ABSTRACT
A successful Indoor Air Quality (IAQ) surveillance plan is essential for healthy and safe workplaces; yet it is costly to sample all air pollutants of the entire community. In Hong Kong, a voluntary IAQ certification scheme for workplaces proposes the acceptable concentration levels of nine common indoor air pollutants, namely carbon dioxide ($CO_2$), carbon monoxide (CO), respirable suspended particulates (RSP), nitrogen dioxide ($NO_2$), ozone ($O_3$), formaldehyde (HCHO), total volatile organic compounds (TVOC), radon (Rn) and airborne bacteria count (ABC). However, technical difficulties have been reported during the full assessment of these pollutants. This study hence investigates the feasibility of a preliminary screening process for presumptive detection of IAQ problems in an air-conditioned environment. Specifically, a simple screening test at certain probability of unsatisfactory IAQ for air-conditioned offices, together with an ‘IAQ index’ which employs the average fractional dose to certain exposure limits of a few ‘most representative’ air pollutants (rather than all of the listed nine) was proposed. This is an alternative for routine inspection in determining the asymptomatic IAQ unsatisfactory for some air-conditioned offices of Hong Kong. And it was evaluated in terms of the test sensitivity, specificity and predictive values. The screening test would be a useful tool for policymakers, building owners and professionals to identify offices with probable IAQ problems and to make decisions on resources for efficient mitigation actions.

KEYWORDS
Screening test, IAQ assessment, Air-conditioned offices, IAQ index

INTRODUCTION
With growing concern in the last decade over complaints attributed to Indoor Air Quality (IAQ), environmental parameters were suggested and adopted for IAQ assessments for an indoor environment by researchers, building owners and facility managers etc. (Chao et al. 2001, Cheong and Chong 2001, Lee et al. 2002, Möhle et al. 2003). The rationales behind the selection of the relevant measuring parameters are the significance of the air pollutant associated adverse effects on human health and sufficient evidence of them causing unacceptable IAQ. Unfortunately, it would be too expansive to sample all air pollutants of entire community therefore air sampling for an IAQ assessment should be conducted in accordance with the surveillance strategy. Surrogate indicators or ‘representative’ indoor air pollutant(s) were suggested for IAQ assessments (Ferguson et al. 1995, Hui et al. 2006, Mui et al. 2006a, Wong et al. 2006).

In Hong Kong, the 8-hour average concentrations of 9 common indoor air pollutants, i.e. carbon dioxide ($CO_2$), carbon monoxide (CO), respirable suspended particulates (RSP), nitrogen dioxide ($NO_2$), ozone ($O_3$), formaldehyde (HCHO), total volatile organic compounds (TVOC), radon (Rn), airborne bacteria count (ABC) were suggested as a ‘full’ IAQ assessments (HKEPD 2003). A number of technical difficulties in the implementation of the ‘full’ IAQ assessment have been reported.
from local building industry. The assessment of all the pollutants involves a considerable amount of resources and manpower in terms of the sophisticated knowledge of application, calibration and regular maintenance of the appliances, interpretation of the data, and on-site operation of the equipment etc. In addition, uncertainties of some sampling protocols were not included in many assessments, the assessment results might be misleading and could not be used effectively to facilitate building management (Mui and Wong 2004, Mui et al. 2006a,b). Sampling point density and sampling period, the number of pollutants were the other concerns for implementation with a balance of measurement efforts and the assessment accuracies (HKEPD 2003, Hui et al. 2006, Mui et al. 2006a,b, Wong et al. 2006). Without details of the rationale behind, an ‘expansive’ IAQ assessment of ‘digging’ problems for the occupants might not seem justified to some building owners.

This study proposes an express assessment protocol (EAP) with a simple screening process as an alternative for routine inspection in determining the asymptomatic IAQ unsatisfactory for some air-conditioned offices of Hong Kong. In particular, some dominant contributors of ‘unsatisfactory IAQ’ would be used to derive an IAQ index, with a screening level set at certain probability of unsatisfactory IAQ. This simple, practical and understandable IAQ measurement tool would promote the public awareness including non-scientists, building owners and maintenance staff of their health effects and qualify as a useful tool of environmental management.

