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Diagnostics of unsatisfactory indoor air quality in air-conditioned workplaces

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Abstract

This study examines a screening process for environmental diagnosis of indoor air quality (IAQ) problems in air-conditioned office buildings. Diagnosis of IAQ problems in relation to the complaints of environmental health effects has not been identified as a precise science and this paper proposes an evaluation tool to address this need. An 'IAQ index', the average fractional dose of a set of three representative indoor pollutants, has been developed for this purpose, to be used as a screening parameter for detecting the unsatisfactory factors which affecting the IAQ in an air-conditioned office. In the case of a wide-ranging set of IAQ measurements is undesired, a set of three measurements can be useful in deciding whether to take any further action (more measurements or remedial measures). This paper presents a useful diagnostic to identify air-conditioned offices of Hong Kong with IAQ problems regarding to existing IAQ standard.

Nomenclature

a, b	arbitrary constants of screening levels
L_r	likelihood ratio for the positive test
N	number of samples
N_d	number of samples with unsatisfactory IAQ
P_d, P'_d	pre-assessment and post-assessment probability of the positive outcome, i.e., unsatisfactory indoor air quality (IAQ)
P_s, P_f	sensitivity and specificity of a diagnostic test
TP, TN, FP, FN	true positive, true negative, false positive and false negative of test results
Φ_i, Φ_j	exposure concentration of i-th pollutant and of j-th IAQ index pollutant
Φ_j^*	fractional dose of IAQ index pollutant j
o_d, o'_d	pre-assessment and post-assessment odds
θ	IAQ index

Subscripts

i	of i-th pollutant
j	of j-th IAQ index pollutant
e	of exposure limit

Introduction

Carrying out any kind of IAQ measurement requires decisions about the time, monitoring parameters, duration and location of measurements [1,2]. Measuring all indoor air pollutants in workplaces might be ideal in identifying the needs for mitigation of indoor air pollutants; however, the manpower and resources involved might not be cost-effective for the desired solution [3]. A cheaper alternative way of screening for IAQ problems like odours and minor transient symptoms would be to survey the occupants' responses which can be more informative. IAQ measurements are only an attempt to explain the symptoms reported. For other kinds of health concerns such as cancer, infections and persistent toxic reactions, however, objective measurements could be more appropriate. IAQ assessment parameters based on IAQ-related human health and/or the adverse effects due to indoor environmental factors, such as air-conditioning system and pollution, emissions from building materials and ingress of traffic fumes, have been suggested for practical application [3-5].

Diagnosis must be initiated prior to remediation of the IAQ problems as it will provide information requisite to resolving the problem [1] Guidelines for IAQ have been introduced in different places, such as in Europe, USA, Canada, Singapore and Hong Kong [3,6-10]; and a number of IAQ surveys have been carried out [11-13]. Although these guidelines have provided the basis upon which judgmental indication of IAQ can be inferred by the public and would raise awareness of the IAQ problems and human exposure issues [14,15], these guidelines do not provide a way for diagnosis problems in relation to health complaint and would not provide a complete picture of the situation. In Hong Kong, an IAQ assessment scheme [3] which was promoted by the Environmental Protection Department (HKEPD) provides a ranking of the office IAQ as 'Good' or 'Excellent' with an 8-hour exposure concentrations of nine indoor air pollutants: 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), to be monitored within the occupied period during working hours, in each 500 m^2 area of the office building. It is noted that the HKEPD scheme would be a guide to determine IAQ in buildings as a means of statutory control; however, it is not definitive about either the pollutant concentrations themselves or whether they will cause health and comfort problems for the occupants. Furthermore, a number of technical difficulties in the implementation of this scheme have been reported [16]. Indeed, some assessed buildings were at a relatively late stage of an IAQ problem when IAQ assessment scheme was introduced. Therefore, the diagnosis of the problem must begin with some simpler screening process, and they must become aware that the IAQ problems may be related to exposure to indoor air pollutants [1,5,16-18]. If any newly proposed screening process is validated against the existing IAQ assessment scheme, then it would be a way of simplifying IAQ monitoring for air-conditioned workplaces.

