Criteria for design of indoor environment in sustainable buildings

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ABSTRACT
There is a worldwide trend to develop a tool that can provide comprehensive assessment of buildings for sustainability. Many efforts were found to propose approaches for energy-saving and resource-recycling, and on the other hand buildings for sustainability should maintain the acceptable indoor environment quality to maintain the occupants' health. This paper presents a comprehensive index, $IEI_{(AHP)}$, composed of the filtered physical indicators, for quantitative assessment on the built environment. A set of the weighting among the physical categories is carried out through the analytic hierarchy process (AHP) method. The criteria of these indicators, from the literature review, were addressed after the adjustment compared to the magnitude-distribution results, which were investigated from the existing apartment houses in Taiwan.

INDEX TERMS
Design criteria; AHP; Comprehensive assessment; Physical indicators

INTRODUCTION
The world grows globally, and those who can respond to the challenges of an emerging sustainable society may have better chances of success. Arthur Rosenfeld, a senior advisor at the US Department of Energy, cited a strong relationship between IAQ and productivity (Turner, 1998). Chen *et al*. (1998) mentioned that indoor environment is important to govern people's health and welfare, because up to 90% of the lifetime is spent indoors. Residents in a built-environment (illumination, acoustics, air quality, diet, thermal comfort and social environment) reflect the situation, which surrounds them by their physiological and mental sensations (sight, hearing, smell, taste, touch and mentality).

The indoor environment of a building is complex and made up of many factors. It is necessary to take various aspects of those environmental factors into consideration, when dealing with the influence of built-environment on tenants (Chiang and Chou *et al*., 1996). A preliminary study has already described the methodology of the indoor environment assessment on existing buildings and intends to draft indoor environment preservation indicators, including acoustics, vibration, illumination, thermal comfort, indoor air quality and electromagnetic environment (Chiang *et al*., 2002). This study continues the previous results and investigates the magnitude of the indoor environment indicators in apartment houses in Taiwan. The statistic distributions are introduced to examine the fitness compared with the criteria from literature review.

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STRUCTURES OF THE ASSESSMENT TOOL

Essential Categories and Weightings

As far as the authors know, we group the indoor environment performance into eight categories: acoustics, electromagnetic field (EMF), greens, illumination, indoor air quality (IAQ), thermal comfort, vibration and water quality. Each environmental category is then expressed in its relevant indicators. There are 47 items of the total indicators as the precise version and 23 selected items as the practical version (Chiang *et al*., 2002). The practical version was utilized to sieve out the essential categories and weightings via experts' questionnaires, due to the consideration of the practicable, economic and acceptable aspects.

The AHP method, which was developed by Satty (1979), is carried out to do the weighting among eight categories and those indicators, respectively. Expertise from domestic experts with respect to every professional field was involved in the process of deciding the relevant weight. The nominal-ratio scale of pairwise comparison among the indicators represented as the score from 1 to 9 was adopted, which was filled in a positive reciprocal matrix to calculate the eigenvector and eigenvalue. The consistency ratio was obtained to filter out the null questionnaire when the value of the consistency index (CI) was greater than 0.1. For each category, the weighting value was obtained by the geometric mean of experts' questionnaires. The original weighting is listed in sequence: 'IAQ' (0.221), 'Thermal comfort' (0.159), 'Acoustics' (0.155), 'Illumination' (0.125), 'EMF' (0.103), 'Greens' (0.070), 'Vibration' (0.054) and 'Water quality' (0.051).

The result indicates the opinions from the experts on the practical aspects of the recent period and the domestic situation. According to convenience, the minor categories whose weightings were less than 0.1 were filtered out. It means that the influence ratio of each minor category is less than 10% of whole benefit for the recent environment. Figure 1 shows the results after the adjustment, where there are five categories left, and the adjusted weighting is listed in sequence: 'IAQ' (0.290), 'Thermal comfort' (0.208), 'Acoustics' (0.203), 'Illumination' (0.164) and 'EMF' (0.135).

