Energy impact of indoor environment quality acceptance for air-conditioned offices of Hong Kong

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Abstract

Indoor environmental quality (IEQ) in air-conditioned offices of Hong Kong can be benchmarked by an IEQ index associated with thermal comfort, indoor air quality, aural and visual comfort. Maintaining an acceptable IEQ for air-conditioned office buildings to occupants consumes a considerable amount of thermal energy. This study correlates thermal energy consumption with the overall occupant acceptance of IEQ in some air-conditioned offices dominated by the thermal comfort and the indoor air quality by dilution. With the input parameters of the building stocks in Hong Kong, the office portfolios regarding the thermal energy consumption and the IEQ index are determined by Monte Carlo simulations. This study reports the unit increment of thermal energy use for the target IEQ acceptance level for air-conditioned offices of Hong Kong and the thermal energy consumption corresponding to a desirable percentage of IEQ acceptances respectively. The results showed a non-linear increasing trend of annual thermal energy consumption for IEQ improvement at the offices of higher IEQ benchmarks. The thermal energy consumption for visual comfort and indoor air quality would also be significant in these offices. This study provides useful information to evaluate thermal energy impact due to the desired IEQ in air-conditioned offices.

Keywords

Indoor environmental quality, thermal energy consumption, air-conditioned offices, occupant acceptance, benchmarks

1. Introduction

Hong Kong, characterized with its ‘hot and humid’ climates, is a developed city with many air-conditioned high-rise commercial buildings. In Hong Kong, the commercial sector accounted for 61% of the 40000 GWh yr^{-1} total annual energy consumption in 2005 [1]. It was reported that an environmental control system maintaining a desirable indoor environment would consume more than half of the total electrical energy of a commercial building. Electricity consumption of an environmental control system would be greatly influenced by the choice of the desired environmental condition. Maintaining a satisfactory indoor environmental quality (IEQ) to the occupants by adjustable indoor environmental set points regarding thermal comfort, aural comfort, visual comfort and indoor air quality (IAQ) were the primary concern in many office buildings [2].

Unfortunately, many energy-saving approaches such as reduction of fresh air supply or increase indoor air temperature set point in summer seasons would require a ‘trade-off’ in the delivery of indoor satisfaction. An environmental control system undergoing economic operations for energy conservations in offices that insufficiently addressed the IEQ acceptance regarding thermal comfort, IAQ, visual and aural needs of some occupants would result in complaints of the indoor environment.

IEQ has been adopted in some building grading systems and can be used to benchmark an office environment [2-3]. The assessments would form part of environmental performance evaluation and diagnosis in workplaces to correlate the reported health symptoms, comfort or odor concerns. In spite of that, many assessments of IEQ focused on some individual environmental aspects, e.g. the thermal comfort, the IAQ, the aural or the visual comfort [2, 4-6]. Indeed, IEQ as a measure for the indoor environmental satisfaction would not be properly rooted in the minds of many building occupants.

In this study, some benchmarked air-conditioned buildings for Hong Kong were investigated using the Monte-Carlo simulations regarding thermal energy consumption. The potential of energy consumption and the occupant votes for IEQ acceptance for benchmarked offices were investigated respectively.

2. Indoor environmental quality (IEQ)

An expression of the IEQ index θ shown below is a quantitative measure for IEQ acceptance which can be used to rank or benchmark the IEQ of an air-conditioned office environment, where $k_i = [-15.02, 6.09, 4.88, 4.74, 3.70]$ are the regression constants for $i = 0 \ldots 4$ [2],

$$\theta = 1 - \frac{1}{1 + \exp\left(k_0 + \sum_{i=1}^{4} k_i \phi_i(\zeta_i)\right)} \qquad \ldots (1)$$