An effective and efficient screening process for detecting any latent IAQ problems of an indoor environment is one of the key elements of good IAQ management for the provision of a healthy and safe workplace. Uncertainty under different assessment approaches such as various measurement periods, the use of professional choices of measurement locations, various numbers of measurement points and assessment parameters were investigated and quantified [1,19-21].

Strategic air sampling should be conducted in accordance with surrogate indicators or ‘dominant’ indoor air pollutants for IAQ assessments. The probable correlations among the listed parameters in the IAQ assessment scheme by the HKEPD were evaluated. Three ‘representative’ parameters namely RSP, CO_2 and TVOC measured in an office environment would be good indicators for unsatisfactory IAQ [21,22]. The choice of these parameters gives engineering indications of effectiveness of filtration in ventilation system, sufficient quantity of fresh outdoor air for dilution of occupants, and emissions of building contents. Validity of the representative parameters was verified with on site measurements from other offices in Hong Kong [23]. It was reported that chronic obstructive pulmonary disease (COPD) patient's emotion is strongly associated with the IAQ indicator [24].

It was also reported that the acceptable CO_2 levels for IAQ can be correlated to 80% of the people who do not express dissatisfaction due to unknown contaminants in harmful concentrations [25]. A recent study demonstrated that the use of occupant acceptance of CO_2 concentrations was a useful screening parameter in quantifying the likelihoods of the office environment with unsatisfactory IAQ [26]. A good correlation between CO_2 and a number of assessment parameters, including radon, was also reported for air-conditioned workplaces in Hong Kong. It was a useful proxy for ventilation rate and body odour when there was a fairly constant occupation level in a space. The exposure of VOCs represents mainly emission from materials indoors and vehicle outdoors, two sources that are quite distinct from the occupant themselves [27]. RSP as an environmental monitoring parameter would associate with the daily prevalence of respiratory symptoms, hospital admissions and mortality [8,28-30]. Effects on building-related symptoms have been demonstrated in offices – suggested in the Danish Town Hall Study and proved in field experiments [31]. It is noted that material on/in surfaces appears to be critical, where particle sizes are too large to be airborne long enough for RSP measurements to detect them. In such cases, observations on cleanliness or surface samples would be more relevant.

The IAQ can be unsatisfactory but only people can express dissatisfaction. An IAQ screening test should be a preliminary procedure, aimed to identify whether an office is likely to be a problem for occupants and would thus give information for further actions. It was noted that if occupants were already complaining, then screening was not appropriate. IAQ measurements should instead be seen as part of the detective work to identify the problem. It was also noted that occupant complaints about poor IAQ are not limited to air-conditioned workplaces, and not all air-conditioned workplaces have IAQ problems. In this study, a 5-level screening strategy using an IAQ index as a measure to quantify the likelihood ratios of unsatisfactory IAQ in air-conditioned workplaces is being proposed. Given the appropriate screening level of choice, the proposed assessment tool would be a useful source of protocol for policymakers and professionals to evaluate the relative environmental performance of the office space and to participate efficiently for a cost-effective investigation of any IAQ problem. In the case of a wide-ranging set of IAQ measurements is undesired, a set of three measurements can be useful in deciding whether to take any further action (more measurements or remedial measures).

