World Academy of Science, Engineering and Technology
International Journal of Architectural and Environmental Engineering
Vol:9, No:7, 2015

An Application-Based Indoor Environmental Quality (IEQ) Calculator for Residential Buildings

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International Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 waset.org/Publication/10001742

***Abstract*—**Based on an indoor environmental quality (IEQ) index established by previous work that indicates the overall IEQ acceptance from the prospect of an occupant in residential buildings in terms of four IEQ factors - thermal comfort, indoor air quality, visual and aural comforts, this study develops a user-friendly IEQ calculator for iOS and Android users to calculate the occupant acceptance and compare the relative performance of IEQ in apartments. "IEQ calculator" is easy to use and it preliminarily illustrates the overall indoor environmental quality on the spot. Users simply input indoor parameters such as temperature, number of people and windows are opened or closed for the mobile application to calculate the scores in four areas: the comforts of temperature, brightness, noise and indoor air quality. The calculator allows the prediction of the best IEQ scenario on a quantitative scale. Any indoor environments under the specific IEQ conditions can be benchmarked against the predicted IEQ acceptance range. This calculator can also suggest how to achieve the best IEQ acceptance among a group of residents.

***Keywords*—**Calculator, indoor environmental quality (IEQ), residential buildings, 5-star benchmarks.

I. Introduction

INDOOR environmental quality (IEQ) assessment has been adopted in building grading systems [1] such as Building Research Establishment Environmental Assessment Method (BREEAM), Building Environment Performance Assessment Criteria (BEPAC) and Hong Kong Building Environmental Assessment Method (HK-BEAM), to name but a few. However, the concept of using acceptable IEQ as an integral part of the total building performance approach is still not fully appreciated.

As the feeling of comfort is a composite state of an occupant's mind responding to the senses to physical environmental parameters including air temperature, relative humidity, local air speed, background noise level, CO_2 concentration and illumination level [2], [3], mathematical expressions with respect to these parameters have been proposed for approximating the occupant's acceptance of the IEQ of an indoor space. Lai et al. [4] established an IEQ index that indicates the overall IEQ acceptance from the prospect of an occupant in residential buildings in terms of four IEQ factors - thermal comfort, indoor air quality (IAQ), visual and aural comforts. The model allows the prediction of the best IEQ scenario on a quantitative scale. Any indoor environments under the specific IEQ conditions can be benchmarked against the predicted IEQ acceptance range. Using the same model, this study develops a user-friendly IEQ calculator for iOS and Android users to calculate the occupant acceptance and compare the relative performance of IEQ in apartments. The calculator can also suggest how to achieve the best IEQ acceptance among a group of residents.

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II. IEQ in Hong Kong Apartments

A regional indoor environmental survey of 32 residential apartments was conducted and 125 respondents accepted the environment they perceived. The physical measurements of air temperature T_a, mean radiant temperature T_r, relative humidity R_h, air velocity V_a, CO_2 concentration ζ_2, horizontal illumination level ζ_3 and sound pressure level ζ_4 from the survey are exhibited in Table I [4]. Based on previous environmental comfort analyses, thermal comfort has the greatest impacts on the overall IEQ acceptance, except for aural comfort in the space of an apartment. Values of thermal comfort in apartments can be worked out using the Fanger's predicted mean vote (*PMV*) model in which the occupant perceptions of cold, cool, slightly cool, thermally neutral, slightly warm, warm and hot are represented by *PMV* values of −3, −2, −1, 0, +1, +2 and +3 respectively [5]. As a function of six parameters including T_a, T_r, R_h, V_a, clothing value C_L and metabolic rate M_e, *PMV* can be related to the predicted percentage dissatisfied (*PPD*) as expressed in (1), which can be correlated to the optimal thermal comfort of an occupant in chamber measurements [5]. The correlation between actual thermal sensation vote (*TSV*) and *PMV*, for occupants who find the thermal environment acceptable, is summarized in (2).

$$PPD = 100 - 95 \times e^{-\left(0.03353\,PMV^4 + 0.2179\,PMV^2\right)}\ ;\ -3 \le PMV \le 3 \quad (1)$$

$$\text{Apartment: } TSV = 2.20PMV + 0.15\ ;\ -3 \le PMV \le 3 \quad (2)$$

Fig. 1 graphs a distinct *TSV* to *PMV* relationship for apartment environments (p<0.01, t-test). In the apartments surveyed, the mean clothing value was 0.48 clo (standard deviation = 0.11 clo). To maximize their thermal comforts, occupants will adjust their clothing values. It should be noted that people in Hong Kong tend to overdress because many air-conditioned places are over-cooled [6]. In the data simulations, the maximum thermal acceptance $\phi_{I,max}$ for a thermal environment was determined using clothing values from 0.3 to 1.7 clo, which represented the probable range of clothing values for the occupants' perceptions of thermal comfort, i.e. $\phi_I = \phi_{I,max}$ [7].