An index $\theta \geq 0.9$, $0.8 \leq \theta < 0.9$, $0.4 \leq \theta < 0.8$ and $\theta < 0.4$ indicate office IEQ ranks of 'Good', 'Average', 'Below average' and 'Bad' respectively [2]. The index θ can be used for the same purpose via a star rating system with a benchmarking value B_j of an air-conditioned office j among all offices in Hong Kong, in which 5 stars are assigned to the top 10% offices ($B_j \geq 0.9$) with best IEQ, 4 stars to the next 22.5% ($0.675 \leq B_j < 0.9$), 3 stars to the next 35% ($0.325 \leq B_j < 0.675$), 2 stars to the next 22.5% ($0.1 \leq B_j < 0.325$) and 1 star to the bottom 10% ($B_j < 0.1$) [7], where the benchmarking value B_j is determined from an occupant's IEQ acceptance of the space θ_j, which is the percentile of the cumulative frequency distribution of the occupant's IEQ acceptance in offices,

$$B_j = \int_{-\infty}^{\theta_j} \tilde{\theta}\, d\theta \qquad \ldots (2)$$

The occupant's IEQ acceptance of the space θ is correlated with the acceptance levels of the thermal environment ϕ_1, the IAQ ϕ_2, the aural environment ϕ_3 and the visual environment ϕ_4 as follows, where ζ_1 (%) is the predicted percentage dissatisfaction (PPD) of thermal comfort, ζ_2 (ppm) is the CO_2 concentration, ζ_3 (dBA) is the equivalent noise level and ζ_4 (lux) is the illumination level [5, 8-10],

$$\phi_1 = 1 - \frac{\zeta_1}{100} \qquad \ldots (3)$$

$$\phi_2 = 1 - \frac{1}{2}\left(\frac{1}{1 + \exp(3.118 - 0.00215\,\zeta_2)} + \frac{1}{1 + \exp(3.230 - 0.00117\,\zeta_2)}\right); \quad 500 \leq \zeta_2 \leq 1800 \qquad \ldots (4)$$

$$\phi_3 = 1 - \frac{1}{1 + \exp(9.540 - 0.134\,\zeta_3)}; \; 45 \leq \zeta_3 \leq 72 \qquad \ldots (5)$$

$$\phi_4 = 1 - \frac{1}{1 + \exp(-1.017 + 0.00558\,\zeta_4)}; \; 200 \leq \zeta_4 \leq 1600 \qquad \ldots (6)$$

The PPD ζ_1 is determined from the predicted mean vote (PMV) index γ which, correlated with the optimal thermal comfort of an occupant in chamber tests, is a function of air temperature T_s (ºC), relative humidity R_h (%), air velocity v_s (ms^{-1}), radiant temperature T_r (ºC), occupant metabolic rate M_e (Met) and clothing volume C_L (clo) [11], i.e. $\gamma \sim \gamma(T_s, R_h, v_s, T_r, M_e, C_L)$.

The PMV index γ was reviewed in open literature [11-12]. Some field studies of direct measurement for thermal acceptability reported a narrower operative temperature range for 80% thermal acceptability than those specified in current design guidelines [13].

This study also found a narrow thermal comfort acceptance range of PMV when compared with the chamber tests. It was reported that, in calculating ζ_1, the preferred PMV γ^* would be correlated with the Fanger's PMV index γ by the following equation (R=0.9876, p<0.001, t-test),

$$\gamma^* = 3.86\,\gamma + 3.05;\ -3 \le \gamma^* \le +3 \qquad \ldots (7)$$

Hence, the PPD ζ_1 (%) is determined by [11, 13],

$$\zeta_1 = 100 - 95\exp\left(-0.03353\gamma^{*4} - 0.2179\gamma^{*2}\right) \qquad \ldots (8)$$

It should be noted that an office occupant will adjust his/her clothing volume C_L to the working environment for maximum thermal acceptance (comfort) $\phi_{1,max}$, i.e. $\phi_1(C_L) = \phi_{1,max}$.

