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An open acceptance model for indoor environmental quality (IEQ)

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Abstract

Indoor environmental quality (IEQ) acceptance prediction is crucial to sustainable building development. A simple yet comprehensive IEQ modelling strategy that can genuinely reflect occupant's responses to environmental conditions is necessary. This study proposes an open acceptance model that uses frequency distribution functions of occupant's responses towards IEQ parameters to assess IEQ. The proposed model is not only flexible enough to encapsulate a diverse range of descriptive model parameters but also feasible for openly available IEQ acceptance data, offering the flexibility to add data incrementally to allow easy model updating as and when a new set of observations arrives, this model can be a solution to the existing problems and limitations encountered in IEQ modelling.

Keywords

Indoor environmental quality (IEQ); Open acceptance model; Thermal comfort; Indoor air quality; Visual comfort; Aural comfort

Introduction

Modern people stay indoor most of the time. Indoor environmental quality (IEQ) has become a major concern for sustainable development as it affects occupant's health and well-being [1–2]. Studies on linkage between IEQ and occupant's comfort, health and productivity can be found in the literature [3–10]. Some research discuss the relationship between IEQ and one particular parameter [11–14], some look at the effects of multiple parameters on the overall IEQ [15–20]. It has been found that maintaining an acceptable indoor environment through controlling a range of IEQ parameters could provide positive effects on one's well-being [20–23], but the relationship between them are complex [24]. Contributions of these parameters to the occupant's overall acceptance are non-uniform in different indoor environments, i.e. one IEQ parameter dominate over another [25–27]. For instant, study showed that aural comfort is the most important contributors to the overall IEQ acceptance in learning environment, while thermal comfort is more important in workplace [28–29]. IEQ acceptance is intricate and shall be addressed at the design stage and throughout the lifecycle of the building to protect the willingness of occupants [24,30] and IEQ acceptance models therefore are important and useful for building designers and facility management when making decisions regarding the building performance.

Models for predicting occupant's responses towards individual IEQ parameters as well as overall IEQ acceptance have been proposed. IEQ could be expressed by various physical parameters [16,21]. Overall IEQ expressed by four major IEQ aspects, namely thermal comfort, indoor air quality (IAQ), visual comfort and aural comfort were proposed [28–29,31–32]. Multivariate logistic regression models for IEQ acceptance in offices, classrooms and residential buildings in Hong Kong were developed [28–29,31]. Moreover, an indexing approach for IEQ assessment was proposed to correlate a set of independent parameters (including climate, building shape and window/wall noise attenuation) with the four major IEQ aspects [32]. A Dwelling Environmental Quality Index was developed to reflect the indoor quality based on the air temperature, relative humidity and carbon dioxide level [33].

Despite large database was used to develop the existing IEQ multivariate logistic regression model which shall be statistical comprehensive enough to represent most indoor environments, it is found to be not promising to describe less favorable indoor environments with poor environmental conditions in very small residential units [34]. It was reported that changing the environmental conditions did not significantly affect the IEQ acceptance when the perception of an indoor space is already adapted. Psychological effects would also influence occupant's IEQ acceptance of an environment. It seems that the predicted acceptance to IEQ parameters could also be influenced by the selection of logistic regression. Discrepancies between predicted IEQ and the actual result of a building performance model were reported of policy significance and the selection of regression model had significant influences to the assessment results [35]. Another study reported huge differences among predictions of seven thermal sensation models suggest the consequence of model selection in environmental prediction practice [36].

Furthermore, a recent study suggested additional IEQ parameters, such as privacy, cleaning and maintenance, vibration and movement, and technology could influence occupant's perception of indoor environment quality [16]. With more contributing parameters being suggested to model IEQ, developing a flexible model framework open to more parameters and their contributions to IEQ with latest available data is therefore essential [37–38].

The robustness of IEQ acceptance prediction models is crucial to sustainable building development [39]. The earlier proposed IEQ models for air-conditioned offices, classrooms and residential buildings [28–29, 31] showed limited flexibility to align with the call for the inclusion of additional IEQ parameters. Collective occupant responses expressed by multivariate logistic regressions were not promising. Indeed, the proposed regressions are yet to be confirmed for other indoor environment or similar environment of deviated conditions [34]. This study proposes an IEQ probabilistic acceptance model that uses frequency distribution functions of occupant's responses towards IEQ. This study aims at providing another IEQ model for occupant's acceptance prediction which allows simpler model updating with frequency distributions used, and is more robust in reflecting occupant's psychological perception towards the indoor environment. The proposed model is free from assumptions of regressions and is flexible to a diverse range/ type of IEQ parameters as well as to the inclusion of new parameters.

This paper first describes the method for developing the open probabilistic acceptance model and evaluates its prediction performance by comparing with existing IEQ logistic regression models with data available in open literature [28–29,31]. The characteristics of the two models and the future development of IEQ modelling are then discussed.

Nomenclature			
x_i	Level of environmental parameter	n_s	Acceptance sample size
δ_i	Acceptance to environmental parameter	n_u	Unacceptance sample size
j	Environmental conditions correspond to environmental parameter i	$\tilde{x}_s$	Collective acceptance occupant responses to the environment
φ_j	Occurrence of environmental condition j	$\tilde{x}_u$	Collective unacceptance occupant responses to the environment
ρ_j	Acceptance to environmental condition j	y_s	Cumulative frequency distributions for the mass density functions of parameters $\tilde{x}_s$
Φ	Overall IEQ acceptance	y_u	Cumulative frequency distributions for the mass density functions of parameters $\tilde{x}_u$
$[a, b]$	Range of level of environmental parameter	x_1	Operative temperature
θ_{su}	Environmental acceptance	x_2	Carbon dioxide (CO_2) level
θ_s	Acceptance	x_3	Equivalent noise level
θ_u	Unacceptance	x_4	Illumination level
x_{su}	Occupant votes	μ	Mean
$\tilde{x}_{su}$	Probability density function of normalized occupant votes	σ	Standard deviation
x^*_{su}	Level of environmental parameter when acceptance and unacceptance are equal	ε_M	Maximum absolute errors
		PMV	Predicted Mean Vote

IEQ acceptance model

It has been found that existing IEQ logistic regression model is not promising to represent occupant's responses and acceptances. Proposed open IEQ acceptance model in this study is developed based on frequency distribution functions of occupant's responses towards IEQ parameters. It shall be flexible to various IEQ parameters and allow easy model updating.

