The Hong Kong Polytechnic University

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An indoor air quality monitoring and assessment protocol for air-conditioned offices in subtropical climates

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Certificate of Originality

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material which has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

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Abstract

Maintaining good Indoor Air Quality (IAQ) aimed at meeting human requirements on health and comfort of a space. Wellbeing concerns related to the IAQ are complex and IAQ is targeted as a minimum provision of statutory control in practice. Indeed, no agreed monitoring and assessment protocol is available for practical environmental control measures in air-conditioned offices in subtropical climates. Investigations through continuous air sampling could provide thorough understanding, and ultimately could help setting up practical IAQ strategies for the environment. It is, however, too expensive to continuously monitor all air pollutants of the general community. Resources justified sampling tactics for a practical IAQ monitoring and assessment protocol including the assessment parameters, sampling locations and time period with quantified uncertainties for correct results interpretation must be worked out.

The objectives of this study are to develop a practical IAQ monitoring and assessment protocol for promoting better IAQ of air-conditioned offices in subtropical climates. The protocol presents IAQ assessment results with a simple IAQ benchmark, using the selected representative pollutant levels obtained from a number of alternative sampling schemes at acceptable assessment uncertainties regarding sampling locations and times. The development and feasibility of the protocol are demonstrated using a comprehensive cross-sectional survey on common indoor air parameters from a long-term measurement in air-conditioned offices of Hong Kong.

Regarding the choice of assessment parameters, it was shown that selecting representative parameters by identifying a small number of dominant contributors of unsatisfactory IAQ would provide acceptable accuracy with reduced measurement effort. Concurrently,

reasonable predictions could be made by another proposed model with assessed carbon dioxide (CO_2), respirable suspended particulates (RSP), and total volatile organic compounds (TVOC) levels. These three parameters were judged to be indicative for the performance of IAQ control through dilution, removal, or source control respectively.

Furthermore, the uncertainties of various sampling schemes were analysed using the year-round longitudinal measurement results. For a selected representative parameter, the required measurement period by a proposed scheme of two random sample average from two time-equal sessions with an opposite reverse time sequence within the occupied period would have potential reductions up to 30%. And reducing the number of sampling points by 50% would decrease the probability of obtaining the sample-spatial average concentration at the same confidence level by 10% only.

In view of the technical difficulties in applications of the schemes, feasibility of accuracy improvement with the epistemic approach was analysed. The use of past information and assessment accuracies to improve present understanding for judging IAQ acceptance from a test sample and regional monitoring were demonstrated.

Finally, a simple IAQ index compiled by the representative indicators were used as a benchmarking parameter for air-conditioned offices of Hong Kong to distinguish the relative performance of IAQ, presented in a widely adopted star rating system. The benchmark system was demonstrated to be an effective indication of IAQ in air-conditioned offices.

Taking the assessment uncertainties into account, this study provided a useful tool for setting up an efficient IAQ monitoring and assessment programme, and ultimately can help promote better IAQ.

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Last but not the least, I would like to express my deepest thanks to my family. Without their unconditional support and endless love, completion of this thesis would not be possible. This thesis is dedicated to my mother.

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List of abbreviations

ABC	airborne bacteria count
ACGIH	American Congress of Governmental Industrial Hygienists
AHU	air handling unit
AM	arithmetic means
API	air pollution index
BRI	building-related illness
CI	confident interval
CO	carbon monoxide
CO_2	carbon dioxide
FB	fractional bias
FN	false negative
FP	false positive
GM	geometric means
GN	Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places
GSD	geometric standard deviations
HCHO	formaldehyde
HKEPD	Hong Kong Environmental Protection Department
IAQ	indoor air quality
IEQ	indoor environmental quality
MVAC	mechanical ventilation and air conditioning
NIOSH	National Institute for Occupational Safety and Health
NMSE	normalized mean square error

NO_2	nitrogen dioxide
O_3	ozone
OES	occupational exposure
OSHA	Occupational Safety and Health Administration
RH	relative humidity
Rn	radon
RSP	respirable suspended particulates
SBS	sick building syndrome
SD	standard deviations
T	temperature
TN	true negative
TP	true positive
TVOC	total volatile organic compounds
V	air velocity
VAV	Variable Air Volume
VOCs	volatile organic compounds
WHO	World Health Organization

List of symbols

A_f	floor area of the space (m^2)
A_s	sampling point density (m^2)
B_i	IAQ benchmark
E	probable error limit
i	independent parameter
j	independent sample
k	constant
L	loading values
n	number of parameters
N	number of sample
P_s	sensitivity
P_f	specificity
P_+	predictive positive
P_-	predictive negative
$\hat{P}$	unsatisfactory rate
Q	Yule's Q statistics
R	correlation coefficient
r	sampling points
S^2	variance of IAQ indices
t	time (h)
w	weighting factor
Φ	concentration
Ω	group

α	fractional concentration of pollutant in a steady state
β	fractional pollutant concentration that can be built-up or removed
ε	uncertainty ratio of a sampling scheme
ε_i	standard error of i
ζ_i	error term of i
θ	IAQ index
λ	effective ventilation rate for a pollutant
μ	time-mean concentration
$\mu_{\Re}$	spatial mean concentration
ξ	confidence level
σ	standard deviation
τ	period
φ	sample correction factor
ω_i	relative residual of i
$\langle\ \rangle$	operator of time average
$\{\ \}$	operator of spatial average
$\overline{\quad}$	operator of sample average

Subscripts

0, 1, 2,…	of conditions 0, 1, 2,…
a, b, c,…	of conditions a, b, c,…
CO2	of carbon dioxide
E	of ‘Excellent’ IAQ
G	of ‘Good’ IAQ

i	of parameter i
m	of sampling
max	of maximum
ob	of observed
of	of occupied
p	of entire measurement
pr	of predicted
Rn	of radon
ref	of reference scheme
s	selected ‘representative’
sc	screening level
sch	of sampling scheme
U	of ‘Unclassified’ IAQ
∞	of long-term

Superscripts

*	exposure limits
"	fractional dose
^	distribution function
–	of satisfactory IAQ
+	of unsatisfactory IAQ

Chapter 1

Introduction

1.1 Background

As a modern life in the developed cities, people mainly stay indoors rather than outdoors. High rise buildings can be seen everywhere around the cities. Many of them, especially commercial buildings are supplied with mechanical ventilation and air conditioning (MVAC) systems. This type of enclosed structure provides a more spacious and comfortable environment to the occupants, but at the same time, increases the difficulties in controlling and maintaining the air quality perceived by the occupants.

Maintaining an acceptable indoor air quality (IAQ) for a healthy and comfortable environment is of primary concern. Occupants' exposures to levels of a number of chemicals and pollutants, which are higher indoors than outdoors, are driving the health concerns of some specific population groups.

The enclosed nature of indoor spaces leads to very high indoor exposures easily when indoor sources are present. Economic growth and urban development change people's lifestyle, and they help increase the use of consumer products containing chemical agents indoors, which maybe harmful to the occupants' health. Concurrently, the substantial part of exposures to air pollution from outdoor air occurs indoors as outdoor air enters indoors via infiltration and ventilation. Furthermore, since the energy crisis in the 1970s, policies for promoting energy conservation for sustainable building designs and operations have been applied. Offices, consuming the major portion of energy, are corresponding to a number of aspects needed to be addressed. Apart from comfort, one of the key emphases is on IAQ. Energy-saving measures such as off-hour control on air conditioning may have adverse effects on IAQ as turning off ventilation can cause accumulation of air pollutants such as radon and volatile organic compounds (VOCs). Occupants may be exposed to excessive levels of pollutants when they resume work in these offices.

Being exposed to such elevated pollutant levels may cause health problems and discomfort, and lower the productivity of the staff. However, maintaining a good IAQ is a two tier problem. The pollutant levels should be kept as low as possible in order to minimize the health risks to occupants, but at the same time, there are practical and economical concerns for the industry. It is, therefore, important to keep a balance of the requirements between the two through addressing the performance of IAQ based on proper assessment methodologies and monitoring plans.

1.2 Limitations of existing IAQ regulations and guidelines

In view of the rising concern over probable health effects associated with IAQ, IAQ assessments were conducted in many indoor spaces and the problems were addressed in literature. But still, limited efforts have been given to move on from the legislation requirements on the health and safety risks of industrial occupations to the legislation related to IAQ factors. The risks are less well-defined, and extended to their interaction with the well-being of building occupants (Curtis 1993).

Currently, well-established environmental regulations in many countries are concentrated on outdoor air pollution which includes hundreds of outdoor pollutants, and just a few concentrated more indoors than outdoors due to indoor sources being largely unregulated. There are regulations in controlling the emission of harmful substances from consumer products, such as VOCs. Efforts are still focusing on emissions, rather than understanding and limiting the human exposure directly (Steinemann 2004).

Countries including Canada, Japan, Korea, Singapore, Sweden, the UK and USA have been aimed at setting up standards and guidelines for a long time. They have conducted a number of IAQ studies to understand the current situation of IAQ in different premises and their health effects. Different criteria were set in the form of standards or guidelines in different places. All these guidelines were more or less like a mandatory program developed to educate the public and arouse their attention to the IAQ and human exposure issues. There are still no existences of international or national standards or guidelines which can be referred to directly to assess whether measured concentration of pollutants is likely to cause health effects for non-industrial workplace environment. The existing reference levels adopted the values from occupational exposure standards (OES), divided by different safety factors being suggested by various groups.

As assessment in compliance with the IAQ standards is difficult both philosophically and practically, the precedents were established based on the regulatory programs for ambient air and occupational exposures. Its effectiveness and economic efficiency in achieving IAQ objectives for health promotion and protection should be considered when setting up regulatory control. Counter-proposals from various interesting parties have been arisen in finding a practicable approach to institutionalize the control of IAQ. Considerations include the ease of implementation, the efficient use of existing control systems, and whether there are conflicting situations that would hinder its smooth implementation. As a balance between the needs of various parties in society, regulations provide the minimum provisions for buildings as a baseline control measure. In the lead time required to put the system in place, an assessment protocol for monitoring would be desirable as we cannot wait and rely solely on regulation development where the problems are fully identified; efforts are needed to prevent health effects from exposure before they occur.

1.3 Significance of IAQ evaluation protocol

In an occupied building, the building management team is the frontline to tackle the corresponding IAQ problems. However, IAQ is a multi-disciplinary issue and the health problems induced by indoor air pollutants are in complex effects which are not easily categorized. Since there is no standard protocol for addressing the IAQ condition, the frontline is hesitated to interpret the perceived IAQ due to practical problems in assessment.

Performing an extensive measurement is costly and labour-intensive. There are numbers of equipments for assessing parameters which are complicated for staff without comprehensive training to handle. Also, information is not sufficient for interpreting the assessment results. The industry is, therefore, in need of an easy to understand IAQ management and assessment system.

1.4 Setting up of the guideline

When setting up a guideline or a scheme for IAQ assessment, several points are needed to be considered or defined. The scheme should help the general public be aware of IAQ. Add-on incentives for various parties can be adopted and appreciated by the industry for enhancing IAQ improvement.

The scheme can be set legally binding or voluntary. If it is set as a requirement in law, current situation of IAQ in the region should be fully assessed, and the definition of the requested levels should be clearly addressed. If it is voluntary, it should be simple and technically and economically practical enough to give initiative of implementation.

The scheme has to define some kinds of indicators to be monitored to reflect the conditions of IAQ of the corresponding premises. The indicators should have the following characteristics: simple, easy to use; easy to measure; representation of the indoor environment; preferably a single indicator; preferably can indicate the relative IAQ levels.

The scheme should include the standardized ways to monitor the levels of indicators with endorsed documentation of measurement record. With traceable record, building management teams could make use of the information for quick response or further mitigation of the problems. They could also enhance further statistical analysis in the long run.

Monitoring procedures should be simple to implement without requiring tremendous amount of resources so that it could be done repeatedly to address the change of environment without an enormous cost. Handy and reliable instruments can also be made used of to implement the scheme and reduce the training and maintenance cost that would be introduced.

Together it should provide well-defined exposure guidelines for the occupants with respect to the indicating air pollutants, suggesting the consequences in case of non-compliance, and provide mitigation measures in accordance with the assessment results.

1.5 Cost, accuracy and results interpretation of sampling strategies

Pollutant concentrations measured during the occupied period of a space is a key parameter to determine the IAQ. Long-term and comprehensive measurements of the indoor pollutant levels could be a good approach to access IAQ performance of a space, as the longer the measurement time, the higher the accuracy and confidence level of the measurement can be achieved. However, a considerable amount of resources is involved in such assessment, measurement efforts increase progressively in an accurate and detailed assessment. Cost increases for losses of data due to instrument break down, data transmission failure or service and calibrating procedures. An effective and efficient judging method for identifying the unrecognized IAQ problems of an apparently healthy indoor environment would help promote good IAQ. Instead of recording a continuous profile, a rapid estimate of the probable space failure rate by express assessment might be useful.

When assessing IAQ, it is not practical to conduct a long-term extensive measurement on all environmental parameters; while measurement accuracies of the sampling schemes and timely information collection are critical for making decisions on resources and manpower management in pollutant levels monitoring. Efforts required for an assessment method should be quantified with feasibility of the implementation, understandable of the results to all levels, and addressable improvement can be followed, at a bearable expenditure.

The interpretation of the data and uncertainties of some sampling schemes were not included in many assessments. The assessment results might be misleading and could not be used in an effective way to facilitate building management. A simple, practical and understandable measurement tool for IAQ interpretation would promote the public awareness and would be a useful tool for environmental management. Setting up an indexing or a benchmarking system for IAQ could also be one of the solutions.