3. Thermal energy consumption

Thermal energy consumption for air-conditioned office buildings in Hong Kong was reviewed as follows [14-15]. Taking account of the conductive heat gain through the building fabric E_{en} (kWh m^{-2} yr^{-1}) and the heat generated by ventilation E_{ve} (kWh m^{-2} yr^{-1}) as well as all other internal loads E_{in} (kWh m^{-2} yr^{-1}) including the occupants E_{oc} (kWh m^{-2} yr^{-1}), lighting system E_{li} (kWh m^{-2} yr^{-1}) and electrical equipment E_{eq} (kWh m^{-2} yr^{-1}), the normalized annual thermal energy consumption for an air-conditioned office E_c (kWh m^{-2} yr^{-1}) is approximated by,

$$E_c = E_{en} + E_{ve} + E_{in};\ E_{in} = E_{oc} + E_{li} + E_{eq} \qquad \ldots (9)$$

The thermal energy consumption through the building fabric E_{en} can be approximated by a multivariate regression model given below, where T_s (ºC) is the indoor air temperature, $L_{f,max}$ (m) is the maximum length of the floor, A_f (m^2) is the floor area, V_f (m^3) is the floor volume, U_{ww} (W m^{-2} K^{-1}) is the average U-value of floor envelope, r_w is the window-to-wall ratio, S_c is the shading coefficient, ε is an error term approximated by a geometrical distribution with a geometric mean of 1 and a geometric standard deviation of 1.4623 [16].

$$\widetilde{E}_{en} = 27749 T_s^{-0.8833} A_f^{-0.7861} V_f^{0.2205} r_w^{0.3936} L_{f,max}^{0.3670} U_{ww}^{0.3591} S_c^{0.4948} + \varepsilon;$$
$$L_{f,max} = \max(L_f, W_f) \qquad \ldots (10)$$

The average U-value of floor envelope U_{ww} is the sum of window U_{wd} (W m^{-2} K^{-1}) and wall U_{wl} (W m^{-2} K^{-1}) U-values weighted by the window area A_{wd} (m^2) and wall area A_{wl} (m^2),

$$U_{ww} = \frac{A_{wd}U_{wd} + A_{wl}U_{wl}}{A_{wd} + A_{wl}};\ r_w = \frac{A_{wd}}{A_{wd} + A_{wl}} \qquad \ldots (11)$$

By defining N_d (d yr^{-1}) as the number of working days per year and O_a (hd m^{-2}) as the occupancy factor, the normalized annual energy consumption for ventilation E_{ve} (kWh m^{-2} yr^{-1}) can be approximated by a regression equation,

$$E_{ve} \approx 3.5 \times 10^8 \zeta_2^{-2.01} T_s^{-0.33} O_a^2 N_d \quad \ldots (12)$$

Based on the total working hours in a year N_h (h yr^{-1}), the thermal energy consumption for the internal loads E_{in} (kWh m^{-2} yr^{-1}) is the sum as shown below, where P_{oc} (W hd^{-1} m^{-2} h^{-1}) is the normalized hourly 'per person' thermal energy consumption while P_{li} (W m^{-2} h^{-1}) and P_{eq} (W m^{-2} h^{-1}) are the normalized hourly thermal energy consumption for lighting and other electrical equipment respectively,

$$E_{in} = E_{oc} + E_{li} + E_{eq} = 0.2778 \times 10^{-6} \times \left(\sum_{i=1}^{N_h} O_a P_{oc,i} + \sum_{i=1}^{N_h} P_{li,i} + \sum_{i=1}^{N_h} P_{eq,i} \right) \quad \ldots (13)$$