**ASSESSMENT TOOL**

An indoor environment with any one of the specified air pollutant parameters $i$ exceeding the exposure limits, i.e. $\Phi_i > \Phi_{ie}$, is deemed to have ‘unsatisfactory’ IAQ; otherwise, i.e. $\Phi_i \leq \Phi_{ie}$, its IAQ is considered ‘satisfactory’ (Wong et al. 2006). With the identified distributions $G$ of a concerning pollutant $i$ in a cross-sectional measurement, the sample unsatisfactory rate $\hat{p}_i$ for the surveyed environment in the region can be approximated (Hui et al. 2006),

$$\hat{p}_i = 1 - \int_{\Phi_{ie}}^{\Phi_i} G(i) \, d\Phi_i$$  \hspace{1cm} (1)

Assuming all contributors to be independent and by measuring the dominant ones only, a preliminary assessment test $A$ of ‘unacceptable IAQ’ is proposed (Hui et al. 2006). The IAQ parameters can be ranked according to their respective unsatisfactory rates for express assessment parameters such that the dominant contributors $\phi$ is given by,

$$\phi = \phi_1 > \phi_2 > \ldots > \phi_m > \phi_0$$  \hspace{1cm} (2)

Apart from the preliminary assessment test using the top dominant contributors, it is assumed that the IAQ unsatisfactory due to other air pollutants not measured in the preliminary assessment would be correlated with an index $\theta_m$ derived from the assessed top dominant contributors (Wong et al. 2005). The probability of ‘unsatisfactory’ IAQ $P(A)$ for the environment can be expressed by a logistic model where $k_1$ and $k_2$ are the regression constants such that,

$$P(A) = \frac{1}{1 + \exp(-k_1 - k_2 \theta_m)}$$  \hspace{1cm} (3)

In this study, an ‘IAQ index $\theta_m$’ using the average fractional dose to certain exposure limits $\Phi_{ie}$ of some dominant contributors $m$ among all listed air pollutants in certain assessments is defined for air-conditioned offices. $\theta_m$ is determined as follows, where $\phi_i$ is the fractional dose of a representative pollutant $i$, $\Phi_i$ is the average level of $j$ assessed over an exposure time period, $\Phi_{ie}$ is the background pollutant concentration of outdoor air (Moschandreas DJ and Sofuoglu SC 2004),
\[ \theta_m = \sum_{m} \Phi^*_m = \frac{\Phi_m - \Phi_i}{\Phi_m - \Phi_i} \quad \ldots \quad (4) \]

For a screening test using the IAQ index \( \theta_m \), the screening level \( \theta_s \) would be set at certain probability of unsatisfactory IAQ \( P(A) \) depending on various screening strategies and considerations, such as cost-effectiveness and feasibility, for asymptomatic IAQ problems of the environment. Various screening levels should be evaluated and established carefully. At certain \( \theta_s \), the sensitivity \( P_s \) and specificity \( P_f \) describe the ability of the screening test to correctly identify an environment which has or does not have the unsatisfactory IAQ. They are the probabilities of testing positive and negative respectively when the unsatisfactory IAQ is truly present and absent. Compared with the ‘full’ IAQ assessment results, taking the test results of the proposed EAP with screening test, the true positive, true negative, false positive and false negative as TP, TN, FP and FN respectively, \( P_s \) and \( P_f \) are (Mausner and Kramer 1985),

\[
P_s = \frac{TP}{TP + FN} \quad \ldots \quad (5)
\]

\[
P_f = \frac{TN}{TN + FP} \quad \ldots \quad (6)
\]

The predictive positive \( P_+ \) and predictive negative \( P_- \) measure the frequency of the test results that correctly identify an unsatisfactory IAQ, i.e. the proportions of testing positive where unsatisfactory IAQ is actually found and testing negative where unsatisfactory IAQ is actually not found.

\[
P_+ = \frac{TP}{TP + FP} \quad \ldots \quad (7)
\]

\[
P_- = \frac{TN}{TN + FN} \quad \ldots \quad (8)
\]

The assessment was illustrated in Figure 1.