The overall acceptance of an indoor environment is defined by a number of acceptances δ_i of the respective environmental parameters x_i,

$$\delta_i \sim \delta(x_i) \tag{1}$$

A total of $j = 1, 2, 3,\ldots, i^2-1, i^2$ environmental conditions can be formed as a result. The occurrence of these conditions φ_j is given by Eq. (2), while the acceptance ρ_j with respect to each environmental condition can be expressed by Eq. (3).

$$\begin{aligned}\varphi_j = [&(1-\delta_1)(1-\delta_2)(1-\delta_3)\ldots(1-\delta_{i-1})(1-\delta_i), (1-\delta_1)(1-\delta_2)(1-\delta_3)\ldots(1-\delta_{i-1})(\delta_i),\\ &(1-\delta_1)(1-\delta_2)(1-\delta_3)\ldots(\delta_{i-1})(1-\delta_i), \ldots\ldots, (\delta_1)(\delta_2)(\delta_3)\ldots(\delta_{i-1})(1-\delta_i),\\ &(\delta_1)(\delta_2)(\delta_3)\ldots(\delta_{i-1})(\delta_i)]\end{aligned} \tag{2}$$

$$\rho_j = \left[\rho_1, \rho_2, \rho_3, \ldots, \rho_{i^2-1}, \rho_{i^2}\right] \tag{3}$$

The overall IEQ acceptance Φ is given by,

$$\Phi = \sum_{j=1}^{i^2} \varphi_j \rho_j \tag{4}$$

The acceptance of an environmental parameter x in the range $x \in [a, b]$ can be from acceptance (δ=1) to unacceptance (δ=0) and vice visa. Hence, the acceptance function δ of an environmental parameter is,

$$\delta = \begin{cases} 1 - \int_a^x \tilde{x}_{su} dx & \delta(a) > \delta(b) \\ \quad ; & \\ \int_a^x \tilde{x}_{su} dx & \delta(a) < \delta(b) \end{cases} \quad (5)$$

$\tilde{x}_{su}$ is the probability density function of normalized occupant votes for the environmental acceptance θ_{su} as expressed in the following two equations, where θ_{su}=1 indicates there are no dominant votes for acceptance or unacceptance, i.e. $\theta_s = \theta_u$ at $x = x^*_{su}$,

$$\tilde{x}_{su} = \frac{\theta_{su}}{\int_a^b \tilde{\theta}_{su} dx} \quad (6)$$

$$\theta_{su}(x) = 1 - |\theta_s - \theta_u| \quad (7)$$

Percentage votes for acceptance θ_s and unacceptance θ_u with sample sizes n_s and n_u are given by the below expressions, where y_s and y_u are the cumulative frequency distributions for the mass density functions of parameters $\tilde{x}_s$ and $\tilde{x}_u$, respectively,

$$\theta_s = \frac{n_s y_s}{n_s y_s + n_u y_u}; \quad \theta_u = \frac{n_u y_u}{n_s y_s + n_u y_u} \quad (8)$$

$$y_s = 1 - \int_a^x \tilde{x}_s dx; \quad y_u = \int_a^x \tilde{x}_u dx \quad (9)$$

$\tilde{x}_s$ and $\tilde{x}_u$, which are the collective occupant responses to the environment, can be obtained from site survey studies.

Data

Occupant responses to four indoor environmental aspects, namely thermal comfort, IAQ, noise level and illumination level, in air-conditioned offices, residential buildings and university classrooms were reviewed [28–29,31,40–42]. Table 1 summarizes the response data under two groups (satisfaction and dissatisfaction) in terms of four (surrogate) parameters: operative temperature x_1, carbon dioxide (CO_2) level x_2, equivalent noise level x_3 and illumination level x_4. The probability density functions of $\tilde{x}_s$ and $\tilde{x}_u$ are approximated by the following expressions, where μ and σ are the mean and standard deviation respectively,

$$\tilde{x}_s = x_s(\mu_s, \sigma_s); \quad \tilde{x}_u = x_u(\mu_u, \sigma_u) \quad (10)$$

Generally, the sample size of the dissatisfaction group was around 5–15% of that of the satisfaction group (a typical result from surveys for any built environments designed to suit the majority). However, for the CO_2 levels in classrooms and offices, the sample sizes of the dissatisfaction groups increased to 20–40%. It was noted that classroom and office occupants usually could not adjust the quantity of fresh air supply, and that might be the reason why.

It was also noted that although relatively large deviations were found within the response data, the average values between satisfaction and dissatisfaction groups in the survey studies were similar, e.g. the illumination level in classrooms (p=0.8, t-test) and the CO_2 level in residential buildings (p=0.7, t-test). For the equivalent noise level in classrooms, the means were equal between the two groups (p>0.95, t-test). There was one case in which the standard deviations were larger than the means (i.e. the illumination level in residential buildings).

Table 2 summarizes the occupant acceptances Φ under 16 environmental conditions in residential buildings, classrooms and offices regarding the four environmental parameters x_1 to x_4. Predicted acceptances made by the existing IEQ equations (i.e. the existing IEQ logistic regression model) from previous studies are presented for comparison [28–29,31]. It can be seen that the predictions made were good for offices but not so for residential buildings and classrooms. It should be noted that small sample sizes ($n \leq 5$) were reported in 6, 12 and 11 (out of 16) environmental conditions for residential buildings, classrooms and offices respectively. Data in Tables 1 and 2 were adopted to evaluate the input parameters of the IEQ model proposed in this study.

Table 1. Indoor environmental quality (IEQ) parameters

Parameters	Satisfaction			Dissatisfaction		
	Mean μ_s	Standard deviation σ_s	Sample size n_s	Mean μ_u	Standard deviation σ_u	Sample size n_u
Residential (Sample size = 125)						
Operative temperature x_1 (°C)	27.3	2.0	113	28.8	1.9	12
Carbon dioxide level x_2 (ppm)	678	327	118	629	370	7
Equivalent noise level x_3 (dBA)	66.8	5.8	113	72.5	7.7	12
Illumination level x_4 (lux)	179	281	116	74.5	85.5	9
Classroom (Sample size = 312)						
Operative temperature x_1 (°C)	22.2	1.5	301	22.8	1.9	25
Carbon dioxide level x_2 (ppm)	1014	278	247	1190	356	79
Equivalent noise level x_3 (dBA)	61.4	9.4	291	61.4	4.0	33
Illumination level x_4 (lux)	369	115	294	363	124.9	29
Office (Sample size = 293)						
Operative temperature x_1 (°C)	21.1	1.3	264	21.4	1.2	29
Carbon dioxide level x_2 (ppm)	935	320	208	1147	268	85
Equivalent noise level x_3 (dBA)	55.3	3.4	242	58.7	4.2	51
Illumination level x_4 (lux)	674	277	246	560	384	47