The thermal energy consumption by an occupant P_{oc} (W hd^{-1} m^{-2} h^{-1}) is related to the occupant's metabolic rate M_e (Met), where 1 Met is taken as 58.2 W m^{-2} for an average person surface area of 1.86 m^2,

$$P_{oc} = 108.25 M_e \quad \ldots (14)$$

The hourly lighting load density P_{li} (W m^{-2} h^{-1}) is related to the illumination level ζ_4 (lux),

$$P_{li} = 14.92 \zeta_4^{1.16} \quad \ldots (15)$$

This model has been verified with data available in open literature. For a standard Hong Kong office floor of an area in between 230 and 6600 m^2, a window-to-wall ratio r_w in between 0.25 and 0.64, and a floor envelop U-value U_{ww} in between 2.4 and 2.7 W m^{-2} K^{-1}, this energy consumption model would under-predict the fabric load by 2.5% on average [17]. For those office floors with r_w ranging from 0 to 1 and U_{ww} from 0.51 to 4.21 W m^{-2} K^{-1}, 63% of the simulation cases were found within the ±20% consumption prediction, while 37% of the cases were in the 20-50% 'overestimation' range [18].

4. Thermal energy consumption with relation to IEQ in air-conditioned offices

The thermal energy consumption model was applied to air-conditioned offices in Hong Kong for the correlation with office IEQ. All input parameters were obtained from the open literature on apposite survey studies for this region [16-18]. Table 1 summarizes the key thermal properties of building fabric, existing indoor environmental conditions, heat contents generated indoors, working hours, illumination level, equivalent noise level, thermal comfort parameters and occupant attributes retrieved. In particular, this study sampled the model input parameters, i.e. IEQ parameters (e.g. T_s, R_h, v_s, T_r/T_s, ζ_2,

ζ_3), occupant attributes, building fabric characteristics and electrical load densities, from distribution functions of the parameters shown in Table 1 via the Monte Carlo sampling technique.

Table 1 – Parameters for IEQ simulations

Parameter φ	Range (average)
Floor area A_f (m^2)	200-3000 (900)
Floor space volume V_f (m^3)	600-15000 (3500)
Floor length and width L_f, W_f (m)	14-54 (30)
Window-to-wall ratio r_w	0.2-0.8 (0.5)
U-value of wall U_{wl} ($W\ m^{-2}\ K^{-1}$)	0.57-3.41 (2.0)
U-value of window U_{wd} ($W\ m^{-2}\ K^{-1}$)	2.97-6.16 (4.5)
Shading coefficient S_c	0.1-0.9 (0.47)
Occupancy factor O_a ($hd\ m^{-2}$)	0.05-0.12 (0.074)
Occupant thermal load P_{oc} ($W\ hd^{-1}$)	94-170 (128)
Lighting system load P_{li} ($W\ m^{-2}$)	10-30 (23)
Indoor air temperature T_s (ºC)	18-26 (22)
Relative humidity R_h (%)	30-80 (60)
Air velocity v_s (ms^{-1})	0.05-0.41 (0.27)
Radiant-to-air temperature ratio T_r/T_s	0.9-1.12 (1.003)
Clothing volume C_L (clo)	0.3-1.8 (0.73)
Indoor CO_2 concentration ζ_2 (ppm)	500-1400 (865)
Equivalent noise level ζ_3 (dBA)	46-66 (56)
Illumination level ζ_4 (lux)	200-1000 (600)
Electrical equipment load P_{eq} ($W\ m^{-2}$)	5-25 (12)
Number of working hours in a year N_h ($h\ yr^{-1}$)	2600

Input parameters φ_i (dummy variables) shown in Table 1 were sampled from the distribution functions $\tilde{\varphi}_i$. The simulation procedure process was as follows. A random number $x \in [0,1]$ was taken from a random number set, which was generated by a prime modulus multiplicative linear congruential generator [19]. Input value $\varphi_{i,x}$ of each parameter φ_i was determined from the descriptive distribution function $\tilde{\varphi}_i$ at the percentile x,

$$\varphi_i = \varphi_{i,x}\ ;\ \int_{-\infty}^{\varphi_{i,x}} \tilde{\varphi}_i d\varphi_i = x\ ;\ \varphi_i \in \tilde{\varphi}_i \qquad \ldots (16)$$

Energy consumption and the corresponding environmental acceptance of the input parameters φ_i of a simulation step were then determined using equations (1) to (15). The simulations were repeated for 10000 times in order to approximate the probable office environments, i.e., the corresponding changes of the expected values and variances of the output parameters, e.g. average thermal energy consumption and IEQ index, were all kept below 0.01% for further simulation to be conducted.