Pre-assessed probability of unsatisfactory IAQ

With proper assessment schemes defined, a simple indication of relative performance would help promoting good IAQ to the general public. In Hong Kong, the IAQ assessment scheme indicated that an indoor environment with any one of the specified air pollutants i exceeding the exposure limits, i.e. $\Phi_i > \Phi_{i,e}$, is deemed to have 'unsatisfactory' IAQ; otherwise, i.e. $\Phi_i \leq \Phi_{i,e}$, the IAQ is classified as 'satisfactory' [3]. Collective IAQ assessments for same types of indoor environment would be informative for the prevalence of unsatisfactory IAQ. The pre-assessment probability P_d of unsatisfactory IAQ in assessments of other similar spaces, where N_d is number of samples with unsatisfactory IAQ in a regional survey of N samples is given by Eq. 1 [4]:

$$P_d = \frac{N_d}{N} \quad \text{… (Eq. 1)}$$

For applications in an indoor environment prior to an IAQ assessment, the pre-assessment odds o_d,which is the ratio of the probability of unsatisfactory IAQ occurring to the probability of its not occurring, is given by Eq. 2:

$$o_d = \frac{P_d}{1 - P_d} \quad \text{… (Eq. 2)}$$

An initial regional IAQ investigation at 40 selected Hong Kong air-conditioned offices was commissioned in 1995 as a consequence of the second review of the 1989 White Paper on pollution issued in 1993 by the Hong Kong government [4]. This investigation result served as a legislative cornerstone of developing an indoor air pollution control policy for workplaces in Hong Kong. It showed that carbon dioxide (CO_2) levels in many Hong Kong offices had exceeded the acceptable exposure concentration, which implied that the existing ventilation system could not serve a high occupancy density properly. Moreover, the airborne bacteria counts and the formaldehyde levels had also exceeded the recommended IAQ standards. Subsequent field IAQ monitoring and assessment results in the past 10 years were reviewed and used to estimate the pre-assessed probability of unsatisfactory IAQ regarding the listed IAQ parameters [4]. Taking the exposure limits in an existing guideline as a reference, measurements in 516 offices reported that the probabilities of unsatisfactory IAQ in air-conditioned offices were less than 1% for CO, RSP, NO_2 and O_3, 1% for Rn, 3% for CO_2, 8% for ABC, 13% for HCHO and 16% for TVOC respectively. It was also estimated that 38% (34-42% for 95% confidence intervals) offices would be rated unsatisfactory using the existing IAQ objectives. The pre-assessment odds of an air-conditioned office of Hong Kong would be taken at 0.6.

Diagnostic tool

An 'IAQ index' proposed earlier is used as a screening parameter in indicating the unsatisfactory IAQ in air-conditioned offices. It is noted that the IAQ index θ is the average fractional dose to the exposure limits $\Phi_{j,e}$ of the three representative measurement parameters (j = 1…3), i.e. CO_2, RSP and TVOC among the listed air pollutants of certain assessments for assessing unsatisfactory IAQ in some air-conditioned offices. An expression of the average fractional dose was correlated to the event of unsatisfactory IAQ with a single screening level using a non-linear expression [32].

The choice of these parameters is surrogate to the IAQ control measures of dilution, mitigation and emission control of pollutants respectively. The three parameters were shown to be independent parameters in air-conditioned offices [21]. In a typical air-conditioned space, most of the RSP is transported from the outdoors while some are related to indoor occupant activities. The RSP level is closely reliant to the filter efficiency of the air-conditioning system. Monitoring the RSP level will give a surrogate indication of pollutant mitigation of the filtration system. Indoor CO_2 is generated by building occupants and diluted by outdoor air; thus it is a good indicator of the occupant load relative to the ventilation rate of a space [25,26]. It was proven that a 'high' ventilation rate for diluting the indoor CO_2 concentration would also dilute the indoor radon emitted from concrete-based building materials in a space [19]. A number of solvent based materials are usually being used in an office. TVOC concentration is a good indicator of the indoor pollutant emissions dominated by building materials, finishing, and human activities, e.g. building renovation works [33].