An indexing system expresses the performance as a single number aggregated mathematically from two or more indicators for simple communication. And benchmarking is a process used in management and particularly strategic management, for comparing an organization's or a company's performance to that of other organizations or companies usually within their own sector. It expresses performance in various aspects of their processes in relation to the best practice using the objective and subjective criteria. This gives a reference point for the company to review its status and position, and then allows organizations to develop plans on how to adopt such best practice and increase some aspects of performance. Similar usages can be applied in evaluating IAQ performance of a space.

Currently, the air pollution index (API), which is the conversion of the ambient pollutant concentrations measured at air quality monitoring to a relative scale, is widely used. It is used to assist the assessment of public's exposure to air pollution; to understand air pollution problems for more cost-effective policies and solutions' development; to assess the extent to which the standards and targets are being achieved or violated; and to provide public information on current and forecast air quality. However, at this moment the API is applied for only outdoor air, and not yet for indoor.

In Hong Kong, extensive studies on IAQ evaluation were conducted. These studies have collected a large number of data, both in longitudinal and cross-sectional measurements of the typical environmental quality parameters for certain buildings. This data enables the development of a comprehensive model and protocol to define the uncertainties of the sampling procedures in pollutant concentration measurement, the differences between the collected results, the year round pollutant profile due to seasonal variations, and hence the overall evaluation of the IAQ of an office environment.

1.6 Objectives

To promote the quality building environment in the prospective of good IAQ for air-conditioned offices, which is one of the major space types that people stay in, hoping that it would be beneficial to occupants' comfort and health. Concerns arisen in understanding and maintaining good IAQ lead to the needs in both social and practical aspects for a standard but practical IAQ monitoring and assessment method.

The aim of this study is to understand the IAQ in air-conditioned offices of Hong Kong for developing an IAQ monitoring and assessment protocol suitable for air-conditioned offices in subtropical climates.

The objectives of this study are:

1. To study the IAQ in air-conditioned offices during working days;
2. To study the feasible IAQ sampling schemes regarding the assessment parameters, sampling periods and sampling locations;
3. To evaluate the assessment accuracies;
4. To develop measures of assessment effectiveness enhancement; and
5. To develop an IAQ benchmark based on the assessment protocol, taking Hong Kong air-conditioned offices as examples to present the proposed benchmark system.

1.7 Research scope

The study is divided into the following four tasks:

Task 1: Database development for long-term measurement in air-conditioned buildings

A structural database of indoor environmental parameters will be developed from longitudinal and cross-sectional measurements of the indoor air pollutant concentrations and the ambient conditions in air-conditioned buildings. It will provide all measurement results of the corresponding indoor/outdoor pollutant concentrations taken on working days for a year at comparable spatial locations of large spaces, and on air-conditioned offices over the region. These results will be used to examine the feasibility and effectiveness of different assessment schemes in this study. The probable errors deviated from the population mean will be used as indicators for comparing the predictions of various schemes.

Task 2: Evaluation of different sampling schemes with various sampling times, sampling point densities and locations, and representative parameters

The probable sample levels at different measurement locations will be determined with the development of different sampling schemes. Calculations will be repeated for different sampling times, sampling point densities and locations and number of representative parameters in these schemes. The probable range of the sample levels will be determined. The calculated sample levels will then be compared with the longitudinal or cross-sectional measurement of the pollutant concentration. The accuracy of the schemes can be assessed by the deviation of the sample levels from the population level. The accuracy of a proposed scheme will be further evaluated by expressing the number of sample levels that fall within the probable error limits of the average concentration determined by the scheme as a percentage of the total number of samples made by the scheme. This percentage could be interpreted as the confidence level that the sampled level is 'representative'. The confidence levels for the predictions of measurements at different locations will be calculated with probable errors deviated from the long-term or regional measurement. When comparing with the recommended assessment scheme from the HKEPD as reference, variations of the potential reduction in measurement effort offered by different schemes at certain confidence levels will also be determined.

Task 3: Enhancement of protocol for improving assessment effectiveness

In view of the technical difficulties in applications of the schemes analysed in Tasks 1 and 2, more effective and efficient assessment will be further developed to provide measures in schemes improvement. An epistemic approach is proposed which enables the use of past information and assessment accuracies to improve present understanding. Example applications of the approach will also be demonstrated with the cross-sectional measurements database.

Task 4: Development of IAQ benchmarking for Hong Kong

The determined countable error distribution and accuracy of different IAQ sampling schemes and the measurement results developed from the previous stages will be gathered and formulated. With the regional database, representative indicators would be used to compile a simple IAQ index for describing the likelihood of IAQ satisfaction for an indoor environment. The IAQ index would be used as a benchmarking parameter for air-conditioned offices of Hong Kong to distinguish the relative performance of IAQ and be presented in a widely adopted star rating system. Site measurement will also be conducted for database refinement. A feasibility study of the proposed IAQ benchmark will be included.

1.8 Organization of thesis

This introductory chapter has examined the background and the motivation for this research. The aim of this study is to understand the IAQ in air-conditioned offices of Hong Kong for developing an IAQ monitoring and assessment protocol suitable for air-conditioned offices in subtropical climates. The objectives and scope of the research were also defined.

The following chapters of this thesis present the major structures and findings of this study. Figure 1.1 shows a flowchart summarizing the organization of the thesis.

Chapter 2 points out current concerns in achieving good IAQ and the significance of monitoring pollutant levels. Then, it reviews the fundamental theories, previous literature on works in IAQ monitoring and assessment, international guidelines or standards for IAQ assessment, and the different alternatives in sampling strategies being suggested.

The framework and methodology of this study are discussed in Chapter 3, which includes the development and rationale of suggested probable assessment schemes in terms of the choice of assessment parameters, different sampling times and sampling point densities and locations, together with the evaluation methods for quantifying their uncertainties associated.

Chapter 4 formulates the structure of the database and measurement required for schemes evaluation, and reports the survey results. The database used includes cross-sectional measurements at 422 offices on 12 indoor parameters as stated in the HKEPD IAQ certification scheme, and a one-year measurement of CO_2 and radon concentrations on an entire office floor at several comparable spatial locations. The surveys conducted in this study also include an interview survey regarding the professional choice of sampling locations, and another cross-sectional survey on 12 indoor parameters in a different group of 103 air-conditioned offices in Hong Kong.

Chapter 5 presents the evaluation results of various sampling schemes and demonstrates their applicability with assessment accuracies accounted. It analyses the proposed assessment protocol with the measurement results of the longitudinal and cross-sectional database. The probable errors deviated from the population mean is used as indicators for comparing the predictions of various schemes. The confidence levels are evaluated. The fractional bias (FB) and the normalized mean square error (NMSE) are presented to show the goodness-of-fit for the proposed assessment schemes in obtaining representative assessment results.

The discussion on the possibility of schemes improvement is then followed in Chapter 6. The proposed idea is used to improve the assessment accuracy in some proposed schemes with limited measurement efforts, through applications of mathematical treatments on already available information. Application of the epistemic assessment for judging the IAQ acceptance and for regional IAQ monitoring exercise is discussed, with example application for feasibility demonstrations.

Chapter 7 proposes an IAQ benchmarking system. It discusses the feasibility in presenting the office IAQ by a 5-star rating system, which uses the IAQ index as the benchmarking parameter. The application of the proposed IAQ benchmarking system is also demonstrated for Hong Kong offices.

Finally, Chapter 8 draws a conclusion for this thesis, which summarizes the key findings, the significance and value of this study, and points out the future research direction.

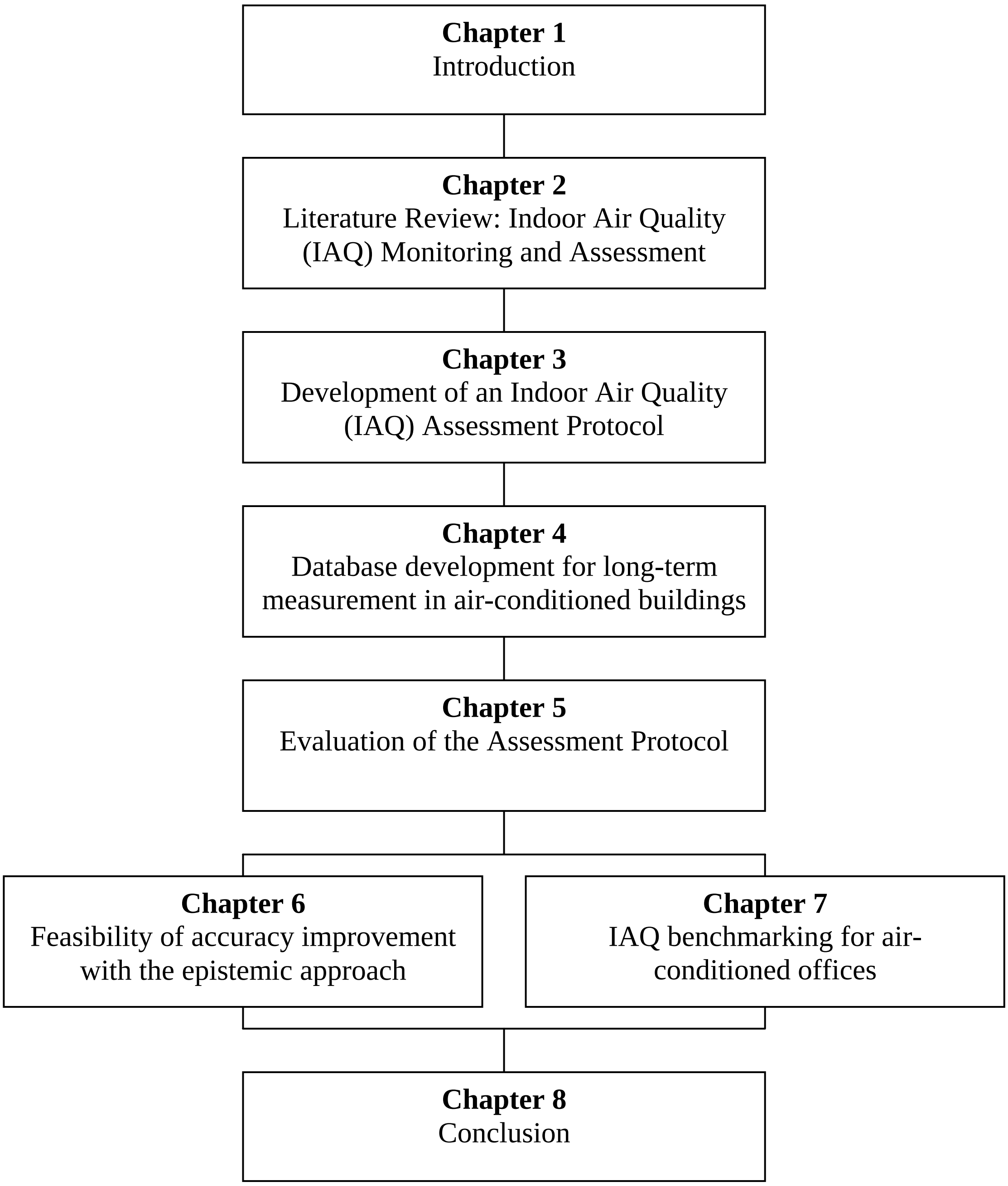


Figure 1.1: Organization of thesis

Chapter 2

Literature Review: Indoor Air Quality (IAQ) Monitoring and Assessment

2.1 Introduction

Indoor air quality (IAQ) refers to the environmental characteristics inside a building that may affect human health, comfort, or work performance. The IAQ of a space can be assessed, monitored and indicated for the minimum provision of buildings regarding regulatory control measures. Acceptable IAQ can be ensured by limiting some concerned organic, inorganic and biological air pollutants presented in indoor air. In addition, maintaining an acceptable thermal comfort condition at certain air temperatures, velocities and humidity is desired in some cases.

2.2 IAQ concerns

There is an increasing awareness of the role of the indoor environment as a major determinant of the population’s exposure to a wide range of air pollutants. Indoor air pollution is a public health problem now while it was originally not an attractive issue being put in the regulatory agenda in contrast to their gravity. A lack of obvious disasters attributable to it may be the reason that limited the motivation of the interest groups (Harrison 1986). Concern was growing in the past decade over complaints attributed to

IAQ, and the probable related hazards identified. People in the industrialized countries typically spend over 80% of their time in indoor environments; the majority is in homes and offices. Their exposures to most indoor-generated and some outdoor air pollutants are dominated by indoor exposures. The concern is becoming more significant as people are spending more time indoors, where modern building materials and consumer products like paints, aerosols containing cleansers would produce a wide range of air pollutants. Although emission from a single indoor source may not pose a significant health concern, general indoor spaces usually associate with more than one air pollutant source. The cumulative effects of these pollutant sources may deteriorate the IAQ which cause significant health and comfort concerns for occupants.

Occupational health problems related to IAQ were identified as early as in the 1960s. The World Health Organization (WHO) has categorized the sick symptoms suffered by occupants in non-industrial workplaces and coined the terms ‘sick building syndrome’ (SBS) and ‘building-related illness’ (BRI).

The SBS usually implies an existence of persistent, non-specific symptoms like eye, nose, and throat irritation, fatigue, headaches and dizziness that occur in more than 25% of occupants and dissipate once they leave the problematic buildings (Brooks and Davis 1992). Sometimes, building occupants experience symptoms that do not fit the pattern of any particular illnesses and so it is difficult to trace any specific sources. People may complain of one or more of the symptoms which may or may not be related to poor IAQ. There is not just a single manner in which these health problems appear. Large-scale surveys carried out in some countries reported that the frequency of complaints on problematic IAQ among the occupants was between 15% and 50% in some office buildings and other buildings for public uses (WHO 1999). However, it is still unclear by the moment of what exactly causes the SBS (Mendell et al. 2008). Further research is required for understanding the extent to which currently observed concentrations pose these health problems (Carslaw 2003).

