THE STUDY ON THE COMPREHENSIVE INDICATORS OF INDOOR ENVIRONMENT ASSESSMENT FOR OCCUPANTS' HEALTH IN TAIWAN

Che-Ming Chiang[1], Chi-Ming Lai[2], Po-Cheng Chou[2], Yen-Yi Li[2], Yu-Feng Tu[3]

[1] Professor, Dept. of Architecture, National Cheng-Kung University, Taiwan, ROC
[2] Ph.D. Candidate, Dept. of Architecture, National Cheng-Kung University, Taiwan, ROC
[3] Master, Dept. of Architecture, National Cheng-Kung University, Taiwan, ROC

ABSTRACT

This paper presents a set of comprehensive indicators for indoor-environment assessment which intend to provide the occupants with the healthy and comfort indoor-environment. These indicators were drawn up by literature review based on the practicability, economic and feasible aspects. The factors we considered were involved from the categories of acoustics, vibrations, illumination, thermal comfort, indoor air quality, water quality, greens and electromagnetic fields. The purpose is to conduct the essential indicators through expertise consultation for quantitative assessment on existing buildings. The AHP (Analytic Hierarchy Process) method was used to carry out the weighting among these indicators in the same category respectively. The consistency ratio was also calculated to filter out the null questionnaire. Finally, a comprehensive index, $IEI_{(AHP)}$ (Indoor Environment Index), composed of the filtered indicators is represented to assess the healthy environment in the built buildings. This will benefit to occupants' productivity and efficiency.

INTRODUCTION

It is a common perception 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 the 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 on occupants' health in the indoor environment.

Chen *et al*. (1998) mentioned that the indoor environment is important to people's health and welfare because up to 90% of a typical person's time is spent indoors, their productivity is also related to the indoor environment. Arthur Rosenfeld, a senior advisor at the U.S. 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*. (1993) 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's necessary to take various aspects of those environmental factors into consideration, when dealing with the influence of built-environment on tenants.

METHOD

This study describes the method of the indoor environment assessment on existing buildings in Taiwan, and intends to draft indoor-environment preservation indicators from eight categories respectively, including acoustics, vibration, illumination, thermal comfort, indoor air quality (IAQ), water quality, greens and electromagnetic fields (EMF).

Structure of the indoor environment assessment

In the similar manner of risk assessment, presented by Gadeau *et al*. (1997), 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 index $IEI_{(AHP)}$ shown in Equation 1 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.

$$IEI_{(AHP)} = \sum S_x \cdot W_x \quad \text{......} (1)$$

In addition, there is not less than one indicator in the physical-environment category. The evaluated score of the i_{th} indicator in the category x, Sxi, 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 Sxi exceeds 60, it means no sanitary risk is incurred. The Sx is based on the scores consisted of Sxi. If there exists $Sxi < 60$, then the score of Sx is the minimum of Sxi in order to emphasize the worst conditions of indoor environment; if for all $Sxi \geqq 60$, it means that no one is reached sanitary risk, we give Sx the arithmetic mean of Sxi , that's:

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

Weighting

The analytic hierarchy process (AHP) method, which was developed by Thomas L. Saaty (1971), is carried out to do the weighting, Wx, among those indicators in the same category respectively. Expertise with respect to every professional field was involved in the process of deciding the relevant weight. To begin with, the literature review, group brainstorming and Delphi method were used for selecting the proposed indicators. 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 maximum 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.