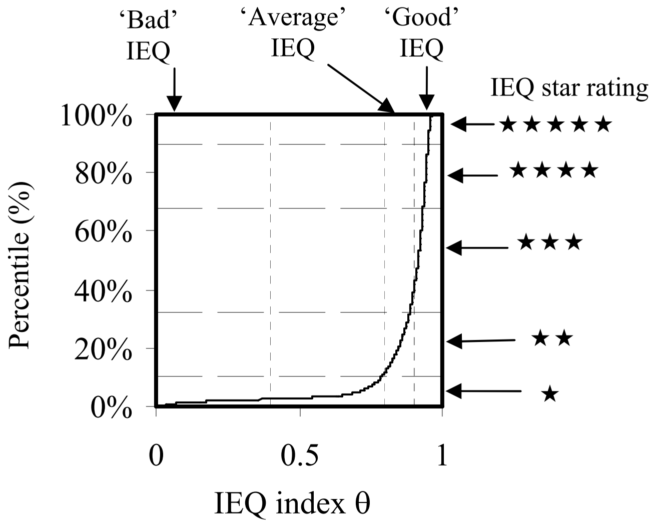

Fig. 1 – IEQ acceptance index for air-conditioned offices in Hong Kong

Simulation results showed that the office samples would associate with an IEQ index θ ranged between 0.005 and 0.969. Figure 1 shows the cumulative frequency distribution of the simulated office IEQ index classified by both of the absolute ranking system and the relative star rating system. The results showed that respectively: (1) 60.3%, 28.1% and 2.5% offices would be ranked as 'Good', 'Average' and 'Bad'; (2) offices with $\theta \geq 0.95$, $0.93 \leq \theta < 0.95$, $0.89 \leq \theta < 0.93$, $0.79 \leq \theta < 0.89$ and $\theta < 0.79$ would be awarded 5 stars, 4 stars, 3 stars, 2 stars and 1 star. The IEQ in all of the benchmarked 4- or 5-star air-conditioned offices in Hong Kong was ranked as 'Good'; the IEQs in around 80% and 20% of the benchmarked 3-star offices were ranked as 'Good' and 'Average' respectively. Moreover, 'Average' IEQ was recorded in over 90% of the 2-star offices while 'Bad' IEQ was registered in about 25% of the 1-star ones.