In contrast, BRI refers to clinically diagnosed disease(s) in building occupants that is resulted from the exposure to some identified indoor air pollutants. The diseases are relatively well documented and have defined diagnostic criteria, identifiable causes, and defined treatments. Occupants suffering from the BRI may require prolonged recovery time after leaving the suspected environment, and require elimination of exposure to the contributing agents. A broad range of health effects may result from indoor air pollutant exposures (Bernstein et al. 2008, Leslie 2000). Air pollutants can be categorized as organic, inorganic, or biological. Bacteria, one of the indoor air pollutants, can cause infectious diseases such as the common cold or influenza, induce or worsen allergy or asthma symptoms. Exposure to certain air pollutants would even increase the risk of cancers or other very serious health effects (Hoskins 2003).

However, the dose-response relationship and the exposure limit for health concerns are only available for some indoor air pollutants. Meanwhile, maintaining good IAQ is not in the first priority within all the aspects in handling problems related to indoor environment. Since the energy crisis in the 1970s, energy conservation measures have been promoted for sustainable building designs and operations. Many buildings in the developed countries were designed to limit infiltration between building compartments. Building envelop is also a key thermal energy conservation measure. Their efforts resulted in energy savings, however, without the fundamental delivery of IAQ satisfaction and, consequently, a built-up in the levels of some air pollutants has been reported for many cases.

A recent study in the UK offices showed that only 15% of the buildings surveyed achieved optimum environmental condition (Vitel 2001). A 1984 World Health Organization Committee report suggested that up to 30% of new and remodelled buildings worldwide might be the subject of excessive complaints related to IAQ. There are still needs for IAQ improvement.

Guidelines for practical control and regulation implemented can provide a clear reference level that IAQ should be achieved, establishing statutory controls is the most effective way to improve and maintain IAQ. In the first step of setting such controls, it is in need of a better understanding of IAQ and factors related. Within those, the IAQ assessment is essential so that problems associated with poor IAQ can be identified. Investigations through air quality monitoring and assessment can lead to an understanding of emission sources, transmission paths and mitigation process of air contaminants and ultimately the practical IAQ strategies of a better environment can be addressed.

2.3 Factors for IAQ

People indoors are exposed to air pollutants at some exposure levels, which are affected by various factors of the indoor environment. An enclosed space in a building would form an indoor environment which connected to the outdoor environment through openings or mechanical ventilation and air conditioning (MVAC) systems. IAQ accounts for indoor air pollutant levels that occupants are exposed to with respect to some indicative exposure limits. The factors contributed to IAQ of an indoor environment are shown in Figure 2.1. In general, they include ventilation designs of the indoor environment, existence of pollutant sources and IAQ control measures of MVAC systems (EPA/NIOSH 1991, Spengler et al. 2001). The existences of indoor air pollutants would source from outdoor by transportation or generate from indoor sources. The excessive air pollutant concentrations in an indoor environment can be improved by dilution of fresh air, control of generation rate, and/or removal of air pollutants.

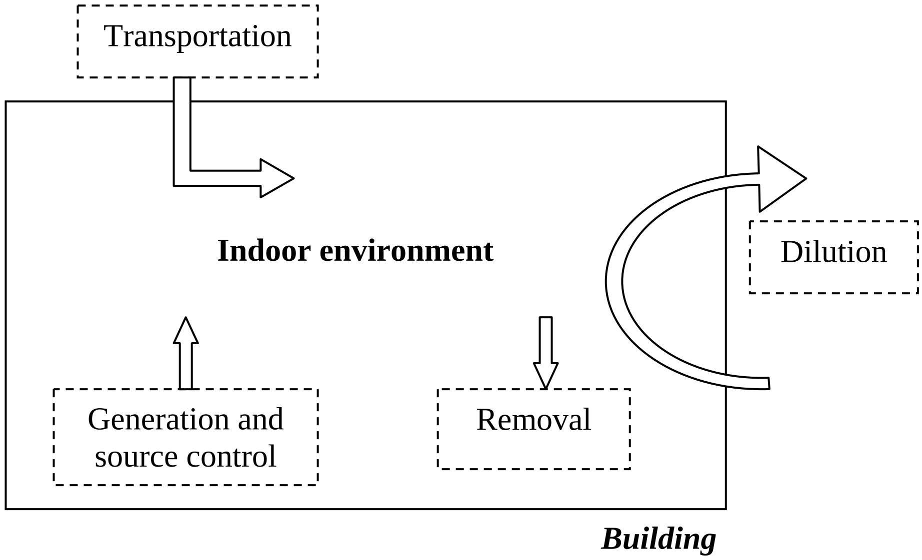


Figure 2.1: Factors for IAQ

Building design and operation

The location and floor level of a building govern the outdoor environment that the space connected to. The building age and usage, floor layout and occupant density affect the possible existence of pollutants. The MVAC system adopted and the sitting of supply and return air in the space set the pathway of pollutant transportation.

The modes of MVAC system operation would also induce IAQ concerns in elevated pollutant concentrations. For example, an energy-saving measure of shutting down the MVAC systems in an air-conditioned office during non-office hours would result to an accumulation of concrete-based building related air pollutants such as radon (Mui and Wong 2004). Occupants resume work in their offices after a long holiday may be exposed to excessive air pollutant levels.

Transportation

'Clean' outdoor air for ventilation is connected to good IAQ as it is the primary source of air supplied into the space. The indoor air pollutant levels depend on the amounts that are transported from outdoor. Air quality problems are generally a regional issue while some localized issues are associated with local industry and traffic. Ozone, a reactive gaseous constituent of outdoor air pollution, and various types of very small invisible particles are examples in developed cities that air pollutants entered the buildings through transportation. Even in rural areas, pollen and fungal spores which can result in poor health and cause allergies are also present (Liddament 1996).

In the air tight air-conditioned buildings, a shut-down air conditioning system during the building non-operating periods would induce the contaminant ingress or growth of biological pollutants if building openings are not closed for minimising outdoor air and humidity infiltration (Law et al. 2001, Wu et al. 2005).

Generation and source control

Indoor air contaminants can source from building contents, including building structure, and/or its furnishing materials, decorations, movable building contents and/or those generated by occupants. Examples of indoor-generated air pollutants include particles and gases released by molds and bacteria growth on damp indoor surfaces, radon from granite in reinforced concrete, and volatile organic compounds (VOCs) (gaseous chemicals containing carbon and hydrogen and often other elements) emitted by some building products, furnishings, and consumer products which include wall paper and covering, paints, tiles, caulking compounds, carpets and all mineral products. In addition, office equipment such as photocopying machines and laser printers or office stationeries such as adhesive tapes, glues, correction fluids and marker pens may also be the sources of VOCs (Destaillats et al. 2008). People are also sources of indoor air pollutants, for example, odorous gases and bacteria, gases and particles produced by tobacco smoking, chemicals from consumer products, or reentrainment of settled dust from floors and carpets by occupant movements (Esmen 1985).

Concentrations of indoor air pollutants are related to the emission rate from the source. As mitigation, some measures for source or emission control are implemented. The most direct way is limiting the use of those pollutant-emitting products. For some pollutants, limiting the actual emission rates rather than the contents are more economical, and practical solutions, with the use of effective coating in either fabrication or on-site application stages. Radon exhalation rate from building materials may be reduced by the covering/finishing materials applied (Yu 1993). Emission rate control on pollutants, including heavy metals, radon, formaldehyde, and VOCs, can be achieved based upon environment chamber testing (Niu and Burnett 2001).

Dilution

Dilution can control the indoor pollutant levels. Mode of MVAC system operation has strong influence on concentrations of indoor air pollutants. The rates of outdoor clean air supply to a building, i.e., the dilution rate of air pollutants by ventilation, are treated as a key design parameter to demonstrate the ventilation system performance. Ventilation is necessary to replace the stale or contaminated interior space air with clean and fresh air. Such performance is addressed by the 'ventilation efficiency', which indicates the degree of mixing between the supplied clean air and the interior polluted space air; and to take away air pollutants rapidly from interior air space (ASHRAE 2007). Concentrations of indoor air pollutants are related to the effective indoor space volume, i.e., the actual volume available for contaminant dispersion, and dependent on the air circulation.

Removal

Air pollutants originated from indoor sources or entrance from outdoor, besides the rate of transportation, generation and dilution, the rate of removal is one of the controlling factors that governed the indoor concentrations. Filtration systems are applied to remove particulates from the air during circulation. Activated carbon and other adsorbing filters are able to remove gaseous pollutants (Liddament 1996). Air purifiers or air cleaners can remove tobacco smoke, bacteria, odour and other toxic gases for individual spaces. Various controlling technologies, including photocatalytic oxidation and negative air ionization, for removal of VOCs and bioaerosols were reported (Cho et al. 2005, Yu and Lee 2007).

2.4 Detection and management of IAQ problem

IAQ detection and management in office environments are essential because the IAQ has significant association on health, comfort and thus productivity of workers (Singh 1996, Jones 1999, Kosonen and Tan 2004). A review of 23 studies suggested that a linkage exists between typical building-related symptoms and productivity indicators such as task or work performance or absence from work (Niemelä et al. 2006). Studies showed that in the US, the economic impact of 1% productivity loss is equivalent to the annual costs of the total air-conditioning system, while, reduction of 5-10% dissatisfaction can lead to 1-2% reduction in the loss of productivity. This calculation indicates that the potential financial benefits of improving contaminant control are huge (Kosonen and Tan 2004).

IAQ studies provide understanding of detection of air quality problems. Proper control measures can also be proposed to ensure the health and safety of facility occupants and protect the valuable resources. To achieve good IAQ that would not pose health risks or discomforts, efforts and researches are needed in five major areas, they are: monitoring, source characterization and mitigation, health effects, risk assessment, and management (Farland 1991). Risk assessment is the critical stage that allows decision to be made, while monitoring is critically important for understanding exposures and characterizing health risks from a particular indoor air pollutant source. Within the five areas, monitoring pollutant levels is the first step to understand the current IAQ status. With the information collected, IAQ problem can be detected and mitigated, and enhance the development of appropriate IAQ management strategies in the long term.

2.5 IAQ monitoring and assessment

The motivation for monitoring IAQ is to estimate the total exposure of an individual with respect to air contaminants so that the needs of total exposure reduction can be identified (Moschandreas 1985). Before any actions aimed at improving IAQ are undertaken, the existing conditions must be assessed to determine the optimal course of action. To assess the IAQ, different ways were suggested and adopted. Each of them results in different representation of the actual IAQ status. The approaches for assessment include by occupants' complaints, indoor-outdoor relationship, direct measurement, and modeling, as summarized in Figure 2.2.

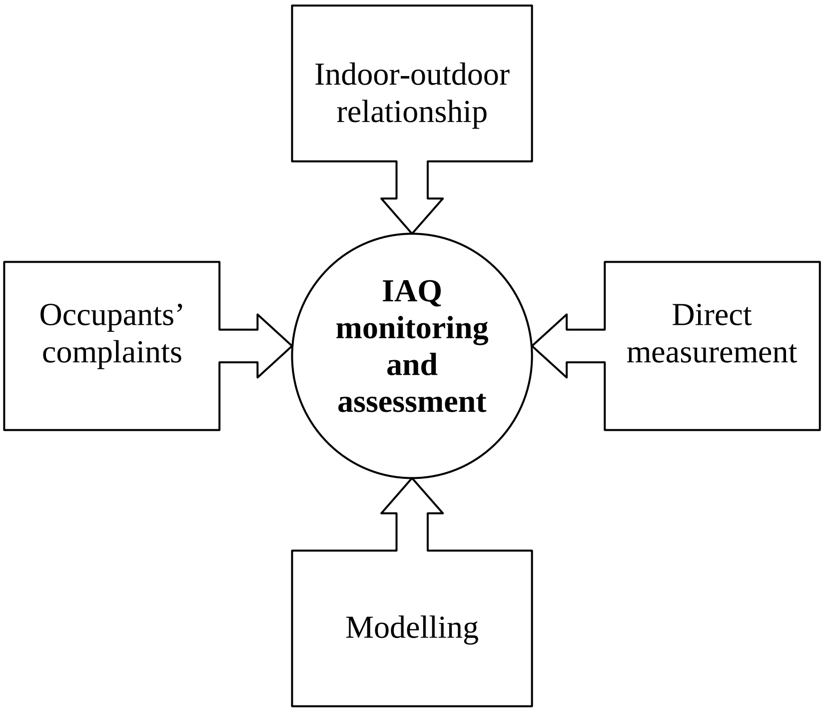


Figure 2.2: Different approaches for IAQ monitoring and assessment

Occupants' complaints

Personal complaints may be an indicator of IAQ problems. Cross-sectional study of the perceived physical work environment, allergies and symptoms in associations with building characteristics have been conducted to examine the relationships between the indoor environment parameters as perceived by the occupants (Haghighat and Donnini 1999, Skyberg et al. 2003). The protocol addresses the psychosocial factors with an environmental survey, that rated the occupants' perceptions of the indoor air to identify the potential IAQ problems, was proposed (Greene et al. 1997). Smell is a good indicator for mould growth, as well as many other irritants, including VOCs. Significant correlations between indoor air parameters and the feelings of people were found (Butala and Muhic 2007). However, direct assessment of IAQ from occupants' perception may sometimes be quite complicated, because the effects of poor IAQ on the inhabitants are often delayed and cumulative. There are many personal differences in sensitivity depending on sex, age, metabolism and other individual factors. Also, dissatisfaction with one or more environmental aspects does not necessarily connect to the overall dissatisfaction on the environment; the aspects would better be assessed individually in some cases (Humphreys 2005).