Physical indicators

Table 1 Lists of the indoor physical-environment indicators

<table>
<tr><th rowspan="2">Physical category</th><th rowspan="2">Indicators for assessment</th><th colspan="2">Precise version</th><th colspan="2">Practical version</th></tr>
<tr><th>general dwelling</th><th>office building</th><th>general dwelling</th><th>office building</th></tr>
<tr><td rowspan="11">Acoustics</td><td>$TNEL_{30}$</td><td>◎</td><td>◎</td><td></td><td></td></tr>
<tr><td>$TNEL_{30}$’</td><td>◎</td><td>◎</td><td>◎</td><td>◎</td></tr>
<tr><td>Equalized sound pressure level in morning time ($L_{eq}M$)</td><td>◎</td><td></td><td></td><td></td></tr>
<tr><td>Equalized sound pressure level in daytime ($L_{eq}D$)</td><td></td><td>◎</td><td></td><td>◎</td></tr>
<tr><td>Equalized sound pressure level in night time ($L_{eq}N$)</td><td>◎</td><td>◎</td><td></td><td></td></tr>
<tr><td>Equalized sound pressure level in 24 hours ($L_{eq}24H$)</td><td>◎</td><td>◎</td><td>◎</td><td></td></tr>
<tr><td>L_{10}</td><td>◎</td><td>◎</td><td></td><td></td></tr>
<tr><td>L_{50}</td><td>◎</td><td>◎</td><td></td><td></td></tr>
<tr><td>L_{90}</td><td>◎</td><td></td><td></td><td></td></tr>
<tr><td>NR curve</td><td>◎</td><td>◎</td><td></td><td></td></tr>
<tr><td>NC curve</td><td>◎</td><td>◎</td><td></td><td></td></tr>
<tr><td rowspan="9">Illumination</td><td>Average illuminance at the targeted face</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Average artificial illuminance at the targeted face</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Uniformity ratio of illuminance at the targeted face</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Uniformity ratio of artificial illuminance at the targeted face</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Ratio of daylight-use</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Direct glare at the window face</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Discomfort glare of lamps</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Color temperature of lamps</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Color rendering index</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td rowspan="9">Thermal comfort</td><td>Indoor temperature</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Indoor humidity</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Indoor air velocity</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>PMV</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Temperature difference in altitude</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Solar heat gain</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Outdoor temperature</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Outdoor humidity</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Outdoor air velocity</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td rowspan="14">Indoor air quality</td><td>Suspended particle, $PM_{2.5}$</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Suspended particle, PM_{10}</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Carbon monoxide (CO)</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Carbon dioxide (CO_2)</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Formaldehyde (HCHO)</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Volatile organic compounds (VOCs)</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Ozone (O_3)</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Radon (Rn-222)</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Bacteria</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Fungus</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Endotoxin</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Allergen</td><td colspan="2">◎</td><td colspan="2"></td></tr>
<tr><td>Ventilation rate</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Locally average air age</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Water quality</td><td>Tap water quality</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Greens</td><td>Greens covered rate</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>Vibration</td><td>Whole body vibration exposure factor</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td rowspan="2">Electromagnetic fields</td><td>ELF electric field intensity</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
<tr><td>ELF magnetic flux</td><td colspan="2">◎</td><td colspan="2">◎</td></tr>
</table>

According to the literature review and the authors' knowledge, the indoor physical- environment performance and quality was consisted of eight physical-environment categories. Each category is then expressed in its relevant indicators for field measurement as illustrated in Table 1. 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 24 items of those significant indicators for simplifying the assessment process as the practical version. These items and their weightings of the physical categories and indicators are determined by the experts' consultation using the AHP analysis.

RESULTS AND DISCUSSION

From Equation 1, there are two processes of the assessment procedure on the indoor physical-environment. Presented in first process is to determine the essential physical-categories and their relative weighting by the experts' questionnaire. Presented in second process is to define the relationship transferred the physical magnitude of each indicator respectively into the score represented from 20 to 100.

Determination of the essential category and the weighting

Figure 1 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). This occurrence reflects the opinions from the experts on the practical aspects of the recent period and the domestic situation. According to the economic sense, the minor categories whose weighting 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 2 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). Substituting the adjusted weighting into Equation 1, we get:

$$IEI_{(AHP)} = 0.203 \cdot S_{Acoustics} + 0.164 \cdot S_{Illumination} + 0.208 \cdot S_{ThermalComfort} + 0.290 \cdot S_{IAQ} + 0.135 \cdot S_{EMF} \qquad (3)$$

