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A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan

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Abstract

This paper presents the methodology of developing the comprehensive indicator for indoor-environment assessment. It intends to provide the occupants with the measures of indoor-environment quality. These indicators were drawn up by literature review based on the practicability, economic and feasible aspects. The categories we considered included acoustics, vibrations, illumination, thermal comfort, indoor air quality, water quality, greens and electromagnetic fields. The purpose is to derive the essential indicators through expertise consultation for quantitative assessment on existing buildings. The analytic hierarchy process (AHP) method was used to carry out the weighting among the categories and these indicators in the same category respectively. The consistency ratio was also calculated to filter out the null questionnaire. Finally, a comprehensive index, indoor environment index ($IEI_{(AHP)}$), composed of the filtered indicators, is proposed to assess the indoor-environment in the built buildings. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: AHP; Comprehensive indicator; Indoor-environment

1. Introduction

It is a common consensus within the "green building" activities that indoor-environment issue has to be an essential part of the global sustainability. There is a worldwide trend to develop a system that can provide comprehensive performance-assessments of buildings in different environmental scales: global, local and indoor issue. The government of Taiwan is toward this trend. One of the main areas of an environmental assessment method under development is the impact of the indoor environment on occupants' health.

Chen et al. [1] mentioned that indoor environment is important for people's health and welfare, because up to 90% of a typical person's time is spent indoors. Their productivity is also highly related to the indoor environment. Arthur Rosenfeld, a senior advisor at the US Department of Energy (1998), cited a cost/benefit analysis of high-efficiency filtration in an office building. The costs are \$23 a person for filters and \$1 a person for energy. The benefits are \$39 a person from a 10% decrease in respiratory disease; \$70 a person from a 1% increase in productivity among the 20% of workers who are allergic; and \$90 a person by decreasing the productivity loss from building-related illness from 1% to 0.75%. Those show a strong relationship between IAQ and productivity, and serious initiatives to improve indoor environment have a tremendous return.

Chiang et al. [2,3] pointed out that occupants 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 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 occupants.

2. Indicators derivation

To begin with, we analyze the indoor-environmental performance and quality in terms of various environmental categories: acoustics, illumination, thermal comfort, IAQ,

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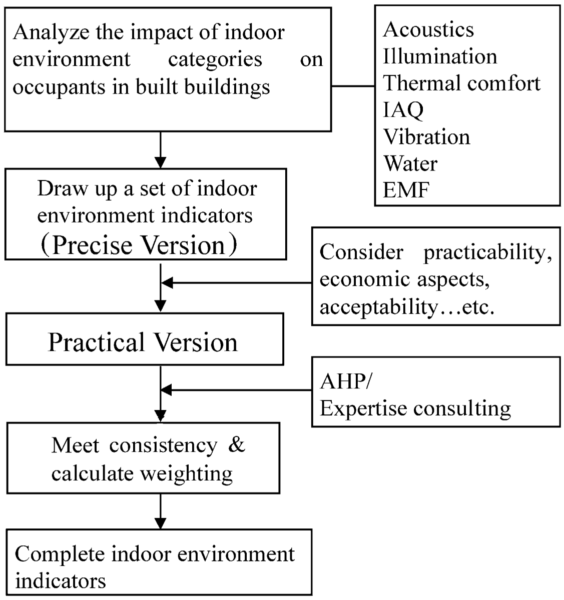

Fig. 1. Process of indicators derivation.

vibration and electromagnetic field, as shown in Fig. 1. Each environmental category is then expressed in its relevant indicators (for example: the acoustic environment can be assessed by $TNEL_{30}$, $L_{eq}24H$… etc.) as illustrated in Table 1 (indicators in precise version). There are 48 items of the total indicators as the precise version, then, due to the consideration of the practicable, economic and acceptable aspects, we select 23 items of those significant indicators for simplifying the assessment process as the practical version.

