Development of a user-friendly indoor environmental quality (IEQ) calculator in air-conditioned offices

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ABSTRACT

The assessment of indoor environmental quality (IEQ), would be used as an environmental performance indicator for environmental diagnosis in workplaces to explain reported occupants' concerns in comfort, odour and working performance. Expressions of the occupants' overall IEQ acceptance on thermal comfort, indoor air quality, aural and visual comfort are developed and the assessed environment is benchmarked by a 5-star rating system of IEQ performance for an indoor environment in Hong Kong. This rating system is a validated expression for indicating 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.

However, for assessing the IEQ in workplaces, it requires sophisticated instrumentation together with an intensive questionnaire. This study develops a user-friendly 5-star IEQ calculator incorporates market available sensors for measuring essential physical parameters, which focusing on five indoor environmental parameters including air temperature (^oC), relative humidity (%), carbon dioxide (CO_2) concentration (ppm), horizontal illumination level (lux) and sound pressure level (dBA). The calculator predicts occupant's acceptance for thermal comfort, indoor air quality, illuminance, noise levels and the overall IEQ acceptance.

Together with the input physical parameters and the additional subjective parameters including activity level (Met), and clothing value (clo), the calculator calculates (i) the predicted thermal perception (Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool, Cold), (ii) the predict indoor air quality (IAQ), lighting and sound level acceptance (Dissatisfactory, Acceptable, Good) and (iii) the relative IEQ acceptance performance using the star rating expression (1 to 5 star).

This user-friendly IEQ calculator not only provides an easy method for the assessment of the indoor environment but also can be used as a tool for professionals to evaluate the relative IEQ performance of air-conditioned workplaces, and allows early diagnosis of IEQ problems.

KEYWORDS

Indoor Environmental Quality (IEQ) logger, 5-star benchmark, air-conditioned offices

INTRODUCTION

Assessment of Indoor Environmental Quality (IEQ) has been adopted in some building grading systems (Chew and Das, 2008), such as the Building Research Establishment Environmental Assessment Method (BREEAM), the Building Environment Performance Assessment Criteria (BEPAC) and the Hong Kong Building Environmental Assessment Method (HK-BEAM). The IEQ assessments are used as environment performance indicators and also environmental diagnosis in workplaces in order to explain the reported health problems, comfort or odour concerns (Sofuoglu and Moschandreas, 2004). However, the concept of using an acceptable IEQ as an integral part of the total building performance approach is still not fully appreciated. One of the major reasons is that instrumentations could be cost prohibitive to sample all IEQ parameters, especially for gas pollutants. This prohibitive investment cost makes promoting the IEQ assessment in building industry as common practices difficult.

The development of micro-electro-mechanical system (MEMS) technology have become popular in markets such as safety and environmental applications (Fine *et al.* 2010). The sensors transduce a measurable electrical signal from the interaction between the electrolytes in the surrounding gas and sensor material. Besides, the accuracy and stability of the sensors have been improved (Wang *et al.* 2010). Although the sensors are not comparable to the laboratory grade instrument or conventional analytical instrumentation such as gas chromatography or optical detection method (Moos *et al.* 2009), the sensors still have a potential for applications in the building industry due to the acceptable accuracy and reasonable cost such as VOC detection and Particulate Matter measurement (Schütze, 2014; Wang *et al.* 2015).

In this study, an IEQ calculator with the solid state sensors which are popular in a market would be developed and the feasibility of assessment the IEQ performance for an office environment in Hong Kong would be accessed. The IEQ calculator not only provides an easy method for assessment of the indoor environment, but it can also be used as a tool for professionals to evaluate the relative IEQ performance of air-conditioned workplaces, and allows early diagnosis of IEQ problems.

AN IEQ ACCEPTANCE MODEL AND BENCHMARK SYSTEM

The IEQ acceptance is an integral state of an occupant's subjective response to the indoor environmental parameters including air temperature (^oC), relative humidity (%), CO_2 concentration (ppm) and horizontal illumination level (lux), sound pressure level and local air velocity (ms^{-1}) (Mendell, 2003). Mathematical expressions in approximating the occupant's acceptance of the IEQ by an overall IEQ index, which was expressed by the four IEQ qualifiers (thermal comfort, indoor air quality, visual and aural comfort) have been suggested (Wong and Mui, 2009). The occupants' acceptability in specific IEQ conditions could be predicted and benchmarked with reference to the related database of indoor air-conditioned office environment.

In previous studies, a regional survey on the environmental factors in offices was conducted to construct the occupants' IEQ acceptance database. The overall IEQ acceptance θ_i can be presented by a multivariate logistic regression model in Equation (1).