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**Figure 1** Screening test
A regional cross-sectional measurement of the 9 common air pollutant levels was conducted at 422 offices in Hong Kong (Wong et al. 2006). That sample size was assumed to be 'large' enough in representing the overall picture of local pollutant levels in offices. The sampling premises were selected with a building age of about ten years such that their building styles and materials used were comparable. They included all regions of major office development. In them, human activities and dress codes were similar. The schedule of air-conditioning operation was well defined and sufficient for the study to focus on the indoor air contaminant parameters. Covering a range of open-plan offices from individual small offices to conference rooms, the samples were of sizes from 10 m$^2$ to 300 m$^2$.

Table 1 shows the averages and standard deviations of the 9 pollutant levels from the measurement results of these offices. Based on the geometric means (GM) and geometric standard deviations (GSD) displayed, each of the parameters would be described by a geometric distribution. The fractions of unsatisfactory offices were also determined and shown (Hui et al. 2006, Wong et al. 2006).

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter (unit)</th>
<th>EPD recommended maximum level</th>
<th>Arithmetic mean concentration (Standard deviation)</th>
<th>Geometric mean concentration (Geometric standard deviation)</th>
<th>Observed unsatisfactory rate (%) (CI = 95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CO$_2$ (ppm)</td>
<td>1,000</td>
<td>660 (159)</td>
<td>642 (1.26)</td>
<td>3% (1-4%)</td>
</tr>
<tr>
<td>2</td>
<td>CO (µg m$^{-3}$)</td>
<td>10,000</td>
<td>1,002 (332)</td>
<td>942 (1.44)</td>
<td>&lt;0.2%</td>
</tr>
<tr>
<td>3</td>
<td>RSP (µg m$^{-3}$)</td>
<td>180</td>
<td>33 (21)</td>
<td>27 (1.89)</td>
<td>&lt;0.2%</td>
</tr>
<tr>
<td>4</td>
<td>NO$_2$ (µg m$^{-3}$)</td>
<td>150</td>
<td>28 (16)</td>
<td>25 (1.71)</td>
<td>&lt;0.2%</td>
</tr>
<tr>
<td>5</td>
<td>O$_3$ (µg m$^{-3}$)</td>
<td>120</td>
<td>46 (40)</td>
<td>38 (2.38)</td>
<td>5% (3-7%)</td>
</tr>
<tr>
<td>6</td>
<td>HCHO (µg m$^{-3}$)</td>
<td>100</td>
<td>54 (113)</td>
<td>32 (2.67)</td>
<td>6% (4-9%)</td>
</tr>
<tr>
<td>7</td>
<td>TVOC (µg m$^{-3}$)</td>
<td>600</td>
<td>397 (341)</td>
<td>291 (2.33)</td>
<td>16% (12-19%)</td>
</tr>
<tr>
<td>8</td>
<td>Rn (Bq m$^{-3}$)</td>
<td>200</td>
<td>52 (39)</td>
<td>40 (2.10)</td>
<td>0.2% (0-0.7%)</td>
</tr>
<tr>
<td>9</td>
<td>ABC (CFU m$^{-3}$)</td>
<td>1,000</td>
<td>580 (382)</td>
<td>447 (2.19)</td>
<td>15% (12-19%)</td>
</tr>
</tbody>
</table>

The 9 pollutants were ranked according to their respective unsatisfactory rates $p_i$ and shown in Figure 2. The top four contributors of unsatisfactory IAQ were TVOC, ABC, HCHO and O$_3$ (Hui et al. 2006).
The performance of the EAP \( A_j \) was expressed by the sensitivity \( P_s \) in assessing the environmental unsatisfactory rate using \( j \) dominant contributors. Shown in Figure 3 is the sensitivity of \( A_j \) determined from the actual unsatisfactory counts in the measurement results. Taking the points of rapid change as references, i.e. \( j=4 \), the accuracy of the test \( A_4 \) was 96% (95% to 98% for CI=95%) from the measurements of TVOC, ABC, HCHO and O3. Hence, the proposed test could be an express assessment tool for unsatisfactory office IAQ.