Indoor-outdoor relationship

Understanding of the outdoor environment is another key to assess indoor air. As the outdoor air is transported to the indoor, the industries that are located nearby the building, and the pollutants that they generate would affect the IAQ. Studies were conducted to characterize the contribution of each indoor and outdoor source using the relationship among measured air pollutant concentrations. Sampling measurements of air pollutants were conducted simultaneously indoors and outdoors, and comparing the measured indoor levels to those taken outdoors which expressed as indoor/outdoor ratios (Baek et al. 1997). The relationships between indoor, outdoor and personal levels are complex. Some studies' results confirmed the importance of ambient air in determining the quality of air indoors, very strong correlations were found between indoor and outdoor levels of vehicle-related pollutants (Baek et al. 1997, Bae et al. 2004). Indoor/outdoor ratios of VOCs were found generally greater than unity in homes, offices and schools (Pekey and Arslanbaş 2008). A review pointed out that better correlation between indoor, outdoor and personal levels were found for finer particle size, and for longitudinal analyses than in cross-sectional analyses. For nitrogen dioxide (NO_2) and ozone (O_3), the indoor O_3 levels were significantly lower and in the absence of indoor sources such as gas appliances, NO_2 indoor/outdoor relationships were strong in some cases (Monn 2001). Though the relationships were established for particular pollutants which also vary from regions, they can be used as reference rather than a solid judgment on the possible risk of the space. Monitoring or assessing the individual pollutant concentration over the space is still crucial in a risk assessment.

Direct measurement

For direct measurement on indoor parameters, the IAQ assessment is normally based on the measurement of different factors, including thermal and air quality conditions. The simple thermal comfort parameters, which are the temperature, relative humidity and air velocity, can be measured quite accurately in normal conditions with simple instruments, while measurement and assessment on exposure concentration of various air pollutants in a room is much more complicated.

For an air pollutant, the ‘concentration’ is the amount of pollutants present in each unit volume (e.g., cubic meter) or unit mass (e.g., kilogram) of air (ASHRAE 2007). The term ‘exposure’ refers to the product of pollutant concentration in the breathing zone of a space and time the person spends in the space, summed for all spaces encountered. Exposure determines the pollutant amount inhaled. The product of time spent indoors and average indoor air pollutant concentration is an often-used estimate of indoor exposure (Moschandreas and Saksena 2002).

Comprehensive studies on exposure concentrations of IAQ parameters have been conducted extensively in different countries in various environment including public facilities, and residential and commercial buildings (Lee et al. 2002, Wong and Huang 2004, Kim et al. 2005, Hummelgaard et al. 2007). These studies provide direct information on the current situation of IAQ in terms of pollutants concentration and/or thermal comforts.

However, reliable assessment of the different chemical and biological impurities in indoor air is complex. One of the problems is the availability of the easily-applicable analytical tools to measure the low concentrations of pollutants found in typical indoor environment. The concentrations of indoor pollutants may also vary considerably over time, depending on the sources and other factors, which pose another challenge in conducting the assessment.

Modelling

Modelling is a powerful and relatively inexpensive research tool that can assist in controlling assessment, cost-efficiency, exposure and health effect studies (Moschandreas

1985). Indoor exposures to air contaminants, especially to those that penetrated from the outdoor environment, depend on a number of parameters such as the ventilation rate, the geometric characteristics of the indoor environment, the outdoor concentration and the indoor removal mechanisms. A number of theoretical models were developed for predicting the mass transfer, emission source, time-concentration profile, and the inhalation exposure in the assessment of IAQ (Kraenzmer 1999, Dimitroulopoulou et al. 2001, Zhao et al. 2004). A recent review compiled 52 indoor emission source models found in literature (Guo 2002). The model basis was the mass balance equation, which described the relationship between the source emitting pollutants into an enclosed well-mixed compartment, the physical parameters of the compartment, and the pollutant concentrations as a function of time.

However, a number of specific parameters required for modelling the concerned indoor pollution remain unclear. One of those is the time lag between indoor pollutant concentrations and outdoors when a rise of outdoor concentrations is detected (Halios and Helmis 2007). From the achievements that IAQ modellers have made in recent years, most models have a certain degree of usefulness, genuine predictive models are still few, and there are undoubtedly many rooms for improvement. Moreover, only a small number of models can predict in the absence of experimental data (Guo 2002).

2.6 Considerations for IAQ sampling strategies

Representative IAQ measurements are essential in comparing the IAQ of a building with the standards specified in the guidelines, or estimating exposures. To quantify IAQ, measurements should, be accurate, reflect the true value at the measurement point, account for both spatial variations in the site and the variation over time, and be accompanied with necessary number and type of sample collected. Assessment strategies should be defined with indoor pollutant concentrations variability being taken into account (Luoma and Batterman 2000).

Sampling parameters

IAQ sampling strategy for selected parameters is used to characterize the air pollutant concentrations present and compare these with the available air quality standards, which aimed at protecting occupants in view of health concerns. Different levels of assessment priorities have been assigned to the parameters for different premises.

In an IAQ assessment, the rationales behind the selection of a particular parameter are the significance of its probable adverse concerns on human comfort and health, and its sufficient evidence of causing unacceptable IAQ.

Occupant perceivable parameters could be used as surrogate indicators when assessing IAQ, occupant perceptions of the overall indoor environment might have some indications on the IAQ. In fact, some cases of IAQ problems were notified due to a reported indoor environmental quality (IEQ) dissatisfaction from a small group of occupants (Fanger 1988, Pommer 2004, Mui and Wong 2007).

The ‘decipol’ concept suggested by Fanger (1988) quantifies how the strength of indoor pollution sources influence air quality as it is perceived by humans, which is sensory pollution strength judged by human nose. However, human nose already adjusted to smells, therefore some air pollutants that cause health effects cannot be detected by smell.

Butala and Muhic (2007) tried to correlate the occupants’ perception of air quality and thermal environment in offices with the actual measured parameters. Humphreys (2005) suggested quantifying the overall occupant comfort with an index that combined different aspects of satisfaction of the indoor environment, and analyzed the effectiveness and consistency in applying the index in different European countries. However, both studies showed that occupants perceived the environment differently in offices or in different countries. Environmental comfort is a flexible perception and not constrained by human physiology only. Therefore, it is difficult to determine the correlated indoor parameters that would be acceptable to the majority of occupants.

The aim of IAQ investigation leads to specific assessment parameters, which can be an understanding on the contemporary performance, for example, assessment on the effectiveness of the applied remedial measures before and after renovation (Shaw et al. 1999), or to understand the profiles of the typical pollutants for a specific type of premises (Junker et al. 2000). More importantly, it can find out the source and effect of the occurrence of a particular IAQ problem. For instance, bacteria and fungi levels were assessed in mold-damaged or water-damaged buildings to analyse the effects on occupants (Park et al. 2006, Salonen et al. 2007), and organic compounds were analysed in the case of reported sensory irritation or odor in a space (Wolkoff and Nielsen 2001,Wolkoff et al. 2006).

Many guidelines and standards for IAQ suggest acceptable concentration of individual pollutant. Studies have looked at one or two aspects of IAQ and a few of them have taken a multidisciplinary approach. In the IAQ measurement, assessment parameters are suggested for evaluation. Carbon dioxide (CO_2) concentration is commonly used as a surrogate indicator for assessing the IAQ and the ventilation efficiency (ASHRAE 2004, ASTM 2003). Studies have been performed to find out the correlations between indoor parameters. A number of relationships were suggested between different pollutants presented in an environment in individual bases (Roelofsen 2003, Jokl 2000, Klánová and Jitka Hollerová 2003, Mølhave et al. 2005).

A study comparing the indoor and outdoor air pollutant concentrations in Japan and Sweden showed that there were differences between the two cities. And it demonstrated the need of larger international studies for comparing indoor and outdoor air pollution of priority pollutants, applying the same sampling procedure and analytical methods in different countries (Sakai et al. 2004). Hence, the current paradigm of categorizing air quality problems according to single independent fields of expertise would probably not provide solutions to most of the unanswered questions.

Sampling Time

Health effects on occupants are depended upon the nature of exposure, whether it is high concentrations over short periods (hours) or much lower concentrations over a long period (months to years). Pollutant exposure in offices of 8-h period each day and the same air quality for 24 hours a day exposure at home may have a different impact. Concentrations of pollutants indoors vary in time and space and the exposure of occupants are influenced by their own activities. Models were developed to describe the physical processes for determining the indoor pollutant concentrations and linked to a time-activity model to calculate exposures for an occupant (Dimitroulopoulou et al. 2001). They were also useful in providing a first estimate of the relative importance of pollutant sources for chronic and acute health effects.

Studies showed that concentrations varied over time for different air pollutants which governed by their generation and removal characteristics in an indoor environment. Climate and outdoor air related pollutants like radon would show seasonal variations over a year (Oikawa et al. 2006). Air pollutants with indoor emission sources, like VOCs, would be influenced by the aging decreases of emission strength (Park and Ikeda 2006) and the mode of building operation (Chuah et al. 1997). In a workplace with a daytime operating ventilation system, building related contaminants normally peak in the morning and occupant related ones normally peak in the afternoon.

Measurement time and duration are chosen for a sampling, where, uncertainty should be quantified for pollutant concentration measurement, the differences between the collected results and the year-round pollutant profile due to seasonal variations (Narayana et al. 1998, Ramola et al. 1998, Rydock et al. 2001).

Measurement errors related to sampling time have been reviewed for some air contaminants (Armstrong et al. 1992, Monn 2001, Wallace and Williams 2005). The errors are critical as they can lead to a bias in the exposure-effect relationship. Uncertainties of the measured quantities must be quantified (Pielke 1998). Several expressions for the standard error of the measured mean concentration have been proposed and used in varying degrees in the atmospheric chemistry literature (Gatz and Smith 1995, Muirhead 2002). In addition, the Gaussian quadrature methods have been extended to an exponentially decaying function with a predetermined decay constant (Cameron 2003, Clyde and Mark 1992). If the uncertainty of the sampling methods can be identified, the policymakers can make a decision on the resources and manpower management in pollutant testing and the inappropriate level of reliance on the results can be avoided (Font et al. 2001, Muirhead 2002, Pielke 1998).

Sampling point density and locations

In deciding the sampling strategy, a range of factors should be considered in selecting the representative locations, including the size of the building and individual rooms, nature of the building use, possible pollutant sources and the temporal variation in pollutant concentration, and the specific occupants' activities or complaints. A personal exposure analysis on CO demonstrated that it is not feasible to predict the exposures by a fixed-site monitoring only, and different activities and microenvironments affect individuals' exposure rate (Vellopoulou and Ashmore 1998).

Currently, there is limited published data about spatial pollutant concentrations variation indoors. Variations of individual pollutants at some locations in a building were reported (Morrison et al. 2006, Milner et al. 2006, Tsai et al. 2007). More information is required about spatial variation in concentrations in order to assess whether the current sampling strategy adequately characterises the exposure of building occupants. Studies attempted to formulate the pollutants distribution over a zone by numerical simulations (Price et al. 2001, Sekhar and Willem 2004, Zhao et al. 2004), or to identify a particular pollutant source location (Demokritou et al. 2002, Liu and Zhai 2008).

The positioning of samplers should relate to the objectives of the measurement, and appropriate sitting criteria should be defined at the beginning of the study. An investigation on indoor pollutant mixing time using CFD suggested that the desirable attribute of a sensor location for pollutant detection should be a location where an airborne pollutant released in a room can be reached quickly (Gadgil et al. 2003). Sensors should not be placed at locations like corners or edges of a room where sources have long mixing times which will cause delay sensing of a pollutant. Conversely, the locations from which a source disperses quickly into the room (e.g., behind a table fan) would also be desirable locations for sensors for quick detection.

However, existing protocol focuses on specific measurement methods using fixed sitting of instrumentation which are always in the perspective of a particular design and purpose for an investigation (Möhle et al. 2003). In implementation, the constraints of a space and the acceptability to occupants would limit the choice of sites and therefore it is important to document the actual locations in detail to assist the interpretation of results.

Rapid locating and the rational method were presented to determine the sampling locations within a building where the highest average concentration of contaminants may occur (Maldonado and Woods 1983, Michael et al. 2002). Selection of the representative locations for an assessment would rely on professional judgment of the assessors, though, uncertainties of the assessment results due to the assessors were not fully addressed in some IAQ assessments.

2.7 Guidelines or standards for IAQ assessment

The decision to perform air monitoring is based on either a regulatory requirement or the needs of quantifying the exposures in hazard evaluation. Air quality assessments are conducted for various purposes and under different circumstances, such as occupational exposures, community environment, IAQ evaluations and energy response (McDermott 2004). It is almost impossible to sample every toxic pollutant of the general community. The air sampling should be conducted based on the assessment strategy and monitoring planning.

The imposition of regulatory requirements is intended to protect and enhance the IAQ in buildings. They provide a clear reference level for different parties to follow with a balance between the needs in reducing health risk and the effort spent for maintaining air quality. Indeed, requirements have already existed in specific cases, such as the regulation of smoking in public places (USSG 1986) and regulations of the asbestos in schools using an EPA-approved protocol (EPA 1987). Assessing the compliance with IAQ standards would be more difficult in both philosophical and practical terms. Based on precedents established in regulatory programs for ambient air and occupational exposures, measures of monitoring activity would be desirable to assess the compliance.

Environmental parameters were suggested and adopted for IAQ assessment by researchers, building owners and facility managers (Cheong and Chong 2001, Möhle 2003). Countries including Canada, Japan, Korea, Singapore, Sweden, UK and USA have been aimed at setting standards and guidelines for a long time (Crandall and Sieber 1996, Malkin et al. 1996, Scitz 1990, Sieber et al. 1996, USEPA 1991). To set out a practical and valid guideline or standard for IAQ monitoring and assessment, many organizations have conducted studies to identify and quantify occupational health problems related to poor IAQ, such as the US Occupational Safety and Health Administration (OSHA), the US National Institute for Occupational Safety and Health (NIOSH), the American Congress of Governmental Industrial Hygienists (ACGIH), and the World Health Organization (WHO).