TABLE I
INDOOR ENVIRONMENTAL PARAMETERS SURVEYED IN APARTMENTS

	T_a (°C)	T_r (°C)	R_h (%)	V_a (ms^{-1})	ζ_2 (ppm)	ζ_3 (lux)	ζ_4 (dBA)
Acceptable	27.3 (2.2)	27.4 (1.9)	84 (10.5)	0.4 (0.2)	689 (328)	178 (253)	67.1 (6.0)
Unacceptable	28.1 (2.5)	28.1 (2.6)	84 (10.9)	0.5 (0.3)	497 (293)	307 (461)	70.6 (8.4)

Standard deviations in brackets

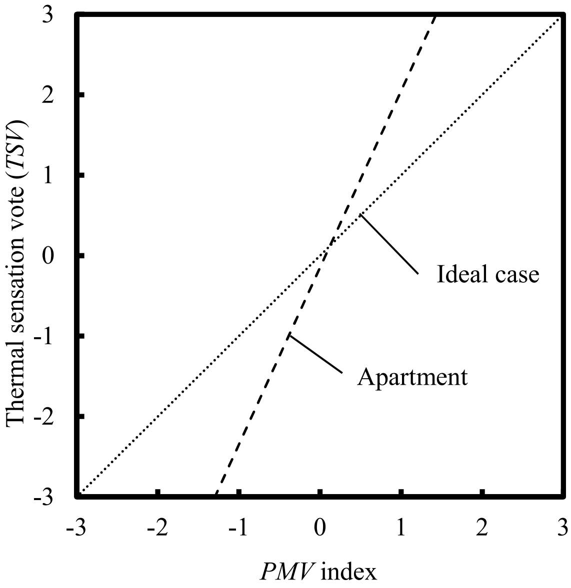

Fig. 1 Relationship between *TSV* and *PMV* for Apartments

III. CONCEPT OF IEQ ACCEPTANCE PREDICTION AND BENCHMARKING

The overall IEQ acceptance θ can be expressed by a multivariate logistic regression model as shown in (3), where C_j are the regression constants which can be determined from the field measurement data for j = (1) thermal comfort, (2) indoor air quality, (3) visual comfort and (4) aural comfort [4],

$$\theta = 1 - \frac{1}{1+\exp\left(C_0 + \sum_{j=1}^{4} C_j \phi_j\left(\zeta_j\right)\right)} \; ; j = 1, 2, 3, 4 \quad (3)$$

The occupant acceptance of thermal comfort ϕ_1 is correlated with predicted percentage dissatisfied ζ_1 and thermal sensation vote ζ_1 as expressed in (4), where m_1 and n_1 are the regression constants determined in the thermal environment [4],

$$\phi_1 = 0.95 \exp\left[-\left(m_1 \zeta_1^2 + n_1 \zeta_1^4\right)\right] \quad (4)$$

The acceptances of indoor air quality ϕ_2, visual comfort ϕ_3 and aural comfort ϕ_4 are respectively correlated with CO_2 concentration ζ_2 (ppm), horizontal illumination level ζ_3 (lux) and sound pressure level ζ_4 (dBA) as expressed in (5), where m_j and n_j are the regression constants determined via field measurement [4],

$$\phi_j = 1 - \frac{1}{1+\exp\left(m_j + n_j \zeta_j\right)} \; ; j = 2, 3, 4 \quad (5)$$

Using the binary notation of acceptance (i.e. 0 = unacceptable, 1 = acceptable) to rank the four contributors ϕ_j in order from most to least important (a total of $k = 2^4$ combinations of possibilities), the surveyed overall IEQ acceptance θ for case k is expressed in (6), where N is the survey sample size and $N_{\theta=1}$ is the acceptance count,

$$\theta_k = \left(\frac{N_{\theta=1}}{N}\right)_k \; ; k = 1 \ldots 16 \quad (6)$$

Good agreements were found between the predicted and observed results for the apartment areas surveyed, and a strong linear association of R=0.99 ($p \le 0.001$, t-test) [4] was reported. IEQ with a benchmarking value B for apartments in Hong Kong can be benchmarked via a 5-star rating system as follows [8]: the system assigns 5 stars to the top 10% samples with $B \ge 0.9$, 4 stars to the next 22.5% with $0.675 \le B < 0.9$, 3 stars to the next 35% with $0.325 \le B < 0.675$, 2 stars to the next 22.5% with $0.1 \le B < 0.325$ and 1 star to the bottom 10% with $B < 0.1$; the benchmarking value B is determined from the IEQ acceptance of the space θ_i by an occupant, and θ_i is the percentile of the cumulative frequency distribution of the occupant's IEQ acceptance in apartments.

$$B = \int_{-\infty}^{\theta_j} \tilde{\theta} \, d\theta \quad (7)$$

IV. APPLICATION-BASED CALCULATOR FOR IEQ ACCEPTANCE PREDICTION

This study used the above models and the IEQ performance data base surveyed for Hong Kong apartments to develop a mobile application calculator (available as a free download for both iOS and Android platforms) for IEQ acceptance prediction in apartments. Based on the input values of environmental parameters including air temperature (°C), relative humidity (%) air velocity (ms^{-1}), apartment size (m^2), activity level (Met), horizontal illumination level (lux) and sound pressure level (dBA), the calculator predicts the occupant acceptance values for thermal comfort (Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool, Cold), IAQ (Dissatisfactory, Acceptable, Good), illuminance level (Dissatisfactory, Acceptable, Good), noise level (Dissatisfactory, Acceptable, Good) and total IEQ.