Table 2. Indoor environmental quality (IEQ) acceptance

Case	Acceptance of parameter				Residential (n=125)	Classroom (n=312)	Office (n=293)	Residential	Classroom	Office
j	$\delta(x_1)$	$\delta(x_2)$	$\delta(x_3)$	$\delta(x_4)$	Survey $\rho_{j,m}$			Predicted $\rho_{j,p}$		
1	0	0	0	0	0*	0.6*	**	0	0.15	0
2	0	0	0	1	0*	0.29	0	0	0.35	0
3	0	0	1	0	**	0*	0*	0	0.57	0
4	0	0	1	1	0.5*	0.57	0	0.50	0.80	0
5	0	1	0	0	**	**	0*	0	0.32	0
6	0	1	0	1	0*	0.67*	0*	0	0.58	0
7	0	1	1	0	0*	0.75*	0	0	0.78	0
8	0	1	1	1	0.833	0.94	0.15	0.83	0.91	0.15
9	1	0	0	0	0*	0*	0*	0	0.37	0
10	1	0	0	1	**	0.67*	0.2	0.55	0.63	0
11	1	0	1	0	**	0.4*	0	1	0.81	0.02
12	1	0	1	1	1*	1	0.38	1	0.93	0.38
13	1	1	0	0	**	0.6*	0*	0	0.61	0.02
14	1	1	0	1	0.857	0.57*	0.41	0.86	0.82	0.41
15	1	1	1	0	1	0.83*	0.67	1	0.92	0.67
16	1	1	1	1	1	0.95	0.99	1	0.97	0.99

Note: x_1: Operative temperature; x_2: Carbon dioxide level (ppm); x_3: Equivalent noise level (dBA); x_4: Illumination level (lux); Sample size: $^*\leq 5$, $^{**}0$

Results and discussion

Acceptance of environmental parameters

Figure 1 plots the voting percentages for acceptance θ_s and unacceptance θ_u of the four parameters x_1 to x_4 in residential buildings, classrooms and offices. The operative temperature range is 19–32°C, CO_2 level range is 400–2000ppm, equivalent noise level range is 50–85dBA and illumination level range is 10–1500lux. Responses to the operative temperature and equivalent noise level are sensitive to different premises categories and they are clearly distinguished in Figures 1(a) and 1(c). As illustrated in Figure 1(b), responses to the CO_2 level are overlapping among the three premises categories. Figure 1(d) shows that the illumination level in classrooms is usually around 500lux, while the range of illumination levels is wider in residential buildings and offices.

Determined from θ_s and θ_u, the probability density functions of normalized votes $\tilde{x}_{su}$ for x_1 to x_4 are shown in Figure 2(i). The results show significant mean differences of $\tilde{x}_{su}$ between functions ($p \leq 0.01$, t-test), except for all CO_2 levels (Figure 2(b)) and the illumination levels between residential buildings and classrooms ($p > 0.01$, t-test). Figures 2(ii)–2(iv) suggest that reasonable normal approximations can be made with $\tilde{x}_{su} \sim x_{su}(\mu, \sigma)$.

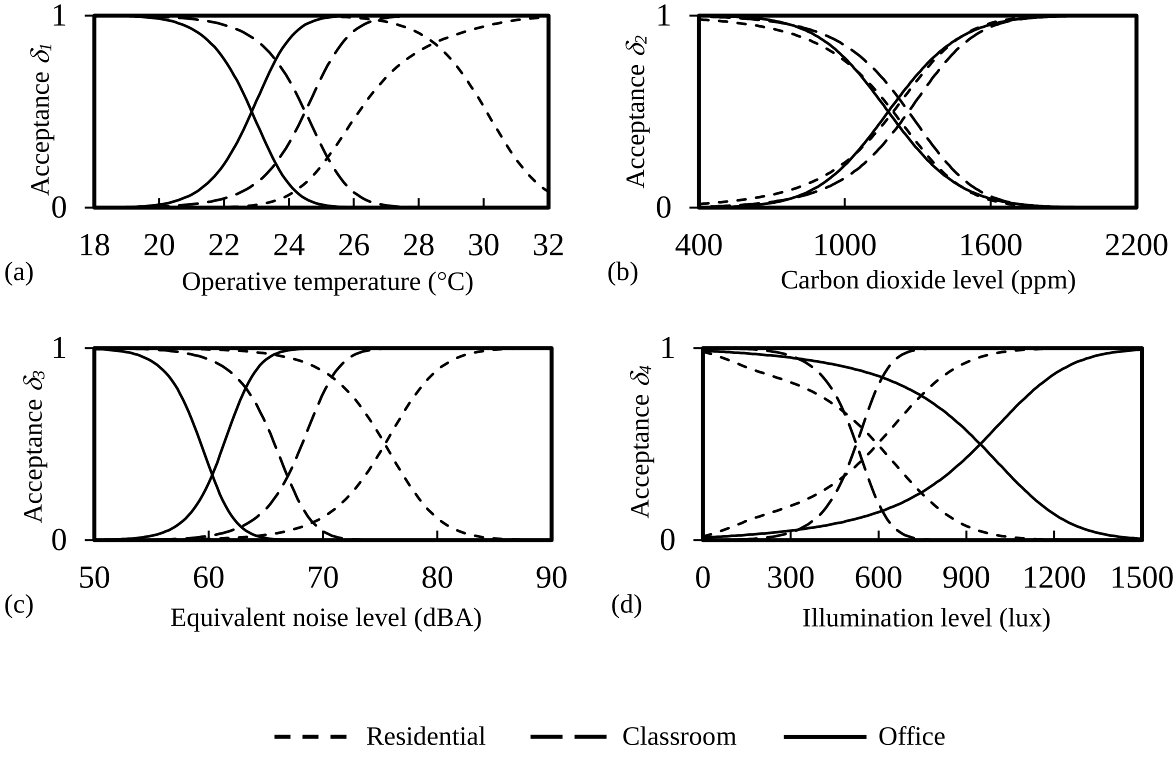

Figure 1. Percentage votes for acceptance (δ_i = 1) and unacceptance (δ_i = 0) with (a) operative temperature; (b) carbon dioxide levels; (c) equivalent noise levels; and (d) illumination.