3. Weighting

The analytic hierarchy process (AHP) method, which was developed by Satty [4] is carried out to do the weighting among eight categories and those indicators in the same category in practical version, respectively. Expertise with respect to every professional field was involved in the process of deciding the relevant weight. These indicators, then, were classified into the independent categories to set up the hierarchy. 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 (C.I.) was greater than 0.1. For each category, the weighting value was obtained by the geometric mean of experts' questionnaires. The number of experts under consultation is 12, inclusive of five architects, three professional engineers and four professors.

4. Essential categories and weightings

Fig. 2 shows the results of the AHP analysis from the experts' questionnaires. The original weighting is listed in sequencing: "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. Fig. 3 shows the results after the adjustment, there are five categories left, and the adjusted weighting is listed in sequencing: "IAQ" (0.290), "Thermal comfort" (0.208), "Acoustics" (0.203), "Illumination" (0.164) and "EMF" (0.135).

5. Score of each indicator

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. Advised indicators are introduced in the left column of Table 2. In "Acoustics" category, two indicators, the equalized sound pressure Leq24H for dwellings and LeqD for offices, were included. In "Illumination" category, four indicators, including the intensity of illuminance for the ambiance and the operated face, uniformity ratio and daylight-use ratio, were used for assessment. In "Thermal Comfort" category, there were four indicators for assessment, including indoor temperature in various season, relative humidity, air velocity and PMV. In "IAQ" category, five common indoor air pollutants were appointed as the characteristic compounds. In "EMF" category, the electric-field intensity and the magnetic flux of the extremely low frequency (50/60 Hz) were used.

Especially when evaluating the indicators we used to present the thermal comfort felt by the occupants, we could easily figure out from the relative weightings that the applicability of PMV far exceeded the other three cursors, which signifies thermal comfort felt by the occupants in terms of the feasibility and convenience. Bearing in mind that it is the direct feeling toward temperature, humidity and air velocity in the surroundings that affect the general public, so even it is relatively convenient to use PMV in academic researches, it will, however, require more time and explanation to win the recognition and understanding from the common people. That is why, we suggest in this paper that all four indicators should be taken into consideration, so as to get a balance between the evaluation results of the academic research and the practicability.

Table 1
Lists of the indoor physical-environment indicators

Physical category	Indicators for assessment	Precise version		Practical version	
		General dwelling	Office building	General dwelling	Office building
Acoustics	$TNEL_{30}$	◎	◎		
	$TNEL_{30}$’	◎	◎	◎	◎
	Equalized sound pressure level in morning time ($L_{eq}M$)	◎			
	Equalized sound pressure level in daytime ($L_{eq}D$)		◎		◎
	Equalized sound pressure level in night time ($L_{eq}N$)	◎	◎		
	Equalized sound pressure level in 24 h ($L_{eq}24H$)	◎	◎	◎	
	L_{10}	◎	◎		
	L_{50}	◎	◎		
	L_{90}	◎			
	NR curve	◎	◎		
	NC curve	◎	◎		
Illumination	Average illuminance at the targeted face	◎		◎	
	Average artificial illuminance at the targeted face	◎		◎	
	Uniformity ratio of illuminance at the targeted face	◎		◎	
	Uniformity ratio of artificial illuminance at the targeted face	◎		◎	
	Ratio of daylight-use	◎		◎	
	Direct glare at the window face	◎			
	Discomfort glare of lamps	◎			
	Color temperature of lamps	◎			
	Color rendering index	◎			
Thermal comfort	Indoor temperature	◎		◎	
	Indoor humidity	◎		◎	
	Indoor air velocity	◎		◎	
	PMV	◎		◎	
	Temperature difference in altitude	◎			
	Solar heat gain	◎			
	Outdoor temperature	◎			
	Outdoor humidity	◎			
	Outdoor air velocity	◎			
Indoor air quality	Suspended particle, $PM_{2.5}$	◎			
	Suspended particle, PM_{10}	◎		◎	
	Carbon monoxide (CO)	◎		◎	
	Carbon dioxide (CO_2)	◎		◎	
	Formaldehyde (HCHO)	◎		◎	
	Volatile organic compounds (VOCs)	◎		◎	
	Ozone (O_3)	◎			
	Radon (Rn-222)	◎			
	Bacteria	◎			
	Fungus	◎			
	Endotoxin	◎			
	Allergen	◎			
	Ventilation rate	◎		◎	
	Locally average air age	◎		◎	
Water quality	Tap water quality	◎		◎	
Greens	Greens covered ratio	◎		◎	
Vibration	Whole body vibration exposure factor	◎		◎	
Electromagnetic fields	ELF electric field intensity	◎		◎	
	ELF magnetic flux	◎		◎	