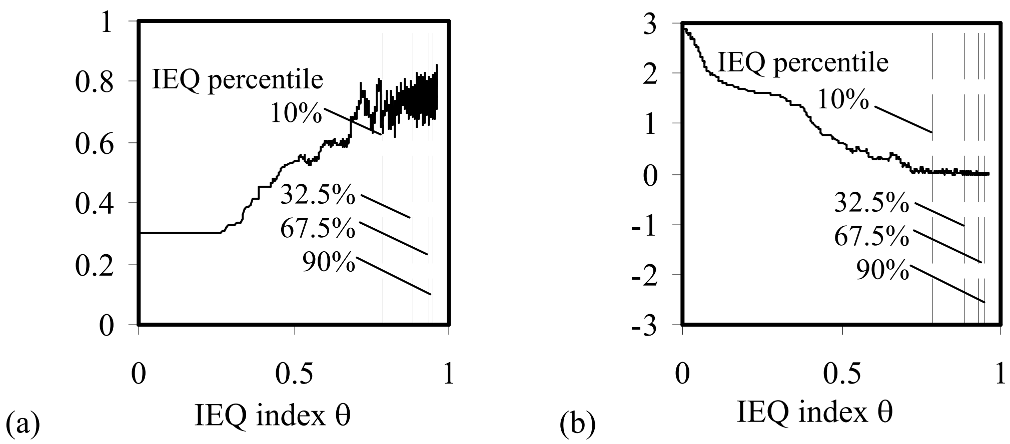

Fig. 2 – Adaptive response of occupants: (a) clothing volume; (b) PMV index

Figure 2(a) shows the average clothing volume C_L of occupants in an office environment against an IEQ index θ; the corresponding PMV index is shown in Figure 2(b). In these figures, the benchmarks (i.e. star ratings j=1 to 5) were partitioned by the percentile lines of 10%, 32.5%, 67.5% and 90% (representing the acceptance values of 0.79, 0.89, 0.93 and 0.95 respectively) of the index θ. The results indicated that occupants in over 90% offices would adjust their respective clothing volumes for maximum thermal comfort (i.e. PMV index close to 0, thermally neutral). According to the standard, a clothing volume is equivalent to thermal insulation of 0.155 m^2 ºC W^{-1}. On an office chair as a reference, the clothing value for an occupant with trousers and a long-sleeved shirt on was 0.71 clo, or 0.77 clo for an occupant wearing a full slip, a knee-length skirt and a long-sleeved shirt. Reportedly, the average clothing values for the maximum thermal acceptance in the benchmarked 2- to 5-star offices were 0.73 to 0.75 clo. However, clothing volume in 1-star offices was further reduced and the average C_L was 0.58 clo. For some extreme cases as shown in Figure 2, warmth/hotness (PMV>+2) was reported even though C_L was adjusted down to 0.3 clo. It was also noted that the clothing volume of a walking occupant with a short-sleeved shirt on was 0.36.
The average operative temperatures T_{op} (ºC) in offices determined for the IEQ benchmarks j=1 to 5 were 23.1ºC, 22.4ºC, 22.3ºC, 22.2ºC and 22.1ºC respectively. Except the significantly higher average (i.e. 23.1ºC) found in the 1-star offices ($p<0.0001$, t-test), all other averages were lower than the preferred operative temperature (22.6ºC±1.7ºC) as well as the default operative temperature (22.8ºC±0.7ºC) surveyed in some Hong Kong air-conditioned offices ($p\leq 0.05$, t-test) [5]. Larger variations of the operative temperature range with lower benchmarks were also observed.

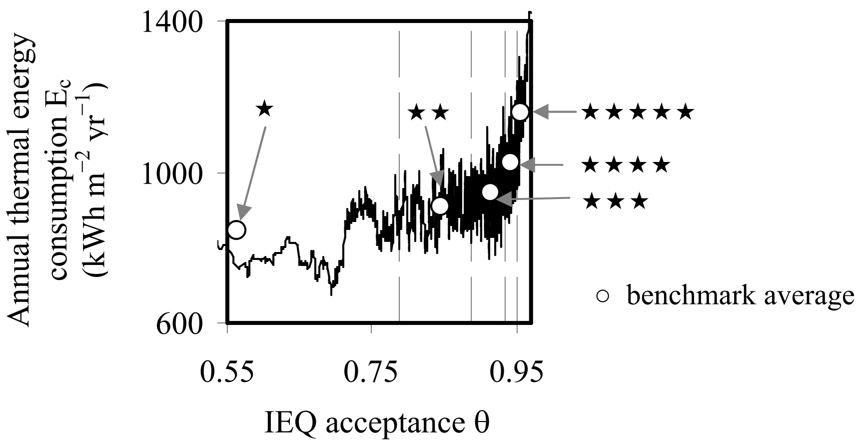

Fig. 3 – Annual thermal energy consumption for air-conditioned offices in Hong Kong

Figure 3 shows the annual thermal energy consumption against IEQ acceptance for air-conditioned offices in Hong Kong. A non-linear increasing trend was observed in those offices of higher IEQ benchmarks, where energy consumption for visual and IAQ acceptance would be significant as well. It was reported that the expected thermal energies required to raise the IEQ index by 0.01 for 2-, 3-, 4- and 5-star offices were 2, 6, 28 and 95 kWh m^{-2} yr^{-1} respectively. Correlation between annual thermal energy consumption and IEQ star ratings for the offices was found significant in the results ($p \leq 0.005$, t-test).