Figure 2  Unsatisfactory rates of nine indoor pollutants in 422 offices

Figure 3  Sensitivity (Accuracy) of the EAP using \( j \) dominant contributors of IAQ unsatisfactory
With the measured TVOC, ABC, HCHO and O₃ (n=4), Figure 4 shows the IAQ index θₘ of the 422 samples, classified into environment of satisfactory Ω⁻ and unsatisfactory Ω⁺ IAQ respectively. It was reported that the range of IAQ index for the satisfactory and unsatisfactory offices were θₘ = 0.11-0.68 and θₘ⁺ = 0.31-3.44, and the difference between the two groups was significant. Obviously, the expected IAQ index determined from the satisfactory offices would be significantly lower than those associated with the unsatisfactory IAQ (p < 0.00011, pair t-test). The IAQ index θₘ would be correlated to the assessed IAQ results by a logistic model, for a space having an unsatisfactory IAQ (event A) P(A) as (p < 0.0001):

\[
P(A) = \frac{1}{1 + e^{(-13.63 - 24.06 θₘ)}} \quad \cdots (9)
\]

Establishing the screening level θₛ would be justified for some surveillance strategies in a balance of cost effectiveness and feasibility for identifying asymptomatic IAQ problems of the environment. Taking the probability of unsatisfactory IAQ P(A) = 0.5 as an example, i.e. the predicted satisfactory was P(A) < 0.5 as the 'low risk group' and the predicted unsatisfactory was P(A) ≥ 0.5 'as the high risk group' respectively, the corresponding screen level θₛ was 0.566.

Table 2 shows the IAQ assessment results using the EAP with screening test and the 'full' IAQ assessment for the 422 sample offices. The results showed that, for the EAP at the screening level θₛ = 0.566 for P(A) = 0.5, the test would correctly identify 87.1% IAQ problem present (Pₛ = 0.871) and 91.5% (Pᵢ = 0.915) IAQ problem absent with the test samples. Among the test positive samples, 86.6% had IAQ problems (Pₛ = 0.866) and for the test negative samples, 91.9% did not have IAQ problems (Pᵢ = 0.919).

<table>
<thead>
<tr>
<th>Assessed unsatisfactory IAQ</th>
<th>Predicted unsatisfactory IAQ</th>
<th>Predicted unsatisfactory IAQ</th>
<th>Total counts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>'No' P(A) &lt; 0.5</td>
<td>'Yes' P(A) ≥ 0.5</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>TN = 21</td>
<td>TP = 142</td>
<td>163</td>
</tr>
<tr>
<td>'No'</td>
<td>TN = 237</td>
<td>FP = 22</td>
<td>259</td>
</tr>
<tr>
<td>Total counts</td>
<td>258</td>
<td>164</td>
<td>422</td>
</tr>
</tbody>
</table>
CONCLUSION

Measuring all indoor pollutants could be the best approach in identifying the needs for the mitigation of indoor air pollutants, but it would consume lots of manpower and resources to obtain the desired results. This study proposes a screening test for the express assessment protocol (EAP) for IAQ evaluation by measuring some ‘representative-set’ common air pollutants in air-conditioned offices of Hong Kong. As identified from the regional cross-sectional measurement at 422 offices in Hong Kong, the proposed assessment tool with the top four contributors of unsatisfactory IAQ, TVOC, ABC, HCHO and O₃, was demonstrated as an example. Furthermore, the performance of the proposed assessment tool in assessing office IAQ was evaluated in terms of the test sensitivity, specificity and predictive values compared with a full IAQ assessment. With screening level set at the probability of unsatisfactory IAQ be 0.5, the test would identify about 90% of IAQ unsatisfactory cases in the test samples. With an appropriate screening level and properly selected representative common air pollutants for the assessment, the proposed assessment tool would be a useful tool for policymakers, building owners and professionals to identify the air-conditioned offices with IAQ index as an indicator for unsatisfactory IAQ and to make decisions on resources and manpower management for efficient IAQ surveillance programme elsewhere.

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