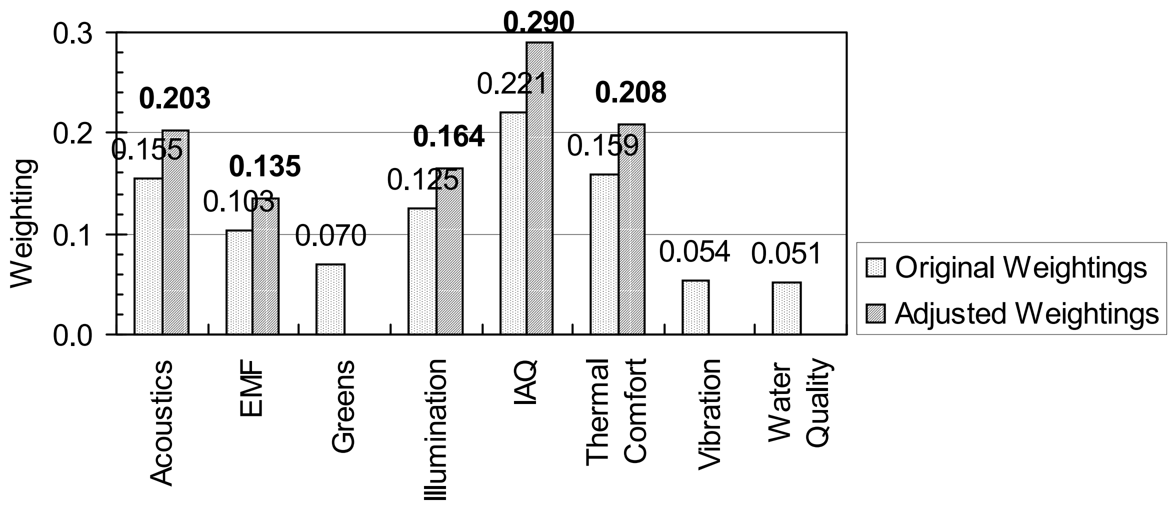

Figure 1 Weightings of environmental categories obtained from the AHP method.

Significant Indicators

The advised indicators are decided eventually via considering experts' suggestions and their relative weightings (AHP results). Due to the restriction of space of publication, the process of experts' consulting and AHP results are not recorded in detail in this study. These significant indicators are introduced in Table 1.

Table 1 List of the significant indoor environmental indicators of the essential categories

Physical category	Significant indicators	Units
Acoustics	Equalized sound pressure level in 24 h (Leq24 h)	dB(A)
Electromagnetic fields	Electric field intensity of extremely low-frequency (ELF)	kV/m
	Magnetic flux of ELF (50/60 Hz)	μT
Illumination	Average illuminance of the ambience	Lx
	Average illuminance at the height of the tabletop	Lx
	Uniformity ratio of illuminance at the height of the tabletop	%
	Daylight-use ratio	%
Indoor air quality	Concentration of suspended particulate matter (PM_{10}), 24 h	$\mu g/m^3$
	Conc. of carbon monoxide (CO), 8 h	Ppm
	Conc. of carbon dioxide (CO_2), 8 h	Ppm
	Conc. of formaldehyde (HCHO), 8 h	Ppb
	Conc. of volatile organic compounds (TVOC), 8 h	mg/m^3
Thermal comfort	Indoor dry-bulb temperature (DBT)	°C
	Indoor relative humidity (RH)	%
	Indoor air velocity	m/s
	Value of predicted mean vote (PMV)	–

Scoring of $IEI_{(AHP)}$

In the similar manner of risk assessment, as presented by Anderson and Hult (1998) and Chiang (2001), we propose a comprehensive index, indoor environment index, $IEI_{(AHP)}$, to evaluate the indoor environment. It is assumed that there is an integrated effect accumulated from every category of physical-environment impact on occupants' health. Therefore, the value of $IEI_{(AHP)}$ is based on the summation of *Sx*, the evaluated score of the physical-environment category *x*, multiplied by *Wx*, the weighting of the physical-environment category *x*, as shown in Eqn (1):

$$\mathrm{IEI}_{(\mathrm{AHP})} = \sum Sx \cdot Wx = 0.203S_1 + 0.135S_2 + 0.164S_3 + 0.290S_4 + 0.208S5 \quad (1)$$

where S_1, S_2, S_3, S_4 and S_5 represent the score of the acoustics, EMF, illumination, IAQ and thermal comfort category, respectively. The score evaluation was done in the score range from 0 to 100. A five-interval scale divided from the physical magnitude and used a set of references as the benchmarks for determining the scores of 20, 40, 60, 80 and 100. Here, the references corresponding to the score 60 were referred to the criteria of the standard adopted widely for human health. In addition, the evaluated score of the *i*th indicator in the category *x*, Sx_i, is evaluated on the above-mentioned score grade, which corresponded to the risk values on the occupants' health. If there exists Sx_i less than 60, then the score of *Sx* is the minimum of Sx_i, in order to emphasize the worst conditions of indoor environment, elsewhere for every Sx_i is greater or equal to 60, it means no sanitary risk is incurred and we give *Sx* the arithmetic mean of Sx_i, that is:

$$Sx = \begin{cases} \min\left(Sx_i\right) & \exists i, Sx_i < 60 \\ \frac{1}{n}\sum_{i=1}^{n} Sx_i & \text{elsewhere} \end{cases} \tag{2}$$