Based on the persistence of the studies, different criteria of IAQ satisfaction have been set in different places in the form of regulations or guidelines (ACGIH 1986, ENV Ministry of the Environment 1996, Environment Australia 2001, Health Canada 1987, HKEPD Indoor Air Quality Information Centre 2003, Institute of Environmental Epidemiology 1996, USEPA 1987, WHO 2000, Womble et al. 1995). In the standards, they defined what pollutants should be measured, how they should be measured, and the pollutants' exposure limits to assess the acceptance of IAQ, as shown in Figure 2.3. These criteria are the base reference in practical monitoring and assessment for acceptable IAQ.

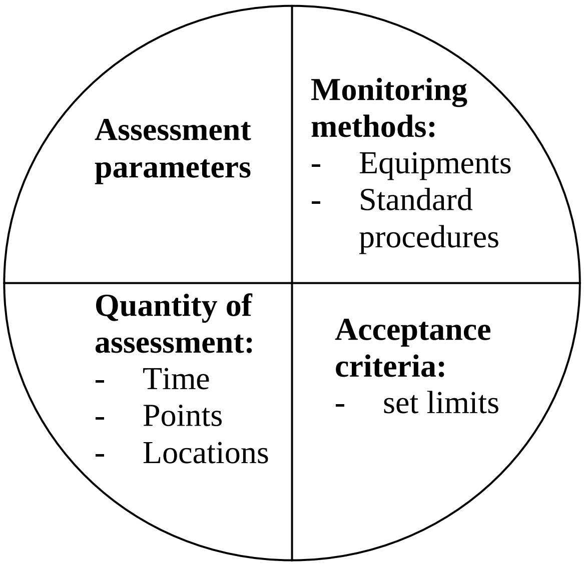


Figure 2.3: Components of an IAQ standard

Table 2.1 shows the recommended assessment pollutants and their corresponding concentration limits defined in those standards or guidelines. The pollutants addressed and the number of parameters required to be assessed vary, and their suggested ceiling level are different. Apart from carbon dioxide (CO_2), the common pollutants stated are carbon monoxide (CO), respirable suspended particulates (RSP), and ozone (O_3). All these guidelines were more or less set as a mandatory educational program to draw public's attention to the IAQ problems and human exposure issues.

Overseas regulatory actions related to IAQ are limited, especially in contrast with regulation of outdoor air quality and industrial workplace. Though some guidance has been provided by authorities or organizations, there is a need for a more structured approach for evaluation and control of IAQ. A severe limitation in many countries is the absence of a single governing authority with responsibility for IAQ.

Table 2.1: Comparison of indoor air quality guideline concentrations for pollutants

Indoor air pollutant	Concentration limits							
	Australia NHMRC (indoor)	**Health Canada (residential)**	**HKEPD (Good/Excellent Class)**	**Japan**	**UK (limit value)**	**WHO (key pollutant)**	**Singapore**	**USEPA***
Radon	200 Bq m^{-3} (1 yr)	800 Bq m^{-3} (1 yr)	200/150 Bq m^{-3} (8h)	-	-	-	-	√
Respirable suspended particles	TSP 90 µg m^{-3} (1 yr)	$PM_{2.5}$ 100 µg m^{-3} (1h)	PM_{10} 180/20 µg m^{-3} (8h)	100 µg m^{-3}	PM_{10} 50 µg m^{-3}	-	150 µg m^{-3}	√
Formaldehyde	120 µg m^{-3}	60-120 µg m^{-3}	100/30 µg m^{-3} (8h)	-	-	-	120 µg m^{-3} (8h)	√
TVOCs	0.218 ppm (1h)	-	0.261/0.087 ppm (8h)	-	-	-	3 ppm	√
Nitrogen dioxide	-	480 µg m^{-3} (1h)	150/40 µg m^{-3} (8h)	80-120 µg m^{-3}	200 µg m^{-3} (1h)	200 µg m^{-3} (1h)	-	
Carbon monoxide	9 ppm (8h)	11 ppm (8h)	8.7/1.7 ppm (8h)	20 ppm (8h)	8.7 ppm (8h)	8.7 ppm (8h)	9 ppm (8h)	√
Carbon dioxide	-	3500 ppm	1000/800 ppm (8h)	-	-	-	1000 ppm (8h)	√
Ozone	0.1 ppm (1h)	0.12 ppm (1h)	0.061/0.025 ppm (8h)	-	0.09 ppm (1h)	0.06 ppm (8h)	0.05 ppm (8h)	
Sulphur dioxide	700 µg m^{-3} (10 min)	1000 µg m^{-3} (5 min)	-	0.04 ppm	125 µg m^{-3}	125 µg m^{-3}	-	
Lead	1.5 µg m^{-3} (3 months)	-	-	-	0.5 µg m^{-3} (1 yr)	0.5 µg m^{-3} (1 yr)	-	
Relative humidity	-	30-80 %	< 70/40-70 % (8h)	-	-	-	70%	√
Room temperature	-	-	< 25.5/20-25.5 °C	-	-	-	22.5-25.5 °C	√
Air movement	-	-	0.3/0.2 m/s	-	-	-	0.25 m s^{-1}	
Airborne bacteria	-	-	1000/500 cfu m^{-3}	-	-	-	500 cfu m^{-3}	√
Fungi	-	-	-	-	-	-	500 cfu m^{-3}	
Photochemical oxidants	-	-	-	0.06 ppm (1h)	-	-	-	
benzene	-	-	-	3 µg m^{-3} (1 yr)	5 µg m^{-3} (1 yr)	-	-	
Sulphates	15 µg m^{-3} (1 yr)	-	-	-	-	-	-	

Values averaged over 24 hours unless specified.

* Sampling parameters suggested but reference concentrations not provided in guideline.

2.8 IAQ certification scheme in Hong Kong

Hong Kong, as a densely populated city with many modern commercial buildings where mechanical ventilation systems are usually applied, occupational health related to workplaces IAQ are of concern like the other cities. In the second review of the '1989 White Paper on Pollution in Hong Kong' in November 1993, the importance of IAQ issue was officially recognized. The Hong Kong Environmental Protection Department (HKEPD) then commissioned a study on IAQ in offices and public places in Hong Kong, which aimed to characterize and quantify indoor air pollution in business and public premises in order to assess the causes of the pollution problems and recommend suitable control strategies. It comprised a questionnaire survey, field sampling and analysis, statistical analysis of the results, and a study on the practice of other countries (HKEPD 1997). Based on its findings and recommendations, a more comprehensive mechanism was established to strengthen and institutionalize the IAQ control. Three options through which the institutionalization could be done were suggested: 1) self-regulation; 2) existing legislation and system; and 3) amendments of existing legislation.

In 1999, a draft of 'Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places (GN)' was issued for mechanically ventilated air-conditioned buildings on self-regulatory basis. To arouse the awareness of IAQ issues and encourage the participation of IAQ management, the HKEPD has launched an IAQ certification scheme in 2003, laying out a framework on how IAQ could be monitored for the building industry to follow in practice. Besides the steps to certify IAQ of a workplace, it also details the sampling requirements for the indoor pollutant level. With references to the proposed parameters from other countries, it proposed twelve common environmental parameters for IAQ assessment in Hong Kong, including nine major indoor air pollutants as well as three thermally comfort-based parameters. The twelve parameters were 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), temperature (T), relative humidity (RH) and air velocity (V). For each of these twelve parameters, an 8-h time weighted average sampling period for a balance between measurement effort and accuracy was specified in determining the exposure level. And the minimum number of sampling points required is specified base on the floor area of the certified space, as shown in Table 2.2.

Table 2.2: Sampling points requirement

Total certified area within the premises (served by MVAC system) (m^2)	Minimum number of sampling points
< 3 000	1 per 500 m^2
3 000 - < 5 000	8
5 000 - < 10 000	12
10 000 - < 15 000	15
15 000 - < 20 000	18
20 000 - < 30 000	21
> 30 000	1 per 1200 m^2

To quantify the acceptable IAQ levels of an environment with these parameters, two levels of classification were proposed: (1) ‘Excellent’, a very good IAQ comparable to the best IAQ standards that a high class and comfortable building should have; (2) ‘Good’, an IAQ recommended for the protection of the public including the very young, the aged and pregnant women (HKEPD 1999). The corresponding acceptable levels for the two classes are as shown in Table 2.1. The scheme was not intended to be detailed as an engineering manual for front-line engineers to follow step by step, but to provide them the flexibility to select the best way of implementation.

2.9 Feedbacks of the scheme from local industries

Nevertheless, the local building industry has given a number of technical difficulties in the scheme implementation as feedback. The assessment of the listed parameters imposed a burden 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. Technical issues such as instrumentation, disturbance of the occupants, time consumption and interpretation of data must be clearly defined before the industry could comprehend such or similar kind of operations.

In addition, the scheme did not define explicitly the correction of survey data for alternative measurement protocols, the rationale behind the parameter selection, the criteria for sampling density determination, and the interpretation of intermittent measurement periods other than the 8-h averaging method specified. Questions remain on resources justification on measurement protocol, application skills and accuracy and detection limit of instruments, and the correlation of sick building syndromes with the measured pollutant levels. All of these could be misleading to the building owners and managers about facilitating their resources for mitigation and building renovations. Refinements of the existing assessment methods are required so that a cost-effective, representative, and user-friendly procedure can be developed for the practitioners to avoid improper level of reliance on the results.

2.10 Conclusion

There are thousands of air pollutants in the world. It is far too expensive to sample all air pollutants of the general community. Air sampling should be conducted in accordance with the assessment strategy and monitoring plan.

When undertaking IAQ assessments, there is a difficult task of representing and characterizing the environment by a limited number of measurements. Obviously, the more measurements that can be made the more representative they can be, but practical and financial constraints would be the major considerations that governed only a limited number of measurements. The IAQ assessment with reduced measurement parameters would reduce the efforts in IAQ monitoring, but suffered with the lost of assessment accuracy. Therefore, the measurement strategy is of the greatest importance to ensure the maximum useful information is obtained with the minimum resource utilization. Moreover, for each parameter there is a need to define when, how often, for how long and where measurements should be made.

Various bodies recommended IAQ exposure concentrations for specific pollutants, generally on a health-related basis. Indoor air parameters are audited against the corresponding exposure limits to determine the IAQ acceptance for typical air-conditioned offices. Indeed, not all the parameters uniformly contribute to the assessed 'IAQ acceptance’ of the offices and the IAQ acceptance could be correctly identified by only few numbers of contributors audited. The judgments on choice of assessment parameters rely on the level of professionalism of the responsible personnel.

For general building investigation, particularly for commercial buildings, a structured step-wise strategy should be used. Indoor air pollutant measurements should be started with some broad indicators early in the strategy (e.g. temperature, humidity, air velocity, carbon dioxide or ventilation rate) and progress to specific air pollutant indicators if needed within the particular investigation. Those indicators are measured in relation to the presence of critical sources rather than applied to all buildings. The significance of the pollutant exposure would vary between buildings because the amount and nature of the substances present and the type of occupancy are different.

Long-term measurements are essential and best for risk assessment so that daily and seasonal variations can be accounted for. However, the long period of time required to obtain those data is a disadvantage, short-term measurements are less expensive in terms of cost and time in buildings with ventilation systems operated for only part of the day. Though, sometimes it is difficult to predict the annual average concentration.

The sampling location selection in a large indoor space would contribute to the assessment results of the spatial average pollutant concentration. Measurement efforts required in terms of the sampling point density and the choices of the sampling locations is crucial in determining the representation of the measured results in the actual exposure levels of the occupants. Measuring the spatial dependence of pollutant concentrations in an indoor environment is useful for pollutant monitoring and assessment.

Protocols must be developed and validated to provide alternatives for IAQ sampling strategies, of which assessment efforts and uncertainties can be quantified.

Chapter 3

Development of an Indoor Air Quality (IAQ) Assessment Protocol

3.1 Basic concept

When assessing IAQ, conducting a long-term extensive measurement on all concerned environmental parameters would be the best way to identify any IAQ problems. As a minimum provision of statutory control in practice, an assessment protocol with less implementation efforts would give a greater motivation for building owners to monitor, and thus achieving good IAQ. For an effective and practical assessment protocol, resources and manpower required for the assessment must be justified with measurement uncertainties. Thus, appropriate decisions can be made on whether it is needed to maintain the existing IAQ measures, to conduct further detailed investigation or take actions of mitigations.

This chapter proposes a flexible and practical IAQ assessment protocol which allows a choice of measurement effort at specified measurement accuracy in assessing IAQ for the statutory control. This assessment protocol may not be used to investigate the specific IAQ problems associated with an environment, but it may indicate the environment which IAQ is accepted by the occupants regarding some regulatory control exposure limits of the concerned air pollutants. A comprehensive survey on IAQ parameters in Hong Kong air-conditioned offices is used as a reference to study the probable relationship among the assessment parameters, choices of measurement periods, locations and measurement uncertainties. With the intention that decisions, regarding an IAQ assessment protocol, can be made for the choice of assessment parameters and sampling methods for pollutant concentration measurement at an acceptable uncertainty.

3.2 Formulation of an assessment protocol

A practical IAQ assessment protocol must address two basic questions: (1) what should be measured, and (2) how they are measured? To answer these two questions, it is important to quantify the accuracy of the assessed acceptance associated with various sampling schemes.

In different indoor spaces, there would be various IAQ problems of elevated exposure concentrations of one or more air pollutants. The concentration of a pollutant is spatially non-uniform and unsteady during a day over a year, as pollutant source emission rate, dilution with outdoor air and mitigation measures for IAQ are transient and affected by indoor activities. The exposure concentration of the selected parameters assessed by a sampling scheme at certain choices of sampling period at some assessment locations would, therefore, be deviated from the actual exposure levels, and the difference in deviation would constitute different accuracy of the schemes.