Two expressions of IAQ index were considered for the fractional dose: One included the difference between the exposure limits and the environment pollutant levels in the denominator; the other expression considered only the exposure limits as the denominator in order to maintain the model stability for unlikely high environment pollution levels close to the exposure limits [32]. In this study, the IAQ index θ is determined as shown in Eq. 3, where Φ_j^* is the fractional dose of the parameters j = 1…3 (e.g.: RSP, CO_2 and TVOC), Φ_j is the exposure level of parameter j assessed over an exposure time period,

$$\theta = \frac{1}{3}\sum_{j=1}^{3}\Phi_j^* \; ; \; \Phi_j^* = \frac{\Phi_j}{\Phi_{j,e}} \qquad \text{… (Eq. 3)}$$

A diagnostic test for unsatisfactory IAQ in a group given screening levels of a and b of the IAQ index θ, i.e. $a < \theta \leq b$, followed a likelihood ratio L_r for the positive test result expressed by Eq. 4 below [24, 34], which is a way of using the sensitivity and specificity of a test to identify if a positive result usefully changes the probability of accessed unsatisfactory IAQ.

$$L_r = \frac{P_s}{1 - P_f} \qquad \text{… (Eq. 4)}$$

The usefulness of performing the test can be assessed by the value of likelihood ratio L_r. A likelihood ratio $L_r>1$ indicates that the test result is associated with the unsatisfactory IAQ. A likelihood ratio <1 indicates that the result is associated with absence of the unsatisfactory IAQ. It was noted that example cut-off values of $L_r<1/5$ and $L_r>5$ were applied in some cases of evidence based medicine [35].

P_s and P_f are the sensitivity and specificity of the diagnostic test, which describe the ability of the test to identify an environment which does or does not have unsatisfactory IAQ. They are the probabilities of testing positive and negative respectively when the unsatisfactory IAQ is truly present or absent, where TP, TN, FP and FN are the true positive, true negative, false positive and false negative of the test result respectively [32].

The post assessment probability P_d' of positive outcome for the indoor environment are given by Eq. 5 and Eq. 6, where o_d' is the post-assessment odds [35].

$$P_s = \frac{TP}{TP + FN}; \; P_f = \frac{TN}{TN + FP} \quad \text{… (Eq. 5)}$$

$$P'_d = \frac{o'_d}{1 + o'_d}; \; o'_d = o_d L_r \quad \text{… (Eq. 6)}$$

Screening levels

Together with previously reported samples of 516 offices and new sample data of 9 samples in this study, a regional cross-sectional measurement of the nine common IAQ parameters conducted in a total of 525 Hong Kong offices was used to evaluate the screening levels of the IAQ index. Simple random sampling technique was adopted and the surveyed samples covered all regions of office development as well as various grades, types and ages of premises and ventilation systems. They included a range of open-plan offices from conference rooms to individual small offices, with sizes ranged from 10 m^2 to 300 m^2. The selection of the sampling periods and locations were based on the recommendation of the IAQ assessment scheme [3]. An 8-hour occupied sampling period and 500m^2 per sampling density approaches were adopted in this study as there was little fluctuation in source strength or ventilation rate and it can identify the short-term or localized peaks for some pollutants within occupied periods.

The result could indicate the overall IAQ situation in Hong Kong offices. Table 1 summarizes the ranges, arithmetic means (AM), arithmetic standard deviations (ASD), geometric means (GM) and geometric standard deviations (GSD) of the measured parameters. It is noted that a number of measured parameters would be better approximated by geometrical distribution functions [21]. The corresponding IAQ index θ using Equation (1) was between 0.19 and 2, with an AM of 0.47 and ASD of 0.2. The 525 sample offices were evaluated with the more comprehensive IAQ assessment of satisfaction [3]. It was reported that IAQ in 32% (28%-36% for 95% confidence intervals) of the office samples were classified as unsatisfactory, which was slightly lower than the earlier estimate of 38% [4].