DESIGN CRITERIA OF INDOOR ENVIRONMENT

Actual State of Indoor Environment in Taiwan

Figure 2 shows the statistic results of the field measurement. The measurement system and method have been addressed in an earlier paper (Chiang *et al.*, 2001). Frequency distributions were plotted used the hourly averages. In order to implement sustainable building, the feasible

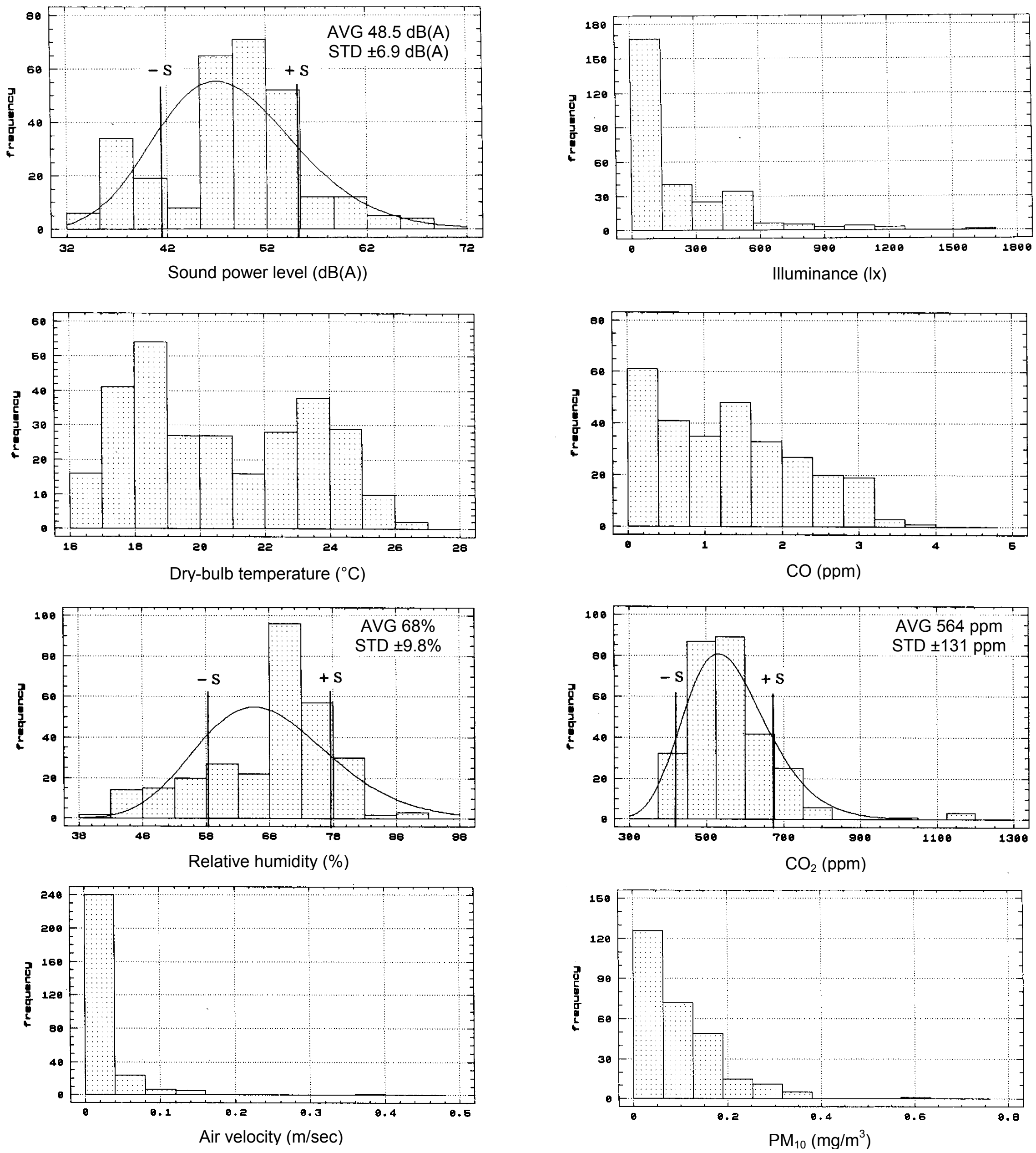

Figure 2 Frequency statistics of physical magnitude of indoor environment.

criteria for Indoor Environment Act play a crucial role in maintaining the built environment. Strict criteria may induce the overloads on indoor environment control. On the contrary, mild criteria may not ensure the healthy indoor environment. It is consequently necessary to realize the actual state of the indoor environment in Taiwan. The amount of 24-h field-measurement reached a total of 21 buildings. Considering the population distribution, nine cases were selected from the northern part of Taiwan, four cases from the middle part and the remaining four cases from the southern part.