Parametric distributions, presented in Table 3, were adopted as the model parameters x_1 to x_4. The goodness of fit was examined using the cumulative frequency distributions δ for $\tilde{x}_{su}$ and $x_{su}(\mu, \sigma)$ shown in Figures 3(i) and 3(ii) respectively. The maximum absolute errors ε_M, determined by Eq. (11), were 0.01–0.08.

$$\varepsilon_M = \max\left(\left|\int_x x_{su}(\mu,\sigma)dx - \int_x \tilde{x}_{su}dx\right|\right);\ \forall x \in [a,b] \quad (11)$$

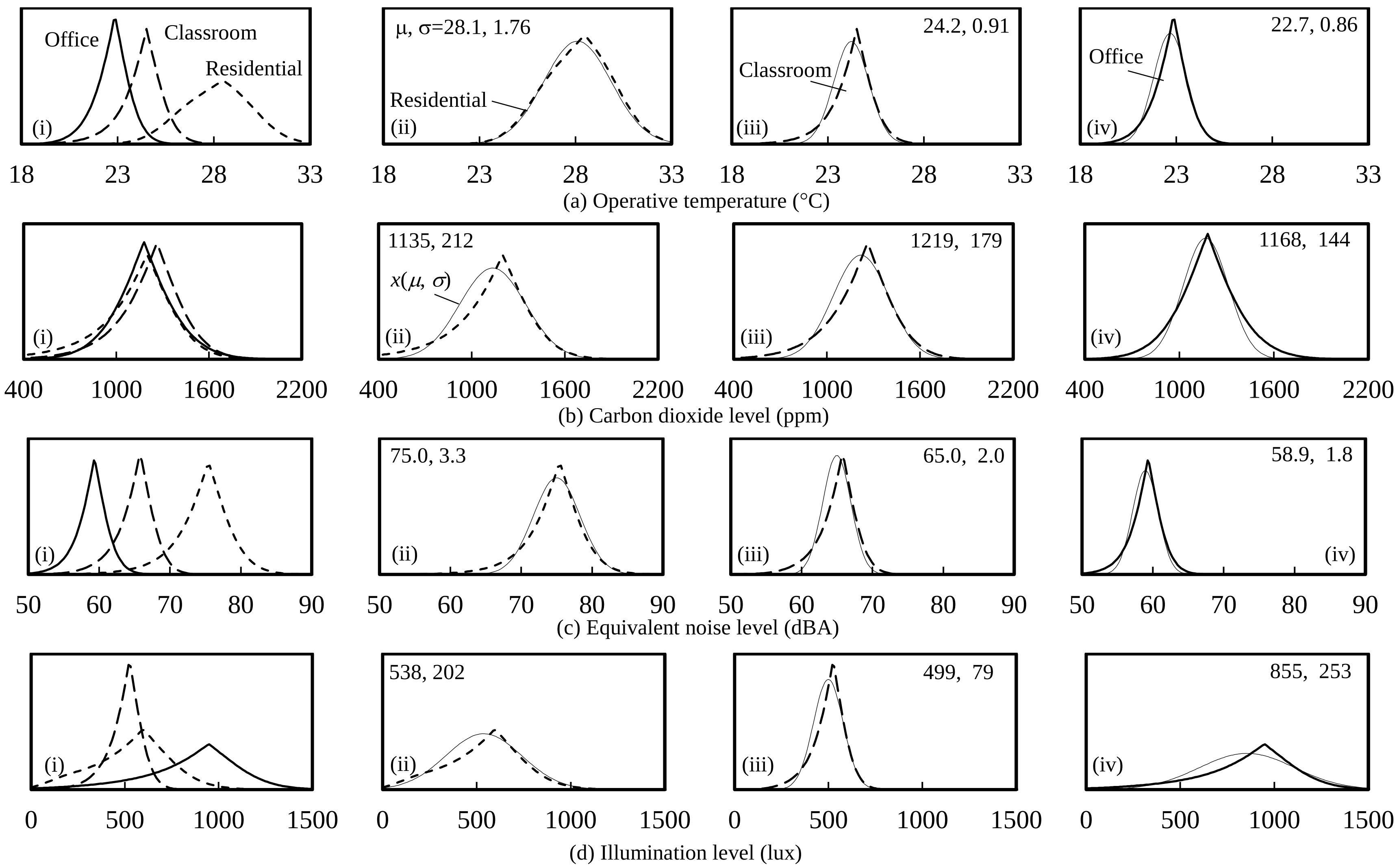

Figure 2. (i) Probability density functions of normalized votes $\tilde{x}_{su}$ approximated with $x_{su}(\mu, \sigma)$; (ii)–(iv) Reasonable normal approximations made with $\tilde{x}_{su} \sim x_{su}(\mu, \sigma)$; for (a) operative temperature; (b) carbon dioxide levels; (c) equivalent noise levels; and (d) illumination.