The regression constants C_i can be determined from field measurement data where i = 1 (for thermal comfort), 2 (for indoor air quality comfort), 3 (for visual comfort) and 4 (for aural comfort) (Wong and Mui, 2009).

$$\theta = 1 - \frac{1}{1 + \exp\left(C_0 + \sum_{i=1}^{4} C_i \phi_i(\zeta_i)\right)} \quad ; i = 1, 2, 3, 4 \qquad \ldots (1)$$

The occupant thermal comfort acceptances ϕ_1 correlated with the predicted percentage of dissatisfied ζ_1 is shown in Equation (2),

$$\phi_1 = 1 - \frac{\zeta_1}{100} \quad ; \textit{for office} \qquad \ldots (2)$$

The acceptances of indoor air quality ϕ_2, visual ϕ_3 and aural comforts ϕ_4 were correlated with CO_2 concentration ζ_2 (ppm), horizontal illumination level ζ_3 (lux) and sound pressure level ζ_4 (dBA) as expressed in Equation (3), respectively. The regression constants m_i and n_i are determined via field measurement (Wong and Mui, 2009),

$$\phi_i = 1 - \frac{1}{1 + \exp(m_i + n_i\, \zeta_i)} \quad ; i = 2, 3, 4 \qquad \ldots (3)$$

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

$$\theta_k = \left(\frac{N_{\theta=1}}{N}\right)_k \quad ; k = 1\ldots 16 \qquad \ldots (4)$$

Good agreements for all cases were found between the predicted and observed results from the survey. A strong linear correlation was reported among offices by t-test ($p \le 0.001$, R=0.986) (Wong and Mui, 2009). A benchmarking value B of all offices in Hong Kong could be ranked by the overall IEQ index with a 5-star rating system (Hui *et al.* 2008): the system assigns 5 stars to the top 10% samples of IEQ benchmarking value ($B \ge 0.9$), 4 stars to the next 22.5% ($0.675 \le B < 0.9$), 3 stars to the next 35% ($0.325 \le B < 0.675$), 2 stars to the next 22.5% ($0.1 \le B < 0.325$) and 1 star to the bottom 10% ($B < 0.1$),

$$B = \int_{-\infty}^{\theta_i} \tilde{\theta}\, d\theta \qquad \ldots (5)$$

where the benchmarking value B is determined by an occupant's IEQ acceptance of the space θ, which is the percentile of the cumulative frequency distribution of the occupant's IEQ acceptance in an indoor environment.

CONSTRUCTION OF THE IEQ CALCULATOR

In order to provide an easy tool for an IEQ assessment in Hong Kong, the IEQ calculator was developed with the IEQ acceptance model and benchmark system for an office environment. The tool allows a prediction of the best IEQ scenario with a quantified scale. The hardware architecture of the calculator is illustrated in Figure 1.

