, e_4, e_5\} = W \cdot \begin{bmatrix} M'_1 \\ M'_2 \\ M'_3 \end{bmatrix} \tag{1}$$

$$e_j = \sum_{i=1}^{3} w_i m'_{ij} \tag{2}$$

According to the maximum membership principle, the evaluation grade corresponding to $e_{\max}$ is the synthetical evaluation result of the light environment.

The above fuzzy comprehensive evaluation model has been written into software, which can realize the evaluation of the actual residential light environment in a convenient way. Model verification in real cases showed that the model can predict the occupants' subjective gradings in most situations.

3 Conclusions

The weights of luminous indicators concerning their importance to luminous quality have been obtained using expert investigation method. Illuminance is the most important factor, accounting for nearly half of the total weights.

The five-grade membership function of each indicator is acquired based on the experiments with a large number of subjective luminous satisfaction data. The uncertainty of occupants' grading process is addressed by the concept of fuzzification.

A fuzzy synthetical evaluation model for residential luminous environment has been established.

The software developed in this work offers a simple way of practical evaluation. Furthermore, this model can hopefully be extended to other occasions like office buildings with minor modifications.

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