Despite the limitation of instrumentation errors, the accuracy of a sampling scheme to determine the IAQ acceptance of a space can be quantified as the combination of the uncertainties associated with the choices of (1) assessment parameters, (2) sampling times, and (3) sampling points, when compared with the long-term average level of all parameters over the space. These three factors formed the basic structure when formulating an assessment protocol, illustrated in Figure 3.1. Knowing the accuracy of each approach taken, one can justify on the cost effectiveness in resources spent on IAQ assessment.

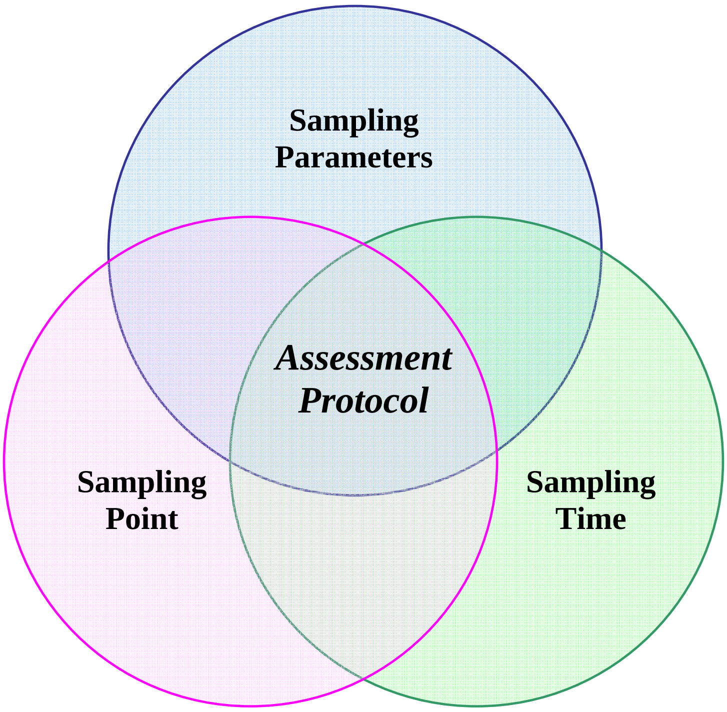


Figure 3.1: Basic structure of an assessment protocol

3.3 Selection of sampling parameters

Thousands of indoor air pollutants can be presented in a space. It is impractical to sample all air pollutants of the general community in terms of the costs and resources required. IAQ assessments with selected sampling parameters should be representative to the overall IAQ acceptance.

The judgement of acceptance in IAQ assessments would be referred to some suggested exposure limits of the selected assessment parameters for the minimum IAQ provision. An indoor environment with any one of the specified independent parameters i of a concentration Φ_i exceeding the exposure limit Φ_i^*, i.e. $\Phi_i > \Phi_i^*$, is deemed to have 'unsatisfactory IAQ'; otherwise, i.e. $\Phi_i \leq \Phi_i^*$, its IAQ is considered as 'satisfactory'.

Compared with the IAQ assessment with all assessment parameters, an IAQ assessment with reduced assessment parameters would reduce the efforts in IAQ monitoring, but it would scarify with the lost of assessment accuracy in indicating IAQ satisfaction. In order to obtain those representative parameters which are essential for investigating the probable acceptance of an indoor environment, and quantify the accuracy of assessments with different number of measurement parameters selected, exposure levels of some listed indoor environmental parameters would be referred to for analysis. The representation of a selected parameter can be discussed under two main categories: (1) a parameter has significant contribution to IAQ dissatisfaction; (2) a parameter surrogates to air pollutant control system performance.

Selection based on high occurrence of IAQ dissatisfaction

The IAQ satisfaction is the result of an intricate series of interactions between factors that would vary between regions, districts or buildings. In an indoor environmental group of similar nature, e.g. air-conditioned offices in Hong Kong, indoor air parameters would not uniformly contributed to the assessed overall 'IAQ dissatisfaction' of the spaces. Some parameters contributed more on the assessed failure over the others and they can be classified as dominant contributors to unsatisfactory IAQ. It is suggested that a large portion of the unsatisfactory IAQ cases could be correctly identified with these dominant contributors.

Assume that the occurrences of unsatisfactory of individual parameters are independent. The independent IAQ assessment parameters i in a total number of parameters n can be ranked in an ascending order according to their respective unsatisfactory rates $\hat{P}$, from the most one to the least one, such that the dominant contributors to an unsatisfactory IAQ,

$$\Phi = \Phi_i \,;\, i = 1 \ldots n;\ \hat{P}_1 > \hat{P}_2 > \ldots > \hat{P}_{n-1} > \hat{P}_n \qquad \ldots(3.1)$$

The unsatisfactory rate $\hat{P}$, with an assessment parameter i expressed by a distribution function $G(\Phi_i)$, can be approximated by the following equation, where Φ^* is the exposure limit of dissatisfaction for an office having $\Phi_i > \Phi_i^*$,

$$\hat{P}_i = 1 - \int_{-\infty}^{\Phi_i^*} G(\Phi_i)\, d\Phi_i \qquad \ldots(3.2)$$

Selecting only the n_s numbers of dominant contributors of unsatisfactory IAQ at reduced resource expenditure for assessing IAQ problems in offices was therefore proposed, i.e. $n_s < n$. This proposal requires substantial assessment records of indoor environment of similar nature to identify the ‘dominant’ contributor(s) of unsatisfactory IAQ. Besides, the lost of assessment accuracy with n_s numbers of dominant contributors is also a concern.

Selection based on surrogate assessment parameters

There may be association between indoor air pollutants and the assessed results of some measured air pollutants, which would be a surrogate indication of acceptance due to some other unmeasured air pollutants. Instead of measuring the pollutants having higher failure occurrence, choosing pollutants that are less possible to be failed but able to indicate the acceptance regarding other air pollutants may also be another possible way of parameter selection. In an air-conditioned building, exposure levels of air pollutants would be controlled based on the principles of dilution, removal, or emission control. The corresponding air pollutants surrogate to the IAQ control principles would, therefore, be professionally judged as representatives to the IAQ acceptance.

The chosen assessment parameters, if more than one, have to be statistically independent to one another and have had significant correlations with other parameters not monitored. The probable correlations among the parameters would also be different. Thus, the relationships among the measurement parameters expressed by their correlations and covariance, and the significances of the correlations between any two of the parameters must be examined. Priority of the assessment parameter set is assigned to those parameters with high loading values L and could be easily measured. The loading value L of each parameter i, which highlights the 'relative importance' of the associated correlations among the parameters, being calculated from the correlation coefficient R_i with respect to all other parameters divided by the summation ΣR_i of all the n measurement parameters is given by,

$$L_i = \frac{R_i}{\sum_{i=1}^{n} R_i} \quad \ldots (3.3)$$

With the set of n_s representative parameters, the dependence of the other parameters on the set can be examined. And the correlations for these parameters using n_s 'representative' parameters as the predictors can also be determined. The 'representative' parameters used as predictors in an air-conditioned office for the IAQ satisfaction regarding the others not assessed parameters can then be evaluated regarding the accuracy.

Expression of assessment results and screening process

In a scheme, representative parameters were suggested for IAQ assessments. In a practical assessment protocol, it is important to have a simple method to present the overall IAQ of the assessed space from the indication of the representative parameters.

It is showed that a simple IAQ index related to the symptoms of office building occupants could be compiled using the fractional dose of representative parameters (Moschandreas and Sofuoglu 2004, Sekhar et al. 2000). Therefore, using the IAQ parameters selected, an 'IAQ index' using the average fractional dose to certain exposure limits of the representative parameters is proposed as an expression of assessment results from the scheme. It is noted that in compiling the index, only the indoor air pollutants are included but not the thermal comfort parameters. The index value would give a quantitative indication of the overall IAQ in the assessed environment with respect to the satisfactory air pollutant exposure levels for the statutory control.

In fact, some of the buildings were at a relatively later stage of an IAQ problem when the investigation or remedy was started. As always, prevention is better than cure. An effective IAQ surveillance plan is essential for a better control in pollutant exposures of building occupants. Pre-screening approach with assessment of those representative parameters might give a preliminary indication on the status of the IAQ. Therefore, a simple screening test using the ‘IAQ index’ for searching asymptomatic IAQ problems in air-conditioned offices are proposed. The screening process provides a judgment on appropriate action that should be taken, based on the assessed air pollutant levels from the scheme.

An ‘IAQ index θ’ is determined from the average fractional dose against the exposure limits Φ_i^* of n_s number of ‘representative’ air pollutants for IAQ assessment as shown below, where $\Phi_i^{''}$ is the fractional dose of a representative pollutant i, Φ_i is the average level of i assessed over an exposure time period.

$$\theta_{n_s} = \frac{1}{n_s}\sum_{i=1}^{n_s}\Phi_i^{''} \; ; \; \Phi_i^{''} = \frac{\Phi_i}{\Phi_i^*} \qquad \text{… (3.4)}$$

A high value of θ would indicate that the environment is associated with a high probability of unsatisfactory IAQ.

Choices of a number of air pollutants as assessment parameters for an IAQ assessment would be investigated and discussed, and would be used for analyses and developing the index for judgment of IAQ acceptance in the space.

As the IAQ index θ indicates the IAQ satisfaction for an indoor environment, the probability of 'unsatisfactory IAQ' P(A) for the environment can be expressed by a logistic model using θ as the indicator, and k_a, k_b as the regression constants determined by the maximum likelihood (Millard 2002),

$$P(A) = \frac{1}{1 + \exp(k_a - k_b\theta)} \quad \ldots (3.5)$$

Figure 3.2 shows the application of the proposed screening process for IAQ assessments using the IAQ index θ with assessment of selected representative n_s parameters. Apart from the offices which failed the assessment required remedies; the offices passed the assessment are examined with the proposed screening test as the offices would be unsatisfactory due to some unmeasured IAQ parameters. With an appropriate screening level θ_{sc}, these 'assessment passed' offices would be classified into the 'high-risk' group and the 'low-risk' group of unsatisfactory IAQ, for some surveillance strategies. A comprehensive IAQ assessment would be required to confirm the IAQ acceptance for offices in the high-risk group, while a continuous IAQ monitoring with the proposed assessment is required for offices in the low-risk group.

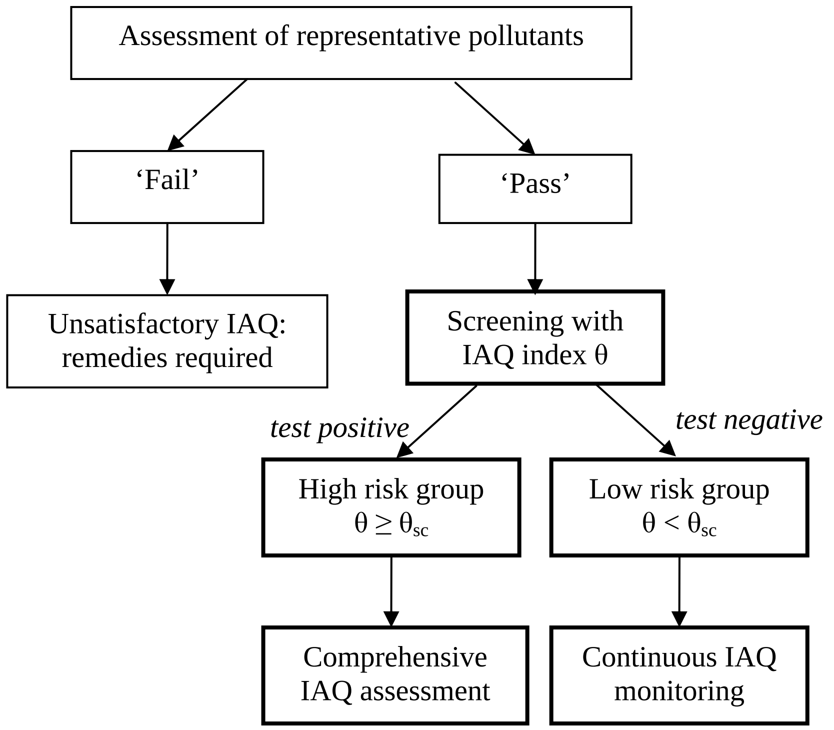


Figure 3.2: Application of screening test in an assessment

Feasibility evaluation of screening process

Two groups of representative pollutant choices were suggested for the composition of the IAQ index. The first group was selected according to the failure occurrence density of IAQ acceptance, and the second group was selected as judged typical to show the performance of IAQ control through dilution, removal, or source control. Calculated indices from the two groups of representative parameters would both be analyzed.