Benchmarking for the apartment can then be performed via the 5-star rating system [4]. It should be noted that the maximum thermal acceptance $\phi_{I,max}$ was determined using clothing values from 0.3 to 1.7 clo. This rating system is validated expression for indicting the relative performance of a service package, where a 5-star and 1-star award is respectively given to the best and the worst 10% samples.

A free mobile application of IEQ calculator for apartment IEQ assessment can be downloaded by smart phone via both iOS and Android system platform, with general information listed on the 'Description' section. After installing the application, an interface for parameter input will be displayed. Fig. 2 exhibits the input interface of the apartment application-based calculator. Target users are occupants without professional-grade measuring tools. It is assumed that the air temperature is equivalent to the radiant temperature at home, the air velocity is 0.2ms^{-1} when the fan is ON or 0.02ms^{-1} when the fan is OFF, and the CO_2 concentration is associated with the window status, apartment floor area A_f (m^2) and number of participants at instant N (ps). Mathematical expressions for CO_2 concentration in apartments are summarized in (8)–(10), where the per occupant CO_2 generation rate is assumed to be 0.00517 Ls^{-1}ps^{-1}, A_{ch} is the air change rate (h^{-1}), Q is the volume flow rate (Ls^{-1}), and C_{in}, C_o and C_s are respectively the indoor, outdoor and occupant-generated CO_2 levels (ppm) [9], [10].

$$C_{in} = \frac{QC_o + C_s}{Q} \tag{8}$$

$$Q = \frac{A_f \times 2.7 \times A_{ch}}{3.6} \qquad \begin{cases} window\ \ Open & A_{ch} = 1.5h^{-1} \\ window\ \ Close & A_{ch} = 0.5h^{-1} \end{cases} \qquad [10]\ (9)$$

$$C_s = 0.00517 \times N \tag{10}$$

Sample input with environmental parameters for apartment is presented in Fig. 2. IEQ acceptance calculation can be performed by clicking the 'Calculate' button after adjusting the desire input parameters. The calculation results will be displayed on an additional screen as shown in Fig. 2. These output examples showed that, regarding the input parameters of concerned apartment environment, (i) the predicted thermal perception (Hot, Warm, Slightly Warm, Neutral, Slightly Cool. Cool, Cold) with optimal clothing value, (ii) the predict IAQ, lighting and sound level acceptance (Dissatisfactory, Acceptable, Good) and (iii) the relative IEQ acceptance performance as compared with our database using the star rating expression (1 to 5 star).

As demonstrated in Fig. 2, a 'Slightly Warm' apartment (T_a = 25^{o}C, R_h = 50% and the fan is off) with 'Good' lighting (350lux) and an 'Acceptable' sound level (60dBA) will be awarded a 5-star rating under the proposed prediction system even if its IAQ is 'Dissatisfactory' (windows closed) because the feedback on its significant IEQ contributors is positive [4].

(a)

(b)

(c)

Fig. 2 Input interface of the apartment IEQ calculator

This calculator allows apartment residents to assess the basic IEQ performance in their living space without complex measurements and provides them with IEQ improvement alternatives such as the use of fans, lights and windows. The calculator can also suggest how to achieve the best IEQ acceptance among a group of residents.

V. Conclusions

Lai et al. [4] established an IEQ index that indicates the overall IEQ acceptance from the prospect of an occupant in residential buildings in terms of four IEQ factors - thermal comfort, IAQ, visual and aural comforts. The model allows the prediction of the best IEQ scenario on a quantitative scale. Any indoor environments under the specific IEQ conditions can be benchmarked against the predicted IEQ acceptance range.

Using the same model, this study developed a user-friendly IEQ calculator for iOS and Android users to calculate the occupant acceptance and compare the relative performance of IEQ in apartments. The calculator can also suggest how to achieve the best IEQ acceptance among a group of residents. Considering the flexibility in clothing change, the model protocol adopted an adaptive thermal comfort approach that occupants' clothing value would be optimised for the perceived thermal environment. IEQ calculator for apartment would provide information of existing IEQ performance to residents in which to strengthen their awareness on IEQ in the living place.

Acknowledgment

The work described in this paper was substantially/partially supported by Internal Competitive Research Grant (CRG: G-YL19), The Hong Kong Polytechnic University, Hong Kong Special Administrative Region, China, and The Environment and Conservation Fund (ECF: K-ZJJV), The Government of the Hong Kong Special Administrative Region, China.

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