Table 2 also shows the relationship between the evaluated score and the field-measurement magnitude. The manner of score-evaluation was represented 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 corresponded to the

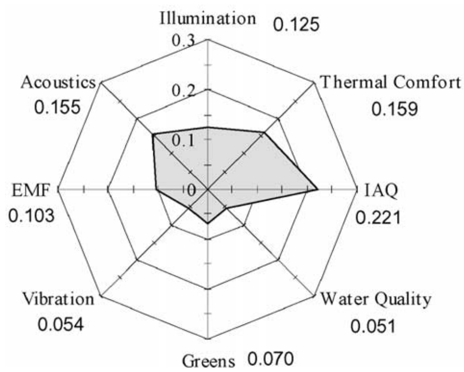

Fig. 2. The original weightings.

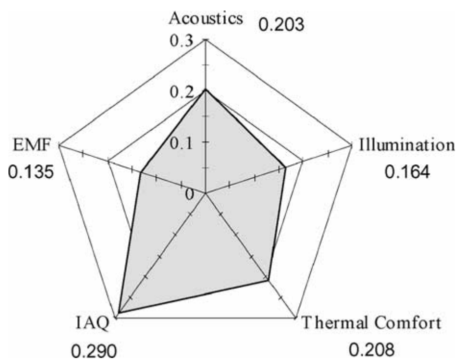

Fig. 3. The adjusted weightings.

score 60 were referred to the criteria of the standard adopted widely for human health, recommended values and building codes.

6. Structure of the indoor environment assessment

In the similar manner of risk assessment, presented by Anderson [5], Hult [6] and Chiang [7], we propose a comprehensive index, indoor environment index ($\mathrm{IEI}_{(\mathrm{AHP})}$), 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 index $\mathrm{IEI}_{(\mathrm{AHP})}$ shown in Eq. (1) is based on the summation of S_x, the evaluated score of the physical-environment category x, multiplied by W_x, the weighting of the physical-environment category x (Fig. 3).

$$\begin{aligned}\mathrm{IEI}_{(\mathrm{AHP})} &= \sum S_x W_x \\ &= 0.203 S_{\mathrm{Acoustics}} + 0.164 S_{\mathrm{Illumination}} \\ &\quad + 0.208 S_{\mathrm{Thermal\ Comfort}} + 0.29 S_{\mathrm{IAQ}} \\ &\quad + 0.135 S_{\mathrm{EMF}}. \qquad (1)\end{aligned}$$

In addition, there is not less than one indicator in the physical-environment category. The evaluated score of the ith indicator in the category x, S_{xi}, is evaluated on a score-grade of 20, 40, 60, 80 and 100, which corresponded to the risk values on the occupants' health. When the score of S_{xi} exceeds 60, it means no sanitary risk is incurred. The S_x is based on the scores consisted of S_{xi}. If there exists $S_{xi} < 60$, then the score of S_x is the minimum of S_{xi}, in order to emphasize the worst conditions of indoor environment; if for all $S_{xi} \geqq 60$, it means that no one is reached sanitary risk, we give S_x the arithmetic mean of S_{xi}, that's:

$$\text{if } \exists i, S_{xi} < 60, \quad \text{then } S_x = \min(S_{xi}), \quad \text{else } S_x = \frac{1}{n}\sum_{i=1}^{n} S_{xi}. \qquad (2)$$

It means occupants were caused the sanitary risk by the exposure to an indoor environment whose evaluated score of any indicator is less than 60, respectively.