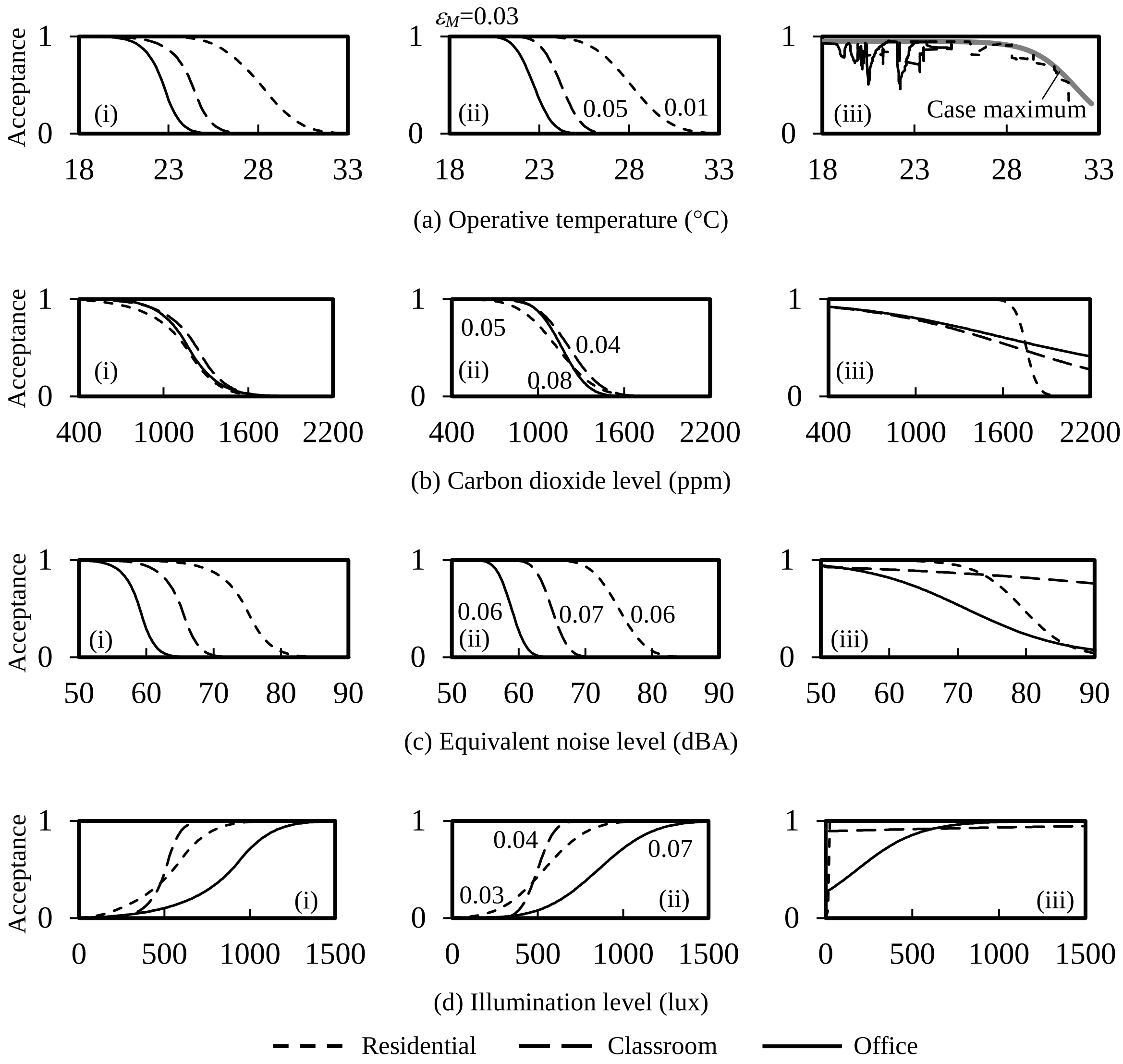

Figure 3. (i) Cumulative frequency distributions δ for $\widetilde{x}_{su}$; (ii) Cumulative frequency distributions δ for $x_{su}(\mu, \sigma)$; (iii) Predicted occupant acceptance δ; for (a) operative temperature; (b) carbon dioxide levels; (c) equivalent noise levels; and (d) illumination.

Figures 3(i) and 3(ii) present zero acceptances at/ beyond the measurement boundaries of dissatisfaction as no occupant responses were previously recorded in typical built environments under extreme environmental conditions. These acceptances can be interpreted as the environmental acceptances from both the occupants and the building designers. Occupant acceptance predictions for environment parameters δ made in the previous studies are shown in Figure 3(iii) for comparison [28–29,31].

In Figure 3(a)(iii), the thermal comfort acceptance calculated using Fanger's Predicted Mean Vote (PMV) is plotted against the operative temperature. A line of case maximum values is shown to indicate the thermal acceptance through clothing adjustment. At 31.4°C, the maximum indoor operative temperature recorded, the minimum predicted acceptance was 0.54. Similar results were observed for IAQ and aural environment. At the recorded maximum CO_2 levels of 1627ppm and 1883ppm, the predicted acceptance values for classrooms and offices were 0.54 and 0.51 respectively; for the entire measurement range of CO_2 levels up to 1499ppm in residential buildings, the predicted acceptance value was 1. At the maximum equivalent noise levels of 78dBA, 67dBA and 68dBA, the predicted acceptance values for residential buildings, classrooms and offices were 0.61, 0.88 and 0.62 respectively. Regarding the visual environment, at the measured minimum illumination level of 189lux, the minimum predicted acceptance for offices was 0.51; and for the entire illumination range recorded in residential buildings and classrooms, the predicted acceptance values were 1 and 0.90–0.92 respectively. However, a rapid (almost a step) change in acceptance from 1 to 0 was found at around 10lux in residential buildings.

Within the measurement range, the proposed would result in zero acceptances at/ beyond the boundaries, while prediction from previous studies most of the time would give an acceptance $\neq 0$ at the measurement boundaries. The acceptance results from proposed model are distinguished from those obtained from the earlier studies [28–29,31]. It can be explained with reason that the built environmental conditions were constrained by some design norms, the predicted acceptance was comparatively higher in the measurement parameter range than in the observable parameter range. As the collective results from a field survey are not only directly from the respondents but also indirectly from those who have contributed to the environmental settings (i.e. building designers and operators), the fundamental settings of a field survey should be taken as constraints for occupant responses.

Moreover, acceptance of environmental parameters is model dependent. In a multivariate logistic regression model, the higher prediction may be interpreted as a bias towards the acceptable environment, whereas in a frequency distribution model, the higher prediction may be interpreted as a bias towards the comfortable environment.

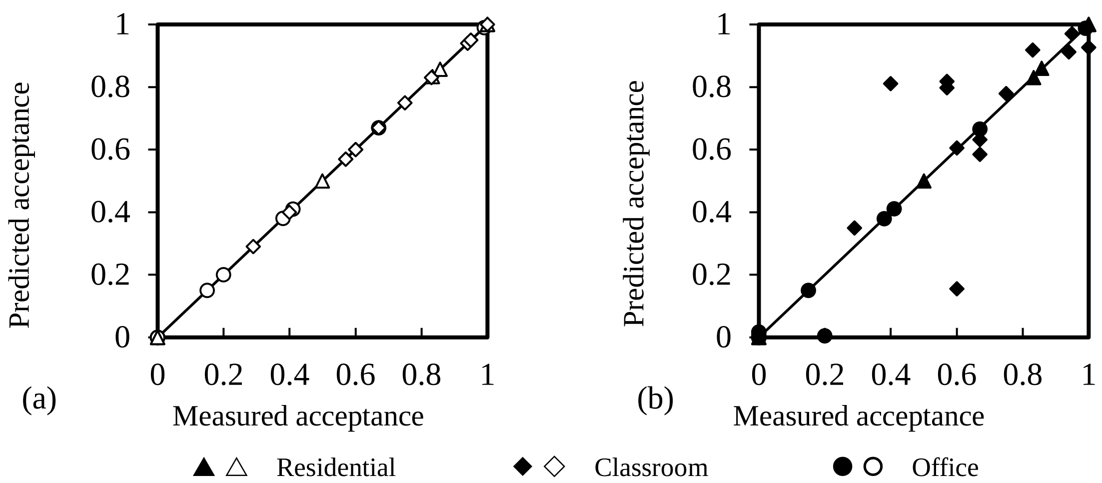

Figure 4. Occupant acceptances of environmental conditions δ_j (a) This study; and (b) IEQ equations.