To examine the feasibility of the screening test using the IAQ index θ as an indicator, assessed indoor environment samples with its IAQ problems already diagnosed is required, i.e. they are classified into a group of satisfactory IAQ Ω^- and another of unsatisfactory IAQ Ω^+. These two groups must be identifiable: the IAQ index of Ω^- (θ^-) must be significantly different from that of Ω^+ (θ^+). The significance would be determined by a statistic pair t-test, where the average IAQ indices of the two groups are unequal (i.e. $\overline{\theta}^+ \neq \overline{\theta}^-$), N is the sample size, and S^2 is the variance of the IAQ indices,

$$t = \frac{\overline{\theta}^+ - \overline{\theta}^-}{S^{-,+}\sqrt{\frac{1}{N^+} + \frac{1}{N^-}}} \; ; \; S^{-,+} = \frac{(N^+ - 1)S^{+2} + (N^- - 1)S^{-2}}{N^+ + N^- - 2} \qquad \ldots (3.6)$$

For a screening test using the IAQ index θ, the screening level θ_{sc} 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 θ_{sc}, 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 an unsatisfactory IAQ. They are the probabilities of testing positive and negative respectively when the unsatisfactory IAQ is truly present and absent. Compared with the reference comprehensive IAQ assessment results, taking the test results of the proposed assessment with the 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),

$$P_s = \frac{TP}{TP + FN} \qquad \ldots (3.7)$$

$$P_f = \frac{TN}{TN + FP} \qquad \ldots (3.8)$$

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.

$$P_+ = \frac{TP}{TP + FP} \qquad \text{… (3.9)}$$

$$P_- = \frac{TN}{TN + FN} \qquad \text{… (3.10)}$$

The association between the predicted and observed unsatisfactory from the screening test can be further evaluated by Yule's Q statistics (Knoke et al. 2002), which is a measure of the correlation between two possibly related dichotomous events, given by the formula,

$$Q = \frac{TN \times TP - FN \times FP}{TN \times TP + FN \times FP} \qquad \text{… (3.11)}$$

The result will be a real number between -1 and 1. When Q = 1, there is a perfect positive correlation between the two events, what happens in one event always happens in the other and vice versa. When Q = -1, there is a perfect negative correlation between the two events, and the occurrence of one event invariably leads to the non-occurrence of the other (and vice-versa). When Q = 0, there is absolutely no correlation between the two events, one event happening or not happening does not influence the other event at all, total statistical independence.

The reference comprehensive IAQ assessment on 9 common indoor air pollutants listed in the HKEPD IAQ certification scheme would be used as the base case for comparison on the effectiveness of the proposed screening test. The database of assessment in 422 air-conditioned offices of Hong Kong would be referred to.

3.4 Selection of sampling time period

Long-term measurements on pollutant concentration are essential in exposure risk assessment to account for daily and seasonal variations. However, the long monitoring period required to obtain those data is a disadvantage for practical IAQ assessment of population. Short-term measurements (e.g. 8-h or less) are generally accepted as a less expensive sampling approach in terms of cost and time, though sometimes it is difficult to represent for the annual average concentration. For each of the sampling pollutant i, measurement time and duration should be chosen with a balance between measurement effort and accuracy. It is engrossed to find out the uncertainty in sampling time period adopted for pollutant concentration measurement, the differences between the collected results and the year-round pollutant profile due to seasonal variations.

In a long-term pollutant monitoring where a large number of measurements are sampled, however, the time-mean concentration μ_i of a pollutant i in the office is approximated by the long-term sample average concentration (arithmetic mean) $\Phi_{i,\infty}$, $\mu_i \approx \Phi_{i,\infty}$ which could better represent the exposure effects from chronic air pollution toxicants (Lange and Thomulka 2000). $\Phi_{i,\infty}$ in the occupied period τ_{of} (h) can be evaluated from the sample average of all sampled concentrations in the entire measurement period τ_p (days).

In a mechanically ventilated indoor environment, the concentration Φ_i (ppm) of pollutant i at a sampling point can be measured in a defined sampling period τ_m (h) with a start time t_a (h) and an end time t_b (h); and the time average concentration of the pollutant $\langle \Phi_i \rangle$ is used to describe the environmental condition at that location (Mui and Wong 2004), where N_{τ_m} is the number of sample measurements taken at a point in that period,

$$\langle \Phi_{i,\tau_m} \rangle = \frac{1}{\tau_m} \int_{t_a}^{t_b} \Phi_i(t)dt \approx \frac{1}{N_{\tau_m}} \sum_{j=1}^{N_{\tau m}} \Phi_j \;\; ; \begin{cases} t \in \tau_m = t_b - t_a \\ 0 < \Phi_i \leq \infty \end{cases} \qquad \ldots (3.12)$$

A sampling scheme employing a continuous sampling over the entire measurement period $\tau_m = \tau_{ab}$ in an occupied period of the office has been used as a reference to measure the time average pollutant concentration (HKEPD 2003). However, currently there is no standard guideline on which day(s) within a year should be selected for assessment as representative for long-term occupant exposure.

It is noted that there are seasonal variations in some outdoor pollutant levels, which also contribute to the probable annual concentration variations of indoor pollutants that originated from outdoors. However, it is hard to define an appropriate day(s) that the industry should follow, as IAQ monitoring should be conducted when it is needed. Also, to have a clear understanding of the probable range of seasonal variations needs few years data of pollutant level, a long-term continuous monitoring on assessment parameters is not always feasible, particularly in the cases of limited resources. Therefore, the annual variation would be covered in this thesis, but the discussions on various feasible sampling times are mainly focused on the variation within a day. And the common practically adopted one day 8-hour measurement is chosen as a basic measurement time unit for analysis of alternative schemes.

Wong and Mui proposed and evaluated four sampling schemes for indoor average pollutant concentration regarding the sampling time required and the probable errors induced, taking CO_2 as an example parameter (Wong and Mui 2007). Adopted the proposed sampling schemes as reference, further tests were conducted in this study for sampling of some other common assessment parameters.

In an office, there would be daily variations of pollutant concentration. The variation of different pollutants concentration could be principally characterized as decay, built-up, or randomly distributed during office hours, depends on the characteristics and the source of individual pollutant. For those building related contaminants, they are continuously emitted from the indoor sources, and their concentration increases if they are not removed or diluted. And it is assumed that in an office with a daytime operating ventilation system, building related contaminants normally will peak in the morning if the MVAC system is shut down at night as pollutants accumulated, and decay in occupied period with operation of a ventilation system. And for occupant related contaminants, concentration increases with occupancy in an occupied period, the rate of built-up depends on the difference in generation rate and removal rate, and concentration will normally peak in the afternoon. For other pollutants which are not constantly originated from the building itself or the occupants, their presence are characterized as random. Their concentrations vary randomly and are described by a normal distribution over a period of time.

A sampling scheme (denoted as ‘Scheme A’) employing a continuous sampling over a measurement period is the commonly adopted practice. In view of the pollutant characteristics, an alternative scheme (denoted as 'Scheme B') proposed that the average concentration $\left\langle \Phi_{B,\tau_m} \right\rangle$ can be determined from the average of two random measurement samples, one from each of the two time-equal sessions τ_{m1} (h) and τ_{m2} (h) in the normal occupied period τ_{of} (h), with an opposite reverse time sequence $\tau_{oa}=\tau_{ef}$ defined by the measurement start times t_a (h) and t_d (h) and end times t_b (h) and t_e (h) as shown in Figure 3.3,

$$\left\langle \Phi_{B,\tau_m} \right\rangle \approx 0.5\left\langle \Phi_{\tau_{m1}} \right\rangle + 0.5\left\langle \Phi_{\tau_{m2}} \right\rangle \qquad ; \ \tau_{m1} = \tau_{m2} = \frac{\tau_m}{2} \qquad \text{… (3.13)}$$

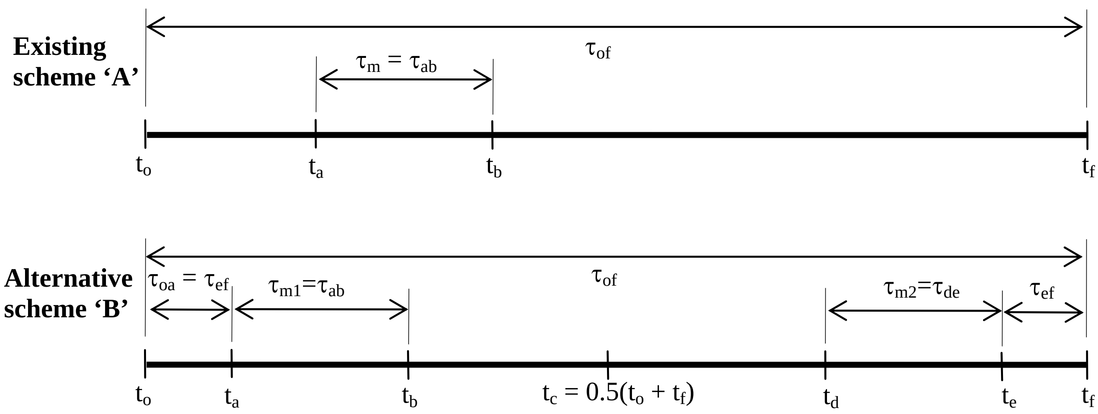


Figure 3.3: Sampling schemes

3.5 Selection of sampling point density and locations

Over an indoor space, pollutant concentration would not be evenly distributed depends on the sitting of pollutant sources and the air-conditioning system arrangement. The sampling location selection in the space would contribute to the assessment results of the spatial average pollutant concentration. Measuring the spatial dependence of pollutant concentrations in an indoor environment is useful for pollutant monitoring and exposure assessment especially over a large space. In an assessment, the number of sampling points required and the locations of measurement must be addressed.

Professional judgment in deciding on an appropriate sampling location r in a space can help obtaining the representative spatial average concentrations with given resources. When considering professional involvement in an IAQ assessment, it is believed that the contribution would be more significant in sampling location selection than sampling time selection. For an assessment, time average of pollutant concentration would be taken within the sampling period, and the variation of concentration over time is governed by the pollutant source characteristic and the mode of air-conditioning system operation which are usually typical in offices. However, the spatial concentration variation depends on various factors including the sitting of possible pollutant source and air supply and return path which is a complex outcome. Professional judgment may help in obtaining a representative spatial average concentration under certain number of sampling points.

Therefore, variations of IAQ assessment results at different sampling locations were analysed, to provide information for justification on choice of sampling schemes regarding the sampling point density and the professional choices of the sampling locations.

Pollutant concentrations within an office vary at different locations; their magnitude and variation can be used to study the significance when compared to the office sample-spatial average concentration. Particularly in a large indoor space, multiple sampling points are required to evaluate the sample-spatial average concentration {Φ} of a pollutant i given by an equation below, where r are the selected sampling points in the space,

$$\{\Phi_i\} = \frac{1}{r}\sum_{j=1}^{r}\langle\Phi_{ij,\tau_m}\rangle = \frac{1}{r}\sum_{j=1}^{r}\mu_{\tau,ij} \qquad \text{… (3.14)}$$

In the above equation, {Φ} can be taken as the spatial mean $\mu_{\Re}$ for the space, i.e. $\{\Phi\} \to \mu_{\Re}$, if the number of measurement points is 'sufficiently large', i.e. $r \to \infty$. However, only a finite maximum number of sampling points could be taken in a realistic assessment. In many assessment circumstances, a smaller number of sampling points would be taken in order to reduce the measurement effort and time for coarse measurements of acceptable measurement uncertainties. The required sampling points r in a space is specified by the following equation, where A_f (m^2) is the floor area of the space and A_s (m^2) is the sampling point density that floor area A_f requires for one sampling point,

$$r = \frac{A_f}{A_s} \text{ ; } A_s < A_f \qquad \text{… (3.15)}$$

Currently, the measurement locations are selected randomly over the large space. Judgment based on certain criteria is proposed for the location selection from the weighting of choices by professionals. Each of them would have different levels of representation on the spatial concentration of the space assessed.

In the study, the probable measurement errors of sampling with different number of sampling points, with randomly selected assessment locations or the professional choice of ‘representative’ sampling locations for IAQ assessment were evaluated. A number of selected ‘representative’ sampling location(s) r_s in an IAQ measurement would be determined by an IAQ assessor such that the assessed pollutant concentration would be ‘close’ to the sample-spatial average. The sample-spatial average concentration would be taken from any one of the combinations of r ‘representative’ sampling point(s) chosen from r_s among r_{max} probable sampling locations in the space according to the ascending order of choices density. And the schemes with randomly selected assessment locations, where choices density for all points are equal to 1, were also analysed for comparison. It is suggested that the sampling points can be reduced when taking the confidence level of assessment into account.

3.6 Sampling uncertainties

To understand the probable profile of the indoor air pollutants in offices, regional comprehensive survey results would be referred to. The probable range of the sample levels at different measurement locations will be determined with the development of different sampling schemes. Calculations will be repeated for different number of representative parameters, sampling time, and sampling point in these schemes. The calculated sample levels of various schemes will then be compared with the longitudinal or cross-sectional measurement of the pollutant concentration. The accuracy of the proposed assessment scheme of a number of selected representative parameters only in assessing office IAQ will be evaluated through comparing the assessed results between the proposed test and a 'reference IAQ assessment' on 12 parameters for Hong Kong offices. And the schemes with various sampling time and points on a parameter would be compared to an existing reference sampling scheme which measures an 8-h exposure concentration at a sampling point density of 500 m^2 floor area per assessment location. Assessed results from the existing reference sampling scheme are considered with acceptable accuracy.

The accuracy of the schemes can be assessed by the deviation of the sample levels from the long-term average level. The accuracy of a proposed scheme will be further evaluated by expressing the number of sample levels that with 'correct prediction' by the scheme as a percentage of the total number of samples made by the scheme. This percentage of probable errors deviated from the long-term or regional measurement could be interpreted as the confidence level that the sampled level is 'representative'. Comparing with the existing reference assessment scheme, variations of the potential reduction in measurement effort offered by different schemes at certain confidence levels will also be determined.

In particular, the accuracy of each proposed scheme can be evaluated by expressing the number of sample N_{μ_i} determined by the scheme that are considered to be 'correct prediction' as a percentage of the total number of samples made by the scheme N. This percentage can also be interpreted as the confidence level of assessment by the scheme.

$$\xi = N_{\mu_i} / N \qquad \dots (3.16)$$

In the case for assessing the accuracies of a scheme with selected representative parameters, 'correct prediction' can be interpreted as the unsatisfactory samples that are identified by the scheme, and N is the total number of unsatisfactory samples being assessed against parameters i.