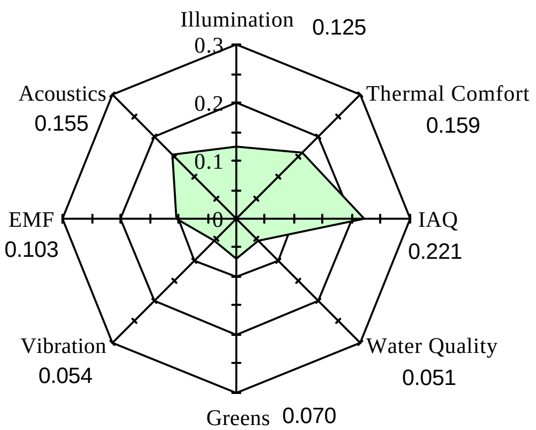

Figure 1 The original weighting from the experts' questionnaire

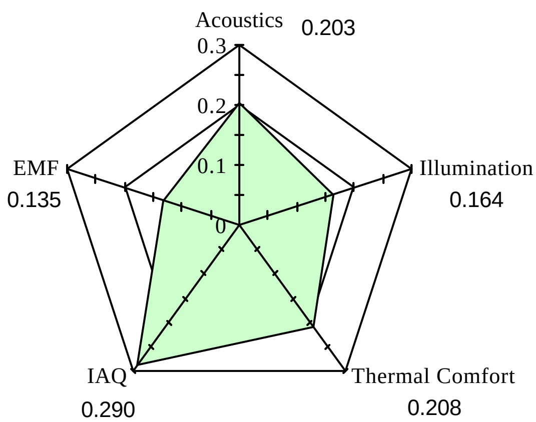

Figure 2 The adjusted weighting of the essential categories

Scale of physical-environment assessment

The scale being used to transmit the value of the field-measurement to a grade is the score of 20, 40, 60, 80 and 100. Table 2 shows the relationship of the evaluated score corresponded to the field-measurement magnitude. These indicators consisted from the five categories were advised through literature review and experts’ consultation on the practicable and essential aspects. 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 score 60 were referred to the criteria of the regulation adopted widely for human-health protection. It means

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

Advised indicators Through literature review and experts’ consultation	Units	Evaluated score corresponded to the field-measured value				
		20	40	60	80	100
■ “Acoustics” Category						
For dwellings, Equalized SPL in 24 hours (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	℃	＞29≧ ＜21≦	＞28≧ ＜22≦	＞27≧ ＜23≦	＞26≧ ＜24≦	
Indoor temperature, spring & autumn season	℃	＞28≧ ＜20≦	＞27≧ ＜21≦	＞26≧ ＜22≦	＞25≧ ＜23≦	
Indoor temperature, winter season	℃	＞27≧ ＜19≦	＞26≧ ＜18≦	＞25≧ ＜17≦	＞24≧ ＜16≦	
Indoor Relative Humidity	%	＞90≧ ＜30≦	＞80≧ ＜35≦	＞70≧ ＜40≦	＞60≧ ＜45≦	
Indoor air velocity	m/sec	＞0.45≧	＞0.35≧	＞0.25≧	＞0.15≧	
PMV	--	＞2.0≧ ＜-2.0≦	＞1.5≧ ＜-1.5≦	＞1.0≧ ＜-1.0≦	＞0.5≧ ＜-0.5≦	
■ “Indoor Air Quality” category						
Suspended particulate matter (PM_{10}), 24 hr	mg/m^3	＞350≧	＞150≧	＞50≧	＞25≧	
Carbon monoxide (CO), 8 hr	ppm	＞15≧	＞9≧	＞4.5≧	＞2≧	
Carbon dioxide (CO_2), 8 hr	ppm	＞2500≧	＞1000≧	＞800≧	＞600≧	
Formaldehyde (HCHO), 8 hr	ppb	＞1000≧	＞100≧	＞16≧	＞8≧	
Volatile organic compounds (VOCs), 8hr	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)	μ tesla	＞1600≧ ＞1100≧ ＞600≧ ＞100≧

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

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 six 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 on the extremely low frequency (50/60 Hz) were used.

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 fitted for the assessment on the built environment to benefit the tenants' health. The experts' opinions, based on the recent situation and the domestic environment, were applied.

The project is now proposing 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 check lists, including the quality assurance system, drawings, descriptions of a building. From many aspects, it is more difficult to predict future.

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