Acceptance of indoor environment

IEQ acceptances ρ_j under environmental conditions j for residential buildings, classrooms and offices are shown in Table 2. For those conditions without any survey data, predictions from the previous studies (Table 3) were adopted.

Figure 4(a) graphs the predictions against the measurements for this study. Figure 4(b) plots the results obtained from the existing IEQ equations for comparison [28–29,31]. As the predicted values from this and the previous studies were found to be highly correlated with a slope of 1 and a constant of 0 (p<0.0001, t-test), the model this study proposed (i.e. Eq. (4)) should statistically give the same overall IEQ acceptance as the existing IEQ logistic regression model.

Table 3. Model parameters

Parameter	Symbol	Residential		Classroom		Office	
		μ	σ	μ	σ	μ	σ
Operative temperature (°C)	$x_{su,1}$	28.1	1.76	24.2	0.91	22.7	0.86
Carbon dioxide level (ppm)	$x_{su,2}$	1135	212	1219	179	1168	144
Equivalent noise level (dBA)	$x_{su,3}$	75.0	3.3	65.0	2.0	58.9	1.8
Illumination level (lux)	$x_{su,4}$	538	202	499	79	855	253
Probability of environmental acceptance ρ_j	ρ_1	0		0.60		0	
	ρ_2	0		0.29		0	
	ρ_3	0		0.57		0	
	ρ_4	0.5		0.57		0	
	ρ_5	0		0.32		0	
	ρ_6	0		0.67		0	
	ρ_7	0		0.75		0	
	ρ_8	0.83		0.94		0.15	
	ρ_9	0		0.37		0	
	ρ_{10}	0.55		0.67		0.2	
	ρ_{11}	1		0.40		0	
	ρ_{12}	1		1		0.38	
	ρ_{13}	0		0.60		0	
	ρ_{14}	0.86		0.57		0.41	
	ρ_{15}	1		0.83		0.67	
	ρ_{16}	1		0.95		0.99	

Note: ρ_j – acceptance scenarios according to Table 2

Model predictions and performance

Figure 5 illustrates the predicted IEQ acceptances calculated from Eq. (4) for residential buildings, classrooms and offices under typical indoor environmental conditions: operative temperature x_1=20–32°C, CO_2 level x_2=800–1800ppm, equivalent noise level x_3=50–75dBA and illumination level x_4=10–500lux. Acceptances predicted by the existing IEQ equations are shown for comparison [28–29,31]. According to Figure 5(a), variations in acceptance are small over a wide range of environmental conditions in residential buildings, except for a sharp drop predicted by the IEQ equations at around 30°C in a dark environment (i.e. x_4=10lux).

It can be seen that the existing IEQ equations work very well for offices. For instance, under typical design conditions of 24°C, 800ppm, 50dBA and 500lux, the predicted acceptance is 0.93. Besides, variations in acceptance are reasonable and no sharp turns or flat variations are observed in Figure 5(b). Although the model proposed in this study gives similar prediction patterns, it is less sensitive to parameter changes. However, data available are insufficient to judge the prediction accuracy of the proposed model or the IEQ equations. Overall, the proposed model presents notable resolutions for the environmental differences.

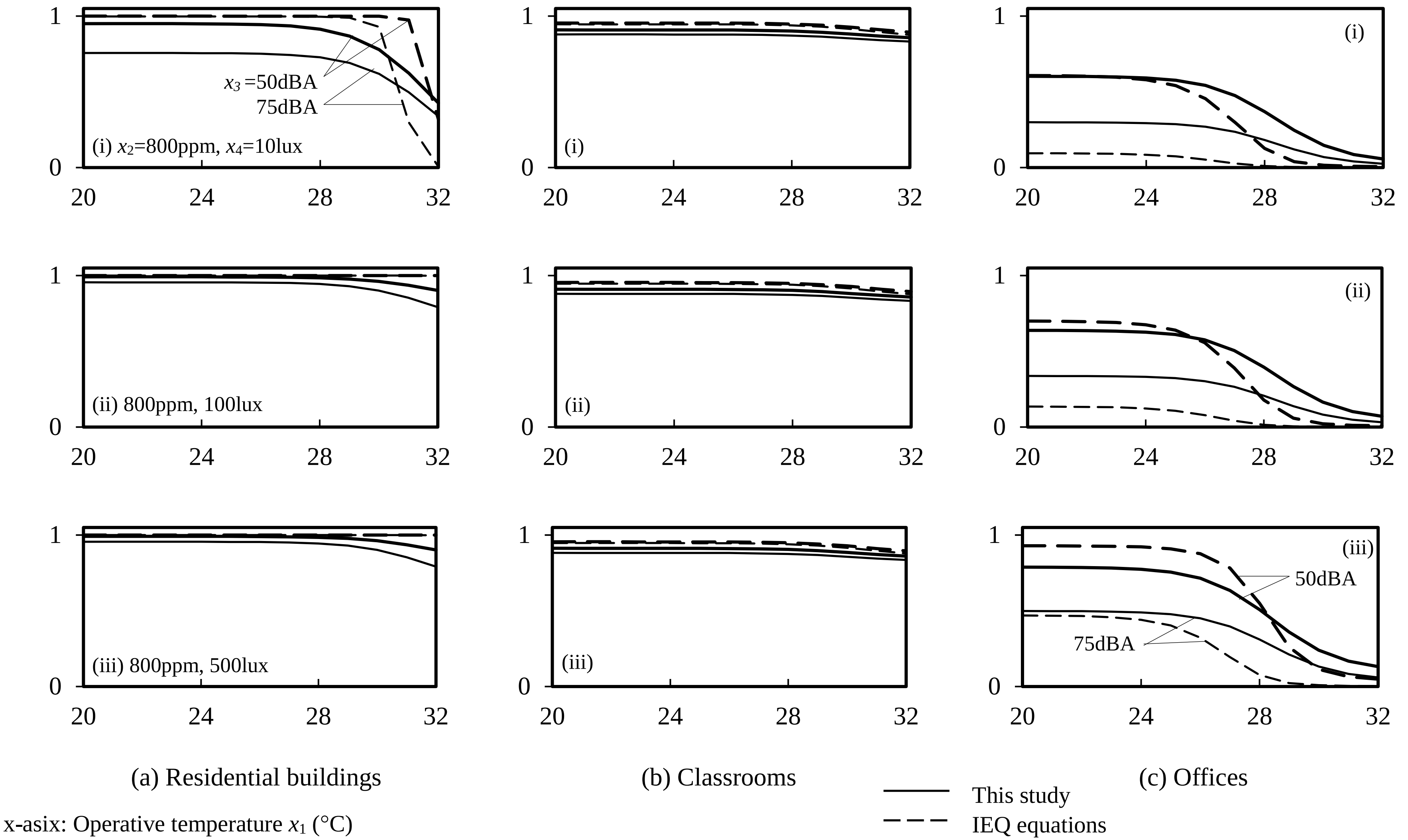

Figure 5(a). Predicted IEQ acceptances for (a) Residential buildings; (b) Classrooms; (c) Offices with a fixed CO_2 level=800ppm (continued on next page)