Proposed Criteria Harmonized with Practical State

Table 2 shows the proposed criteria harmonized with practical state compared with the measured results of the sampled cases. The measured results were showed that the criteria, from literature reviews, of acoustic and thermal-comfort indicators should be adjusted, and the rest could be used for the assessment in Taiwan. Because of the dense dwelling area in Taiwan, approximately 75% of the sampled cases have SPL values worse than the criteria of a developed country. And nearly 60% of the cases failed in RH assessed by the criteria range of 40–70%, because the latitude of Taiwan is part of the hot-and-humid subtropical climate.

Table 2 Score conversion of $IEI_{(AHP)}$ corresponding to field-measured value

Significant indicators	Units	Benchmark references for evaluated scores									Score
		20		40		60		80		100	
'*Acoustics*' category											S_1
Equalized SPL in 24 h (Leq24h)	dB(A)		>55≥		>50≥		>45≥		>40≥		☐
'*Electromagnetic field*' category											S_2
Electric field intensity of ELF (50/60 Hz)	kV/m		>30≥		>10≥		>5≥		>2≥		☐
Magnetic flux of ELF (50/60 Hz)	µT		>1000≥		>500≥		>100≥		>25≥		
'*Illumination*' category											S_3
Average illuminance of the ambience	lx		<50≤		<100≤		<150≤		<300≤		☐
Average illuminance at the tabletop	lx		<300≤		<500≤		<750≤		<1000≤		
Uniformity ratio of illuminance	%		<30≤		<50≤		<70≤		<90≤		
Daylight-use ratio	%		<0.5≤		<0.7≤		<1.0≤		<1.2≤		
'*Indoor air quality*' category											S_4
Suspended particulate matter (PM_{10}), 24 h	µg/m^3		>350≥		>150≥		>50≥		>25≥		☐
Carbon monoxide (CO), 8 h	ppm		>15≥		>9≥		>4.5≥		>2.2≥		
Carbon dioxide (CO_2), 8 h	ppm		>1500≥		>1000≥		>800≥		>600≥		
Formaldehyde (HCHO), 8 h	ppb		>1000≥		>100≥		>16≥		>8≥		
Volatile organic compounds (TVOC), 8 h	mg/m^3		>3≥		>0.3≥		>0.1≥		>0.05≥		
'*Thermal comfort*' category											S_5
Indoor DBT, summertime	°C		>29≥		>28≥		>27≥		>26≥		☐
			<21≤		<22≤		<23≤		<24≤		
Indoor DBT, wintertime	°C		>27≥		>26≥		>25≥		>24≥		
			<19≤		<20≤		<21≤		<22≤		
Indoor DBT, natural ventilation	°C		>29≥		>28≥		>27≥		>26≥		
			<16≤		<17≤		<18≤		<19≤		
Indoor relative humidity (RH)	%		>85≥		>75≥		>65≥		>55≥		
			<35≤		<40≤		<45≤		<50≤		
Indoor air velocity	m/s		>0.45≥		>0.35≥		>0.25≥		>0.15≥		
Value of predicted mean vote (PMV)	–		>2.0≥		>1.5≥		>1.0≥		>0.5≥		
			<–2.0≤		<–1.5≤		<–1.0≤		<–0.5≤		

CONCLUSION AND IMPLICATIONS

This paper proposed a comprehensive index named $IEI_{(AHP)}$ to assess the built environment, which consists of 16 significant indicators in five physical categories (acoustics, electromagnetic field, illumination, indoor air quality and thermal comfort). The weightings of essential categories were determined by AHP method, which listed in sequence: 'IAQ' (0.290), 'Thermal comfort' (0.208), 'Acoustics' (0.203), 'Illumination' (0.164) and 'EMF' (0.135). The evaluated scales corresponding to the field-measured values were proposed in the score range from 0 to 100. It is feasible for the assessment on the indoor environment to benefit the occupants' health. The assessment results are useful for the designers to clarify the negatively significant factors of the actual reform case, and to obtain more performance with lesser costs. The proposed criteria, harmonized with the practical state, are especially useful for the use in subtropical zone.

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