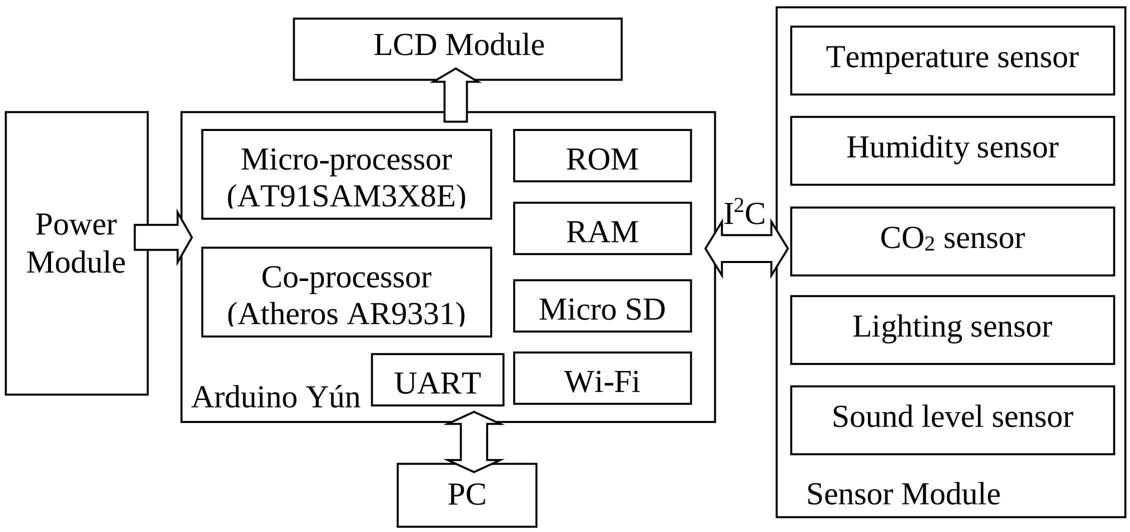

Figure 1. The hardware architecture of the IEQ calculator

Arduino Yún board, which is an open source electronics platform, was used and incorporated with market available sensors to construct the IEQ calculator. The board is based on AT91SAM3X8E as a micro-processor to receive the sensors' signals, process the signals and calculate the overall IEQ acceptance index θ and the benchmarking value B by the Arduino programming language, which is based on Wiring. The Atheros co-processor supports a micro-SD card for data storage and a built-in Wi-Fi chipset for wireless communication. Thus, the measurement data could be recorded and stored in a micro-SD card or transferred to other Wi-Fi enabled devices such as tablets or mobile phones. For PC, a universal asynchronous receiver/transmitter (UART) port was built-in for USB communication. In order to provide a user-friendly interface, an LCD module was connected to display the calculation results in a text-based format. For example, the LCD returns (i) the predicted thermal perception (Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool or Cold) (ii) the predicted IAQ, lighting and sound level acceptance (Dissatisfactory, Acceptable or Good) and (iii) the relative IEQ acceptance performance using the star rating expression (1 to 5 star).

Table 1. Specifications of the IEQ sensors

Sensor	Parameter	Accuracy	Resolution	Range	Price (USD)
Grove temperature & humidity sensor Pro	Temperature (ºC)	±0.5 ºC	0.1 ºC	-40 to 80 ºC	14.9
	Relative humidity (%)	±2%	0.1%	5-99%	
K-30 10,000pm CO_2 sensor	CO_2 concentration (ppm)	±30 ppm	20 ppm	0-10,000 ppm	85
Grove digital light sensor	Horizontal illumination level (lux)	±5 lux	1 lux	0.1-4000 lux	9.9
Grove sound sensor	Sound pressure level (dBA)	±2 dBA	0.1 dBA	30-80 dBA	4.9

To measure the environmental parameters, air temperature, humidity, CO_2, lighting and sound level pressure sensors were purchased from a commercial market as shown in Table 1. Due to the radiant temperature and air velocity sensors were not available in the market. The radiant temperature is assumed to be equivalent to air temperature regarding less heat source presented in Hong Kong office environments. For an air-conditioned office, the average air velocity was commonly found as 0.1 ms^{-1} (Wong and Mui, 2009). With the cost of the Arduino Yún board, the total hardware cost is under 200 USD. The measured signals were transferred to the micro-processor via inter-integrated circuit (I^2C) bus in every 0.1 second. The signals were averaged for 10 seconds in the micro-processor to reduce the noise and the occupant acceptances of thermal ϕ_1, indoor air quality ϕ_2, visual ϕ_3 and aural comforts ϕ_4 were calculated by Equations (2) and (3). Then overall IEQ acceptance θ and benchmarking value B were calculated by Equations (1), (4) and (5) respectively.

RESULTS

In order to evaluate the accuracy and feasibility of the IEQ calculator, the IEQ sensors' data were compared with the laboratory grade instruments, which are listed in Table 2, for each parameter.

Table 2. Specifications of the laboratory grade instrument for comparison

Instrument	Parameter	Accuracy	Resolution	Range	Price(USD)
Lurton WBGT-2009	Temperature (ºC)	±0.8 ºC	0.1 ºC	0 to 50 ºC	500
	Relative humidity (%)	±3%	0.1%	5-95%	
Telaire 7001	CO_2 concentration (ppm)	±50 ppm	1 ppm	0-10,000 ppm	465
Lurton LX-101A	Horizontal Illumination level (lux)	±5 %	1 lux	0-50,000 lux	91

Lurton SL-4001	Sound pressure level (dBA)	±5%	0.1 dBA	30-130 dBA	259

The correlations between the IEQ sensors and the instruments are summarized in Table 3. Generally, linear regressions were found for all five IEQ parameters. High accuracy and sensitivity of the sensors were demonstrated from the results (i.e. R^2>0.95, p>0.7), except for sound pressure level (i.e. R^2>0.65, p>0.45). The tolerance might be caused by the fluctuation of background noise. Fortunately, the sound pressure level contributes less to the overall IEQ index in Equation (1).

Table 3. Correlation between the IEQ sensors and laboratory grade instruments

Parameter	**IEQ sensor**	**Instrument**	**Regression coefficient**	R^2	p
Temperature (°C)	Grove temperature & humidity sensor (HDC1000)	Lurton WBGT-2009	0.9975	0.9626	0.92
Relative humidity (%)			0.963	0.9885	0.73
CO_2 concentration (ppm)	K-30 10,000pm CO_2 sensor	Telaire 7001	1.0429	0.9869	0.74
Horizontal Illumination level (lux)	Grove luminance sensor	Lurton LX-101A	1.0003	0.9957	0.98
Sound pressure level (dBA)	Grove sound sensor	Lurton SL-4001	0.9349	0.6561	0.45

Based on these regressions, 500 sets of IEQ sensor data were predicted from the corresponding simulated instrumentation data. The simulated ranges were: air temperature=20~30 °C, RH=30~100%, CO_2=500~2100 ppm, Illumination level=10~1600 lux, SPL=40~90 dBA for common office conditions (Wong and Mui, 2009). For other subjective parameters, activity level (Met) and clothing value (clo) were supposed to be 1.1 and 0.61 as typing activity and wearing trousers, long-sleeve shirt, respectively. By comparison, the IEQ performance between the instrument and IEQ sensor readings, the feasibility of the IEQ calculator for assessment the IEQ performance could be fully demonstrated in Figure 2.