The thermal energy consumption for the IEQ index can be expressed by an energy-to-acceptance ratio α (kWh m^{-2} yr^{-1}),

$$\alpha = \frac{E_c}{100 \times \theta} \qquad \text{… (17)}$$

The results showed that for all 'Average' and 'Good' offices, the expected energy-to-acceptance ratio was α=10.5 kWh m^{-2} yr^{-1}; an exception was the benchmarked 5-star offices where generally 14% more thermal energy (i.e. α=12 kWh m^{-2} yr^{-1}) was consumed to maintain the high acceptance.

The additional thermal energy required for an office to move one benchmark up (e.g. from 1 star to 2 stars) can be evaluated by the energy-to-IEQ improvement ratio β_j (kWh m^{-2} yr^{-1}),

$$\beta_j = \frac{E_{c,j+1} - E_{c,j}}{100 \times \left(\theta_{j+1} - \theta_j\right)}\ ;\ j=1\ldots4 \qquad \text{… (18)}$$

Respectively, the reported energy-to-IEQ improvement ratios and the corresponding percentage ratios for the benchmarked 1-, 2-, 3- and 4-star offices were β_j=2.2, 5.6, 28 and 95 kWh m^{-2} yr^{-1}. They indicated a non-linear relationship between thermal energy consumption and IEQ upgrade.

5. Conclusion

This study presented mathematical expressions to correlate thermal energy consumption with the overall occupant acceptance of IEQ in some air-conditioned offices dominated by the thermal comfort and the indoor air quality by dilution. Using the survey parameters for office building stocks of Hong Kong, the distribution profiles of office environmental quality and the associated thermal energy consumption were determined by Monte Carlo simulations.

For the benchmarked air-conditioned offices in Hong Kong, the IEQ index was $\theta \geq 0.95$ for the top 10% offices (i.e. 5-star rating), $0.93 \leq \theta < 0.95$ for the next 22.5% (4-star rating), $0.89 \leq \theta < 0.93$ for the next 35% (3-star rating), $0.79 \leq \theta < 0.89$ for the next 22.5% (2-star rating), and $\theta < 0.79$ for the bottom 10% (1-star rating). The performance of energy consumption for the IEQ in the air-conditioned offices was measured by an energy-to-acceptance ratio which indicated the thermal energy consumption corresponding to a desirable percentage of IEQ acceptances, and an energy-to-IEQ improvement ratio which described the additional thermal energy required for an IEQ upgrade. It was found that the expected energy-to-acceptance ratio was 10.5 kWh m^{-2} yr^{-1} for all 'Average' and 'Good' offices, except for the benchmarked 5-star offices where 14% more thermal energy (i.e. a ratio value of 12 kWh m^{-2} yr^{-1}) was consumed to maintain the high acceptance. Moreover, for the benchmarked 1-, 2-, 3- and 4-star offices, the energy-to-IEQ improvement ratios were 2.2, 5.6, 28 and 95 kWh m^{-2} yr^{-1}, respectively. A non-linear increasing trend of annual thermal energy consumption for IEQ improvement was observed in those offices of higher IEQ benchmarks, where thermal energy consumption for visual comfort and indoor air quality would also be significant. This study provides useful information that incorporates the IEQ in air-conditioned offices into the development of performance evaluation measures for thermal energy consumption.

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