The IAQ indices of the office samples were evaluated and presented in a 5-level screening test as shown in Table 2. It is noted that the choice of the 5 screening levels is closely related to the thresholds for test and remedy. A threshold level of $L_r = 10$ (or as low as $L_r = 1/10$) would be used in developing multilevel likelihood ratios for some medicine applications, with a ratio as high as $L_r = 50$ (or as low as $L_r = 1/50$) in few extreme cases [35]. In this analysis, it intends to retain at least 5 sample counts (i.e. about 1% of total sample) of unsatisfactory/satisfactory IAQ cases in each of the 5 groups of screening levels in order to satisfy some statistical tests. For simplicity, the intermediate levels other than the levels of 'very negative' and 'very positive' are evenly distributed between the levels of concern and remedy. The qualitative interpretations (i.e., very negative, moderately negative, slightly negative, moderately positive and very positive) regarding screening levels (θ = 0.315, 0.425, 0.535, 0.645) were given according to the likelihood ratios L_r for the five office sample groups. The number of office samples in each group for IAQ satisfaction/dissatisfaction (i.e. TP and TN) were counted and the corresponding sensitivity and specificity were shown in Table 2 with the values (TP + FN) and (TN + FP) of 167 and 358 respectively. It was also noted that the screening test results of the IAQ satisfaction based on exposure concentration of pollutants would correlate with the occupants' perception of the assessed indoor environment [34]. An increased likelihood ratio would be associated with decreased occupant acceptability.

Application examples

Bayesian theorem used in the areas of diagnostic testing that the pre assessment odds of unsatisfactory IAQ, multiplied by the likelihood ratio, determines the post test odds (Eq. 6) is applied in this study to deal with the new information from the screening test in revising the probability estimates [35]. A screening test resulting in a post-test probability below threshold of test would lead to a suggestion of maintaining the current measures for the office IAQ. Many other diagnostic tests could be done but the screening test suggested that they are not necessary. However, if the screening test result came back with a high post-test probability, the office would be recommended immediate and appropriate remedial measures for the likely IAQ problems regarding dilution with outdoor fresh air, mitigation of suspended particles and/or emission control of TVOC. For decision purposes, threshold of test and threshold of remedy were proposed as illustrated in Figure 1. It is only the test result return stranded between the thresholds of test and remedy which would follow another test (or a more comprehensive test) for the IAQ problem.

The overall framework of the proposed screening and decision making process for IAQ management is shown in Figure 2. With the concentrations of representative parameters assessed, an IAQ index can be compiled and compared with the screening levels for likelihood of unsatisfactory IAQ. The calculated post-test probability can lead to an appropriate IAQ management decision based on the set thresholds. Although setting the thresholds would require detailed analysis for the test accuracy, expenditure and benefits of correct/incorrect test results, professional judgments on the acceptable risk would be adopted in some office IAQ assessments [20]. It is noted that the ‘IAQ index’ is not primarily correlated to the occupant discomfort, an air-conditioned office of Hong Kong with high IAQ index, however, might be detected by occupants [34].

Table 3 shows the post-test probabilities of office with unsatisfactory IAQ using the proposed screening test at various pre-test probabilities. Taking the mean pre-test probabilities of 35% for Hong Kong calculated from the average P_d of 32% and 38% in the past surveys, the post-test probabilities for the test results very negative, moderately negative, slightly negative, moderately positive and very positive were 5%, 18%, 30%, 48% and 93% respectively. Taking example thresholds of test and remedy at the post-test probabilities of unsatisfactory IAQ P'_d = 0.1 and 0.9 for discussion, about 26% of the air-conditioned offices in Hong Kong of IAQ index $\theta < 0.315$ would require no immediate action for further IAQ diagnosis, but about 2% of the offices of $\theta \geq 0.645$ would require immediate IAQ remedial actions.

Conclusion

A simple but effective screening tool is useful to identify the high and low risk groups of air-conditioned offices with indoor air quality (IAQ) problems for practical environmental management. A comprehensive IAQ assessment would not be considered as a general adoption for the entire office stock due to various reasons including the high implementation efforts, the lack of flexibility in alternative measurement protocols, the lack of clear rationale behind the parameter selection, the lack of quantitative uncertainties for the choice of the sampling density and the long measurement period.