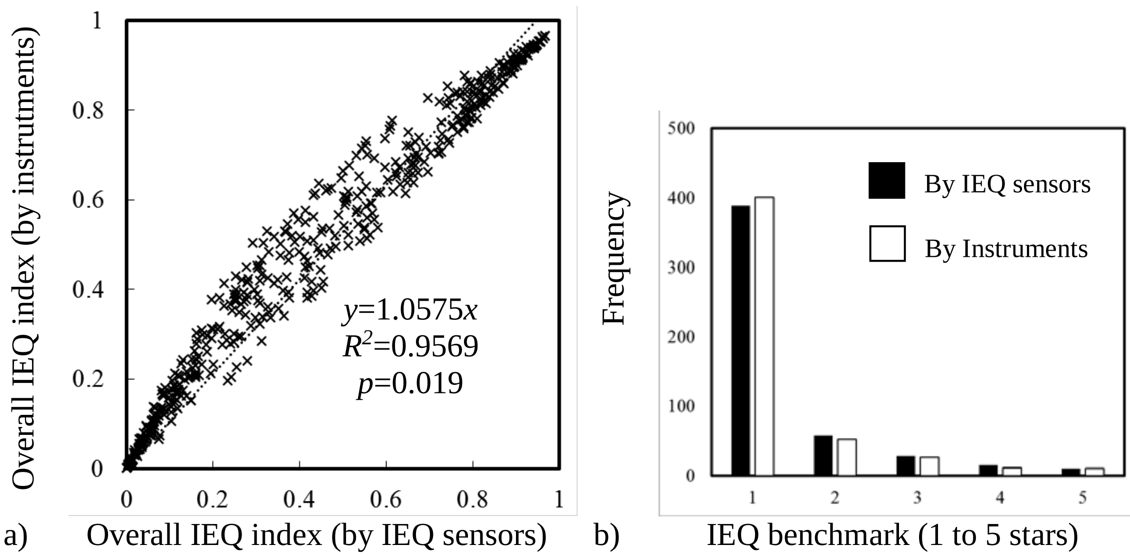

Figure 2. The measurement difference between IEQ sensors and instruments: a) Overall IEQ acceptance index, and b) IEQ benchmark

The overall IEQ acceptance index θ against IEQ sensors with instruments was plotted in Figure 2a. A strong correlated linear regression was reported ($R^2>0.95$). This demonstrates the measurement data from IEQ sensors could be reliable to predict the overall IEQ index instead of using the laboratory grade instruments. Some deviations were observed around 0.4 to 0.8. Lower IEQ index values θ were found from IEQ sensors. More pessimistic results could be good for early diagnosis of IEQ problems due to higher sensitivity and false negative outcomes in the screening process (Hui *et al.* 2010). The deviations did not affect the prediction of benchmarking value B between IEQ sensors and instruments since the difference was insignificant. Similar numbers of counts were found in each rating category (i.e. 1 to 5 stars) in Figure 2b ($p>0.7$, chi-squared).

The IEQ calculator with solid state sensors suggests reliable IEQ acceptance index θ and benchmarking value B. It enables facility management personnel to assess IEQ performance in offices and to have a reference in evaluating probable IEQ acceptance of different office environments in a cost-effective way.

CONCLUSIONS

Indoor environmental parameters would be the determinant factors on the IEQ acceptance as an integral occupant's subjective response to their perceived environments. This study constructed an IEQ calculator incorporates with market available sensors for measuring these essential physical parameters to assess IEQ performance in air conditioned offices. The parameters of the sensors include air temperature, relative humidity, CO_2 concentration, horizontal illumination level and sound pressure level. According to these physical readings, the occupant's acceptances for thermal comfort, indoor air quality comfort, visual comfort, aural comfort, the overall IEQ acceptance index θ and relative IEQ benchmarking value B were calculated based on the IEQ acceptable model and benchmark system. The acceptable accuracy and feasibility of the IEQ calculator were demonstrated by comparing with the laboratory grade instruments.

With the IEQ acceptance model and benchmark system, the IEQ calculator was developed in this study to enable a user-friendly method for an IEQ assessment in offices. The assessed environment is ranked as a star rating of IEQ performance related with the previous office database. The IEQ calculator can be used as a tool for participants in the building industry and related parties to evaluate the relative IEQ performance of air-conditioned workplaces, and allow early diagnosis of IEQ problem.

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