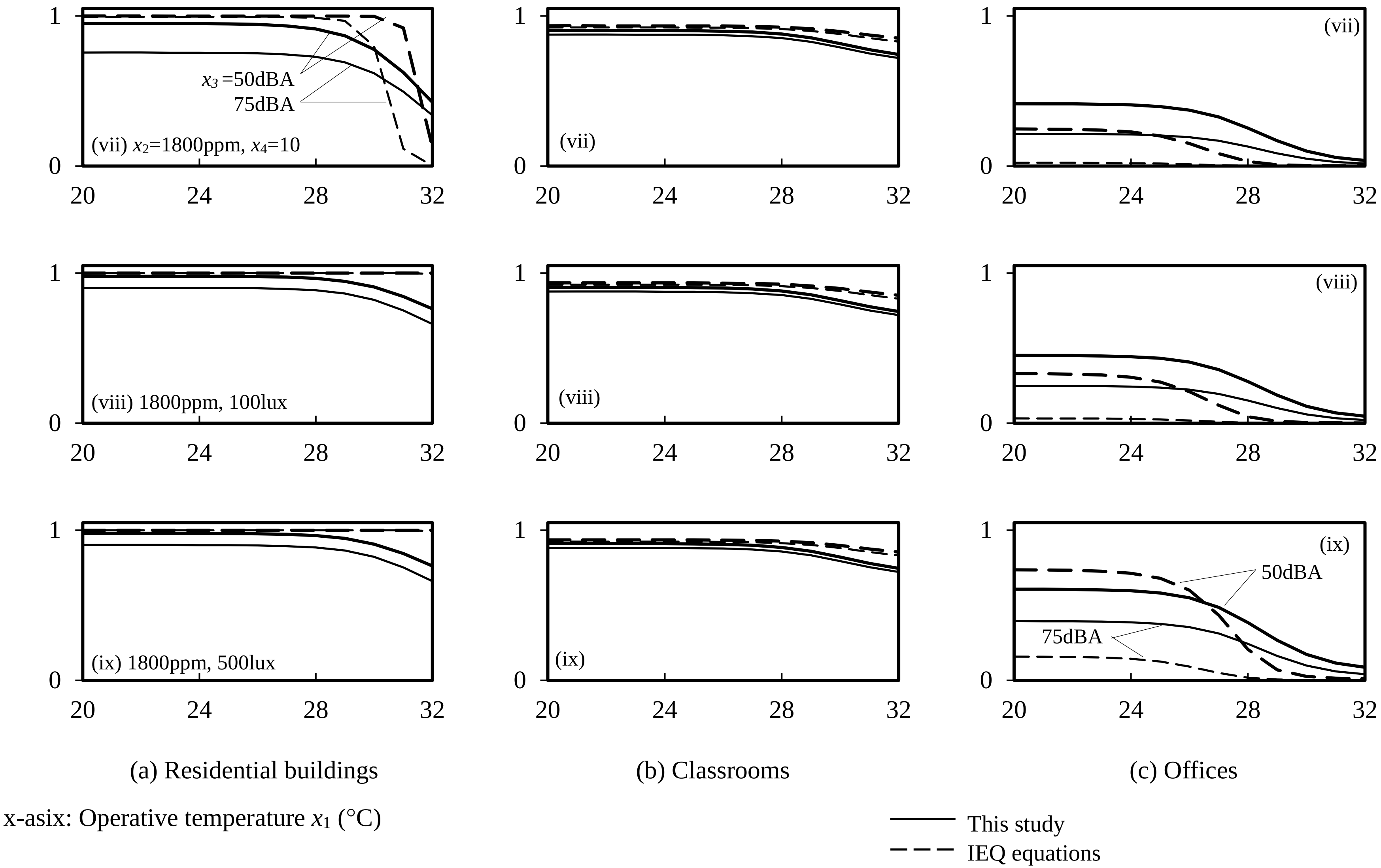

Figure 5(b). Predicted IEQ acceptances for (a) Residential buildings; (b) Classrooms; (c) Offices with a fixed CO_2 level=1800ppm.

Tested compatible with the existing IEQ equations for environmental acceptance predictions in residential buildings, classrooms and offices, the proposed model is considered to be valid. It is not only flexible enough to encapsulate a diverse range of descriptive model parameters but also feasible for openly available IEQ acceptance data. Furthermore, the direct use of frequency distribution functions of survey parameters makes model updating simpler as no regression analysis is involved.

Conclusions

This study proposed an open acceptance model that uses frequency distribution functions of occupant responses towards IEQ parameters to assess IEQ. Acceptances of individual IEQ parameters and of the overall IEQ predicted by this model were tested against those predicted by an existing IEQ logistic regression model (i.e. the existing IEQ equations). While the individual acceptance results were compatible, the overall acceptance values predicted by both models were statistically the same. The proposed model is not only flexible enough to encapsulate a diverse range of descriptive model parameters but also feasible for openly available IEQ acceptance data. Offering the flexibility to add data incrementally to allow easy model updating as and when a new set of observations arrives, this model can be a solution to the existing problems and limitations encountered in IEQ modelling.

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References

[1] United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development (A/RES/70/1). New York: UN General Assembly, 2015.

[2] Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Analysis and Environmental Epidemiology 2011;11:231–252.

[3] Heerwagen JH. Green Buildings, organizational success and occupant productivity. Building Research and Information 2000;28(5):353–367.

[4] Abbaszadeh S, Zagreus L, Lehrer D, Huizenga C. Occupant satisfaction with indoor environmental quality in green buildings. In: Proceedings of the 8th International Conference of Healthy Buildings 2006; June 4th–8th 2006, Lisboa, Portugal. vol. 3. P. 365–370.

[5] Clements-Croome D. Creative and productive workplaces: a review. Intelligent Buildings International 2015;7(4):164–183.