For examples, results of field-measurements of the thermal environment in apartment A are shown in Table 3. Scores of temperature, relative humidity, air velocity and PMV all exceed 60, the score of the thermal environment is $(80 + 100 + 100 + 100)/4 = 95$.

A contrary example is shown in Table 4. Temperature in apartment B is 29°C and the score is 40. Due to the prerequisite of avoiding risk, the score of the thermal environment, $S_{\mathrm{Thermal\ Comfort}}$, is 40 unconditionally. Then, we can get $S_{\mathrm{Acoustics}}$, $S_{\mathrm{Illumination}}$, S_{IAQ} and S_{EMF}, respectively, in the same manner and put them into Eq. (1) to obtain the value of $\mathrm{IEI}_{(\mathrm{AHP})}$.

7. Conclusion and further development

The presented results, announced a set of physical indicators, the weightings of various physical categories and evaluated scales corresponded to the field-measured values, are feasible for the assessment on the built environment to benefit the occupants' health. The experts' opinions, based on the recent situation and the domestic environment, were applied.

The project is now proposed to continue with the field measurement and occupants' questionnaire to make up the assessment system, especially on identifying the weightings and the evaluated scales. Also, for a planned building, the project is proposing to develop the assessment method, which suit to the planned building. The same structure will be used, but the input will be taken the place of the data obtained from the checklists, including the quality assurance system, drawings, and descriptions of a building. From many aspects, it is more difficult to predict future.

Table 2
Scale of the evaluated score corresponded to field-measured value

Advised indicators Through experts' consultation and AHP results	Units	Evaluated score corresponding to the field-measured value				
		20	40	60	80	100
"*Acoustics*" *category*						
For dwellings, equalized SPL in 24 h (L_{eq}24H)	dB(A)	> 55 ≧	> 50 ≧	> 45 ≧	> 40 ≧	
For offices, equalized SPL in daytime (L_{eq}D)	dB(A)	> 59 ≧	> 56 ≧	> 53 ≧	> 50 ≧	
"*Illumination*" *category*						
Average illuminance of the ambiance	lx	< 70 ≦	< 150 ≦	< 300 ≦	< 500 ≦	
Average illuminance at the operated face in offices	lx	< 500 ≦	< 750 ≦	< 1000 ≦	< 1500 ≦	
Uniformity ratio of illuminance at the targeted face	%	< 0.5 ≦	< 0.6 ≦	< 0.7 ≦	< 0.8 ≦	
Ratio of daylight-use	%	< 0.5 ≦	< 0.7 ≦	< 1.0 ≦	< 2.0 ≦	
"*Thermal comfort*" *category*						
Indoor temperature, summer season	°C	> 29 ≧	> 28 ≧	> 27 ≧	> 26 ≧	
		< 21 ≦	< 22 ≦	< 23 ≦	< 24 ≦	
Indoor temperature, spring & autumn season	°C	> 28 ≧	> 27 ≧	> 26 ≧	> 25 ≧	
		< 20 ≦	< 21 ≦	< 22 ≦	< 23 ≦	
Indoor temperature, winter season	°C	> 27 ≧	> 26 ≧	> 25 ≧	> 24 ≧	
		< 19 ≦	< 18 ≦	< 17 ≦	< 16 ≦	
Indoor relative humidity	%	> 90 ≧	> 80 ≧	> 70 ≧	> 60 ≧	
		< 30 ≦	< 35 ≦	< 40 ≦	< 45 ≦	
Indoor air velocity	m/s	> 0.45 ≧	> 0.35 ≧	> 0.25 ≧	> 0.15 ≧	
PMV	—	> 2.0 ≧	> 1.5 ≧	> 1.0 ≧	> 0.5 ≧	
		< − 2.0 ≦	< − 1.5 ≦	< − 1.0 ≧	< − 0.5 ≦	
"*Indoor air quality*" *category*						
Suspended particulate matter (PM_{10}), 24 h	mg/m^3	> 350 ≧	> 150 ≧	> 50 ≧	> 25 ≧	
Carbon monoxide (CO), 8 h	ppm	> 15 ≧	> 9 ≧	> 4.5 ≧	> 2 ≧	
Carbon dioxide (CO_2), 8 h	ppm	> 2500 ≧	> 1000 ≧	> 800 ≧	> 600 ≧	
Formaldehyde (HCHO), 8 h	ppb	> 1000 ≧	> 100 ≧	> 16 ≧	> 8 ≧	
Volatile organic compounds (VOCs), 8 h	mg/m^3	> 3 ≧	> 0.3 ≧	> 0.1 ≧	> 0.5 ≧	
"*Electromagnetic fields*" *category*						
Electric field intensity of extremely low frequency (ELF)	kV/m	> 25 ≧	> 19 ≧	> 12 ≧	> 5 ≧	
Magnetic flux of extremely low frequency (ELF)	μT	> 1600 ≧	> 1100 ≧	> 600 ≧	> 100 ≧	