This study reported the use of 'IAQ index' as a useful screening parameter in quantifying the likelihoods of the office environment with unsatisfactory IAQ. In particular, a 5-level screening tool is proposed to identify an air-conditioned office that required remedy, further diagnostic or maintaining the current strategies for IAQ. With the use of pre-test probabilities of IAQ failure of Hong Kong air-conditioned offices, the feasibility of the screening process for test offices with the post-test results of very negative, moderately negative, slightly negative, moderately positive and very positive was reported. It was proposed that 26% of the Hong Kong offices with a likelihood ratio of unsatisfactory IAQ 0.1 or below were the low-risk group and all ongoing IAQ measures in those offices should be kept; however, 2% of the offices with a likelihood ratio of 25 or above were the high-risk group and would require immediate remedial actions for the poor IAQ. This study presented useful information in diagnosing the air-conditioned offices with IAQ problems. The proposed screening test is not exhaustive, with assumptions made for the air-conditioned offices in subtropical areas and has only been determined from measurements in Hong Kong, which perhaps will limit the model's usefulness elsewhere.

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Table 1

Measured 9 IAQ parameters in 525 air-conditioned offices of Hong Kong

No.	Parameters (unit)	HKEPD recommended exposure concentration	AM (ASD)	GM (GSD)
1	CO_2 (ppm)	1000	658 (151)	642 (1.25)
2	CO (μg m^{-3})	10000	1105 (4594)	755 (2.41)
3	RSP (μg m^{-3})	180	30 (20)	24 (1.89)
4	NO_2 (μg m^{-3})	150	27 (17)	22 (2.08)
5	O_3 (μg m^{-3})	120	40 (38)	30 (2.52)
6	HCHO (μg m^{-3})	100	48 (103)	27 (2.80)
7	TVOC (μg m^{-3})	600	358 (328)	252 (2.46)
8	Rn (Bq m^{-3})	200	46 (39)	32 (2.50)
9	ABC (CFU m^{-3})	1000	505 (385)	372 (2.28)

Table 2

Screening test

Test result	**IAQ index θ**	**Unsatisfactory IAQ**		**Satisfactory IAQ**		**Likelihood ratio L_r**
		Counts	**%**	**Counts**	**%**	
Very negative	<0.32	5	3%	93	26%	0.1
Moderately negative	0.32-0.42	24	14%	131	37%	0.4
Slightly negative	0.43-0.53	33	20%	85	24%	0.8
Moderately positive	0.54-0.64	33	20%	43	12%	1.7
Very positive	≥0.65	72	43%	6	1.7%	25
	Total:	167	100%	358	100%	

Table 3

Example post-test probabilities generated by the five-level screening test result

Likelihood ratios, L_r	**pre-test probabilities**					
	5%	**15%**	**25%**	**35%**	**50%**	**70%**
Very negative, 0.1	0.5%	1.7%	3%	5%	9%	19%
Moderately negative, 0.4	2%	7%	12%	18%	29%	48%
Slightly negative, 0.8	4%	12%	21%	30%	44%	65%
Moderately positive, 1.7	8%	23%	36%	48%	63%	80%
Very positive, 25	57%	82%	89%	93%	96%	98%