[6] UK Centre for Mental Health 2011. Managing Presenteeism. Access on 10th March, 2018. Available online at: www.centreformentalhealth.org.uk

[7] Newsham G, Brand J, Donnelly C, Veitch J, Aries M, Charles K. Linking indoor

environment conditions to job satisfaction: a field study. Building Research & Information 2009;37(2):129–147.

[8] Sadick AM, Issa MH. Occupants' indoor environmental quality satisfaction factors as measures of school teachers' well-being. Building and Environment 2017;119:99–109.

[9] ASHRAE. Guideline 10P, Interactions Affecting the Achievement of Acceptable Indoor Environments, Second Public Review. Atlanta, USA: ASHRAE, 2010.

[10] De Giuli V, Da Pos O, De Carli M. Indoor environmental quality and pupil perception in Italian primary schools. Building and Environment 2012;56:335–345.

[11] Haynes BP. The impact of office layout on productivity. Journal of Facilities Management 2008;6(3):189–201.

[12] Sakhare VV, Ralegaonkar RV. Indoor environmental quality: review of parameters and assessment models. Architectural Science Review 2014;57(2):147–154.

[13] Yu W, Li B, Yao R, Wang D, Li K. A study of thermal comfort in residential buildings on the Tibetan Plateau, China. Building and Environment 2017;119:71–86.

[14] Zhai Y, Zhang H, Zhang Y, Pasut W, Arens E, Meng Q. Comfort under personally controlled air movement in warm and humid environment. Building and Environment 2013;65:109–117.

[15] Astolfi A, Pellerey F. Subjective and objective assessment of acoustical and overall environmental quality in secondary school classroom. The Journal of the Acoustical Society of America 2008;123(1):163–173.

[16] Bae S, Asojo A, Guerin D, Martin C. A Post-Occupancy Evaluation of the Impact of Indoor Environmental Quality on Health and Well-Being in Office Buildings. Journal of Organizational Psychology 2017;17(6):25–36.

[17] Brager G, Baker L. Occupant satisfaction in mixed-mode buildings. Building Research & Information 2009;37(4):369–380.

[18] Frontczak M, Schiavon S, Goins J, Arens E, Zhang H, Wargocki1 P. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. Indoor Air Journal 2012;22(2):119–131.

[19] Kamaruzzaman SN, Egbu CO, Mahyuddin N, Ahmad Zawawi EM, Chua SJL, Azmi1 NF. The impact of IEQ on occupants’ satisfaction in Malaysian buildings. Indoor and Built Environment 2017;0(0):1–11.

[20] Feige A, Wallbaum H, Janser M, Windlinger L. Impact of sustainable office buildings on occupant's comfort and productivity. Journal of Corporate Real Estate 2013;15(1):7–34.

[21] Alhorr Y, Arif M, Kaushik A, Mazroei A, Katafygiotou M, Elsarrag E. Occupant productivity and office indoor environment quality: A review of the literature. Building and Environment 2016;105:369–389.

[22] Edwards L, Torcellini P. Literature review of the effects of natural light on building occupants. No. NREL/TP-550-30769. National Renewable Energy Lab., Golden, CO.(US), 2002.

[23] Boyce P, Hunter C, Howlett O. The benefits of daylight through windows. New York: Rensselaer Polytechnic Institute, 2003.

[24] Alhorr Y, Arif M, Katafygiotou M, Mazroei A, Kaushik A, Elsarrag E. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. International Journal of Sustainable Built Environment 2016;5:1–11.

[25] Lee YS, Guerin DA. Indoor environmental quality differences between office types in LEED-certified buildings in the US. Building and Environment 2010;45(5):1104–1112.

[26] Altomonte S, Schiavon S. Occupant satisfaction in LEED and non-LEED certified buildings. Building and Environment 2013;68:66–76.

[27] Malmqvist T. Environmental rating methods: selecting indoor environmental quality (IEQ) aspects and indicators. Building Research & Information 2008;36(5):466–485.

[28] Wong LT, Mui KW, Hui PS. A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices. Building and Environment 2008;43:1–6.

[29] Lee MC, Mui KW, Wong LT, Chan WY, Lee EWM, Cheung CT. Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms. Building and Environment 2012;49:238–244.

[30] Kua H, Lee S. Demonstration intelligent building—a methodology for the promotion of total sustainability in the built environment. Building and Environment 2002;37(3):231–240.

[31] Lai ACK, Mui KW, Wong LT, Law LY. An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings. Energy and Buildings 2009;41:930–936.

[32] Catalina T, Iordache V. IEQ assessment on schools in the design stage. Building and Environment 2012;49:129–140.

[33] Laskari M, Karatasou S, Santamouris M. A methodology for the determination of indoor environmental quality in residential buildings through the monitoring of fundamental environmental parameters: A proposed Dwelling Environmental Quality Index. Indoor and Built Environment 2017;26(6):813–827.

[34] Mui KW, Tsang TW, Wong LT. Evaluation of an indoor environmental quality model for very small residential units. Manuscript accepted for publication 2017.

[35] Majcen D, Itard LCM, Visscher H. Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: discrepancies and policy implications. Energy Policy 2013;54:125–136.

[36] Koelblen B, Psikuta A, Bogdan A, Annaheim S, Rossi RM. Thermal sensation models: a systematic comparison. Indoor Air 2017;27(3):680–689.

[37] Raftery P, Keane M, Costa A. Calibrating whole building energy models: detailed case study using hourly measured data. Energy and Buildings 2011;43:3666–3679.

[38] Lam KP, Zhao J, Ydstie EB, Wirick J, Qi M, Park J. An Energyplus Whole Building Energy Model Calibration Method for Office Buildings Using Occupant Behavior Data Mining and Empirical Data. In: Proceedings of ASHRAE/IBPSA-USA Building Simulation Conference 2014; September 10–12 2014, Atlanta, GA, USA. P.160–167.

[39] Andersen RK, Fabi V, Corgnati DP. Predicted and actual indoor environmental quality: Verification of occupants' behaviour models in residential buildings. Energy and Building 2016;127:105–115.

[40] Mui KW, Wong LT. A method of assessing the acceptability of noise levels in air-conditioned offices. Building Services Engineering Research and Technology 2006;27(3):249–254.

[41] Mui KW, Wong LT. Acceptable illumination levels for office occupants. Architectural Science Review 2006;49(2):116–119.

[42] Mui KW, Wong LT. Neutral temperature in subtropical climates – A field survey in air-conditioned offices. Building and Environment 2007;42:699–706.