Table 3
Score-calculating of thermal environment in apartment A

Indicators of thermal environment	Units	Evaluated score corresponding to the field-measured value					
		20	40	60	80		100
"*Thermal comfort*" *category*							
Indoor temperature, summer season	°C	> 29 ≧	> 28 ≧	> 27 ≧	27	> 26 ≧	
		< 21 ≦	< 22 ≦	< 23 ≦		< 24 ≦	
Indoor temperature, spring & autumn season	°C	> 28 ≧	> 27 ≧	> 26 ≧		> 25 ≧	
		< 20 ≦	< 21 ≦	< 22 ≦		< 23 ≦	
Indoor temperature, winter season	°C	> 27 ≧	> 26 ≧	> 25 ≧		> 24 ≧	
		< 19 ≦	< 18 ≦	< 17 ≦		< 16 ≦	
Indoor relative humidity	%	> 90 ≧	> 80 ≧	> 70 ≧		> 60 ≧	50
		< 30 ≦	< 35 ≦	< 40 ≦		< 45 ≦	
Indoor air velocity	m/s	> 0.45 ≧	> 0.35 ≧	> 0.25 ≧		> 0.15 ≧	0.1
PMV	—	> 2.0 ≧	> 1.5 ≧	> 1.0 ≧		> 0.5 ≧	0.29
		< − 2.0 ≦	< − 1.5 ≦	< − 1.0 ≦		< − 0.5 ≦	

Table 4
Score-calculating of thermal environment in apartment B

Indicators of thermal environment	Units	Evaluated score corresponding to the field-measured value						
		20		40	60	80		100
"*Thermal comfort*" *category*								
Indoor temperature, summer season	°C	> 29 ≧	29	> 28 ≧	> 27 ≧		> 26 ≧	
		< 21 ≦		< 22 ≦	< 23 ≦		< 24 ≦	
Indoor temperature, spring & autumn season	°C	> 28 ≧		> 27 ≧	> 26 ≧		> 25 ≧	
		< 20 ≦		< 21 ≦	< 22 ≦		< 23 ≦	
Indoor temperature, winter season	°C	> 27 ≧		> 26 ≧	> 25 ≧		> 24 ≧	
		< 19 ≦		< 18 ≦	< 17 ≦		< 16 ≦	
Indoor relative humidity	%	> 90 ≧		> 80 ≧	> 70 ≧		> 60 ≧	50
		< 30 ≦		< 35 ≦	< 40 ≦		< 45 ≦	
Indoor air velocity	m/s	> 0.45 ≧		> 0.35 ≧	> 0.25 ≧	0.2	> 0.15 ≧	
PMV	–	> 2.0 ≧		> 1.5 ≧	> 1.0 ≧	0.77	> 0.5 ≧	
		< − 2.0 ≦		< − 1.5 ≦	< − 1.0 ≦		< − 0.5 ≦	

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