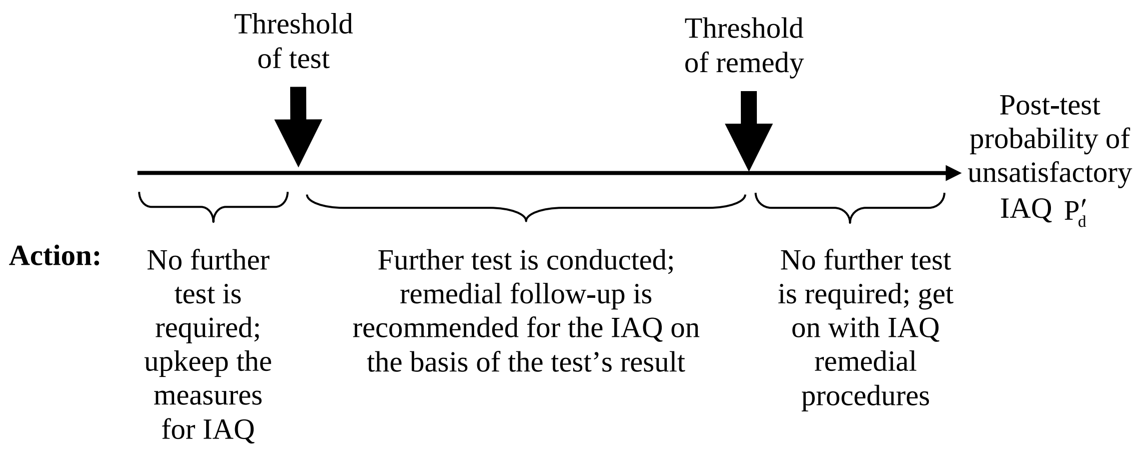

Figure 1. Test-remedy thresholds

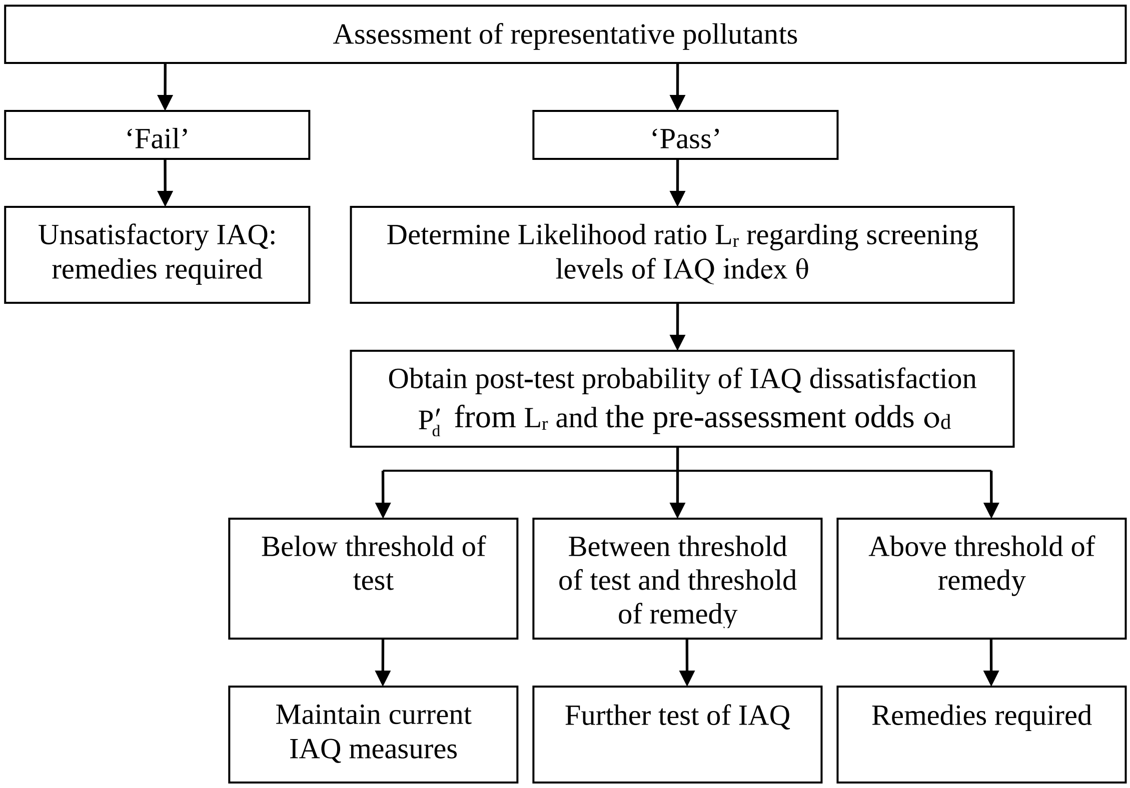

Figure 2. Screening and decision making process for IAQ management