For assessing the schemes with various sampling time or points, the number of 'correct prediction' samples would be counted as the number of sample means N_{μ_i} that fall within the probable error limits E of the average concentration determined by the scheme,

$$(1-E)\Phi_{i,\infty} \leq \Phi_i \leq (1+E)\Phi_{i,\infty} \qquad \ldots (3.17)$$

In the case of random sampling points, the sample-spatial average concentration in a measurement would be randomly taken from any one of the combinations of r sampling points, and from a maximum number of m sampling points. The total number of samples made by the scheme N is equal to the r-combination from the set of r_{max} sampling points, which is given by,

$$C(r_{max}, r) = \frac{r_{max}!}{r!(r_{max}-r)!} \qquad ; r_{max} > r \qquad \ldots (3.18)$$

Apart from the confidence level, the accuracies of the proposed measurement strategies were further evaluated with some statistical measures. The goodness-of-fit for the proposed assessment schemes in obtaining the long-term sample average concentration $\Phi_{i,\infty}$ of a pollutant i was further examined by the fractional bias (FB) and the normalized mean square error (NMSE), where N is the number of measured data from an assessment scheme for each parameter i, $\Phi_{ij,pr}$ is the predicted average concentration obtained by the scheme and $\Phi_{ij,ob}$ is the observed actual average concentration from the database of longitudinal or cross-sectional measurement.

$$FB_i = \frac{1}{N_i}\sum_{j=1}^{N_i}\frac{\Phi_{ij,pr} - \Phi_{ij,ob}}{\frac{1}{2}\left(\Phi_{ij,pr} + \Phi_{ij,ob}\right)} \qquad \ldots (3.19)$$

$$NMSE_i = \frac{1}{N_i}\sum_{j=1}^{N_i}\frac{\left(\Phi_{ij,pr} - \Phi_{ij,ob}\right)^2}{\Phi_{ij,pr}\Phi_{ij,ob}} \qquad \ldots (3.20)$$

FB is a measure of the over- or under-prediction of a model; it measures how large the difference between observations and model output is relative to the average magnitude of the observed and modelled values. For a perfect model FB = 0, while if FB > 0 (< 0) the model output on average overestimates (underestimates) the observed concentration values. NMSE is a measure of the relative fit of a model to the measured data, the smaller the NMSE is, the better model output agrees with observations.

3.7 Conclusion

This chapter discussed the framework and methodology of this study. As the accuracy of an assessment protocol to determine the IAQ acceptance of a space can be quantified as the combination of the uncertainties associated with the choices of (1) assessment parameters, (2) sampling times, and (3) sampling points, the development and rationale of suggested probable assessment schemes of the protocol were presented in terms of these three factors.

For assessment parameters, the representation of a selected parameter will be discussed under two main categories: (1) a parameter has significant contribution to IAQ dissatisfaction; (2) a parameter surrogates to air pollution control system performance. The assessment results with those representative parameters were proposed to be expressed by a screening process using an IAQ index for judgment of IAQ acceptance. Feasibility of the screening process will be investigated and discussed with reference to database of exposure levels of some listed indoor environmental parameters.

For each of the sampling pollutant, sampling time and duration, and sampling point density and locations are chosen with a balance between measurement effort and accuracy. The uncertainties of various sampling schemes will be analysed using the year-round longitudinal measurement results. A part of the analysis is the required measurement period by a proposed scheme of two random sample average from two time-equal sessions with an opposite reverse time sequence within the occupied period. And the other part of the analysis is the difference for schemes with various number of sampling points, selected by random or professional judgment. The evaluation methods for quantifying the uncertainties of the schemes were also defined in this chapter.

Chapter 4

Database development for long-term measurement in air-conditioned buildings

4.1 Planning for field measurements

In this study, offices IAQ in Hong Kong were taken as a typical example to study and analyse the feasibility of various sampling schemes in the IAQ assessment protocol. A structural database of indoor environmental parameters in air-conditioned offices was used to determine the parameters, to test the feasibility and to quantify the accuracy of sampling schemes with various sampling parameters selected, sampling time and sampling points in the protocol.

To understand the current levels of various major indoor air pollutants and the dominant parameters that cause unsatisfactory IAQ, a regional survey of common indoor parameters are needed. In defining the sampled parameters, current practices suggested in codes and guidelines were considered. As discussed in Chapter 2, different counties issued guidelines on IAQ assessment where different parameters are included. Within those, the HKEPD IAQ certification scheme covered the most pollutants and has relatively high concentration restriction levels. Therefore, the measurement requirements on the 12 parameters stated in the scheme were adopted as a baseline for comparison in this study. The 8-hour exposure concentration levels for ‘Excellent’ and ‘Good’ IAQ were referred.

To evaluate the effects of selecting a sampling time and also duration within the occupied period, the probable pollutant concentration variation within a day should be taken into account. This would be best presented by an annual measurement on typical pollutants which include all types of variation as possible. Common air pollutants that were easy to be measured, surrogate indicators of IAQ problems, and with known possible sources and corresponding control strategies were given higher priorities in assessment parameter selection. Based on the pollutant characteristics, there maybe build-up, decay, or random variation of pollutant concentration. In this study, a one-year measurement of two common indoor pollutants representing build-up and decay characteristics, i.e. CO_2 and radon were used for analysis. These two pollutants normally show greater differences in concentration within a working day. They are also typical occupants or building related pollutants commonly found indoors.

Radon is a natural indoor contaminant from building materials and outdoor environment but not a by-product of the occupants' activities. Since the contaminant 'radon' would be diluted by the ventilation air from outdoor diverted by the mechanical ventilation system, the radon concentration would be dependent on the ventilation rate, and the seasonal variations of the environmental conditions (e.g., relative humidity, wind speed). Radon was not considered among the causes of Sick Building Syndrome which is associated with short-term symptoms. However, radon is of concern because of its long-term human related health effects (Jones 1999). It can be detected by the presence of its short-lived progeny and the radiations emitted in the progeny's decay processes. The decay products of radon have been recognized as important indoor pollutants and classified as major environmental pollutants in buildings (Gamo et al. 2003, USEPA 1992). Radon is undoubtedly a concern of public health, it has been identified that by far the greatest source of exposure to ionizing radiation arises from the inhalation of radon indoors (Darby 1995).

In reality, CO_2 concentration significantly contributes to indoor air pollution of a typical air-conditioned environment and thus has been selected as a surrogate indicator for assessing the IAQ (ASHRAE 2004, CEN 1998, Persily 1997). Its present directly related to occupants' activities. Monitoring CO_2 concentration allows us to estimate the occupants' comfort in a space and the installed ventilation system's performance. A number of relationships were suggested between indoor CO_2 concentration and IAQ, such as the health effects of elevated CO_2 concentrations, the impact of CO_2 concentration on the occupants' perceptions of an indoor environment, the relationship between CO_2 concentrations and other contaminants, and the association between CO_2 and outdoor air ventilation rate (ASHRAE 2004, Möhle et al. 2003, Hoskins 2003).

Finally to study the spatial concentration variation on an office floor for determining appropriate sampling points, therefore, CO_2 was also selected as an indicator. It was monitored at several comparable spatial locations on the same entire office floor over a year. As CO_2 levels closely related to occupancy level and the design of ventilation system which are knowledgeable to engineers or building management team, selecting CO_2 as example in sampling locations for pollutant levels can show the best scenario that professional can judge for, and the maximum benefit from professional judgment can be demonstrated.

Therefore, the database used includes a one-year measurement of CO_2 and radon concentrations on an entire office floor at several comparable spatial locations, and cross-sectional measurements at 422 offices on 12 indoor parameters as stated in the HKEPD IAQ certification scheme.

In addition to the above available database, surveys were conducted in this study in conjunction for analysis of the schemes and protocol. In this study, variations of IAQ assessment results at different sampling locations selected were investigated. Professionals participating in IAQ engineering were interviewed regarding the choice of sampling locations in an air-conditioned space. Associations between the professional choices of the sampling locations and attributes of the assessors were examined to quantify the uncertainties of the IAQ assessment results. Furthermore, another cross-sectional survey was conducted in other air-conditioned offices in Hong Kong for final evaluation of the assessment protocol, and demonstration of application. Similar to the first regional survey, 12 parameters were monitored following the requirements in the HKEPD IAQ certification scheme. Table 4.1 summarized the available databases used and new surveys conducted in this study.

Table 4.1: Summary of existing database and new surveys

Type	Parameter(s)	Sampling period	Details of samples	Purpose
Existing database				
regional measurement	12 parameters as stated in the HKEPD IAQ certification scheme	8 hours for each sample	422 offices in Hong Kong	To identify and analyze schemes with various choice of representative assessment parameters
long-term measurement	radon	1 year during working hours	1 point in an open-plan office	To evaluate schemes with various sampling time period
long-term measurement	CO_2	1 year during working hours	17 points in an open-plan office	To evaluate schemes with various sampling time period, sampling point density and locations
New surveys				
regional measurement	12 parameters as stated in the HKEPD IAQ certification scheme	8 hours for each sample	103 Grade A offices in Hong Kong	For final evaluation of the assessment protocol
interview survey	choice of representatives IAQ assessment locations	--	19 professionals in the field of IAQ	To evaluate sampling locations selection with professional judgements

4.2 Cross-sectional pollutant concentration measurements

Measurement details

A proper understanding of the indoor air pollutant concentrations on the premises can be found from a longitudinal monitoring process and cross-sectional measurements for a number of spatial locations. To be used for analysis, a regional cross-sectional measurement of the 12 indoor environmental parameters conducted in 422 offices in Hong Kong was referred. The 12 assessment parameters include 9 common indoor air pollutants, which are 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), and 3 thermal comfort parameters, temperature (T), relative humidity (RH) and air velocity (V). However, measurements for the IAQ parameters on the same site could hardly be extended beyond the scheme's requirements due to occupant disturbance (HKEPD 2003). Some basic assumptions and exclusions were made in the database set-up: the building age of the premises did not contribute a specific source of pollution to the sampling results; the classification of pollution sources was valid on all of the sampling sites; the human activity patterns were similar on all sampling sites within the same type of microenvironments; and the building structural type and ventilation layout had less significant effects on the measurements. The contributions of these factors were 'lumped' in an error term of the proposed model in this study.

The sample size necessary for estimation within 95% confidence interval is 385, therefore, the sample size of 422 in the regional survey conducted was 'large' enough in representing the overall picture of the local pollutant levels in offices of Hong Kong. The samples were randomly chosen in a way that they could cover all regions of office development as well as various types and ages of premises and ventilation systems in Hong Kong. The sampling premises were selected with a building age about ten years such that the building style, materials used and the period after construction of each of them did not vary much from the others. All the selected locations were in commercial office buildings among which human activities and dress codes were similar. They included a range of open-plan offices from conference rooms to small individual offices. Their sizes were from 10 m^2 to 300 m^2. The schedule of the air-conditioning operation was well-defined and sufficient for the study to be focused on the indoor air contaminant parameters than other co-founding factors that would affect the IAQ.

To show the application of the protocol, an IAQ survey was performed in this study at another 103 Grade A offices, with the comprehensive IAQ assessment of 8-hour average concentrations of the 12 indoor air parameters as reference. The selected offices are located in the major commercial centres of office development in Hong Kong. The samples included a range of open-plan offices from conference rooms to small individual offices. In these offices, central air-conditioning system is provided, and the design and maintenance of the air-conditioning systems would be better in general among all the offices in the region. There are also regular cleanings of systems and air ducts, replacement of filters, and use of air-cleaners in some offices. Thus, better IAQ is expected in the Grade A offices when compared with the randomly chosen offices in the region. This would demonstrate the feasibility of the proposed protocol when applying it in different IAQ environment.

In each office, 8-hour measurements of the 12 indoor environmental parameters were conducted in the working days following the practice stated in the IAQ certification scheme of HKEPD. All sampling methods applied were based on two assessment approaches namely real-time and integrated as recommended in the GN. For the required detection level of an instrument, it is in the range that can indicate the well-being of the occupants and enable the evaluation of any health impacts. For data validation, the lower detection limit is assessed before going into the field; ideally it should be 10% of the recommended IAQ objective or below. All instruments, listed in Table 4.2, were calibrated prior to the measurements (Chao et al. 2001). An 8-hour continuous monitoring for CO_2, CO, temperature, relative humidity, air velocity, RSP, O_3, HCHO, TVOC and radon was adopted. All of these parameters were measured by hand-held or easily carried equipment for laboratory grade accuracy. For NO_2, air sampling bags made of Tedlar film were used to collect air samples 4 times a day evenly distributed over the 8-hour interval. Each sample period lasted for 5 min. The NO_2 in the collected air would then be analysed by a chemiluminescence based NO_2 analyser. For bacteria sampling, four 5-min sample periods evenly distributed over the 8-hour interval were collected. The intermittent measurement strategy was needed since continuous measurement is not practical for bio-aerosol sampling. Samples were collected with an impactor, allowed bacteria to grow on suitable agar medium, and perform bacterial count after culturing.

Table 4.2: Summary of the selected equipment specifications

Parameter	Principle	Accuracy	Resolution	Response time	Time constant
Carbon Dioxide (CO_2)	Real-time non-dispersive red (NDIR) analyzer	±3% of reading, ±50 ppm	1 ppm	20 s	Adjustable from 2 to 60 s
Carbon Monoxide (CO)	Electrochemical oxidation devices	±3% of reading or 3 ppm, whichever is greater	1 ppm	<60 s to 90% of final value	Adjustable from 2 to 60 s
Particulate (RSP)	Light scattering	NA	1% of reading or 0.001 mg/m^3, whichever is greater	NA	Adjustable from 1 to 60 s
Ozone (O_3)	Heated-metal oxide semiconductor (HMOS) sensor	±0.5 ppm	0.01 ppm	Within 10 s (<0.1 ppm); A few seconds (>1 ppm)	NA
Nitrogen Dioxide (NO_2)	Sampling bag collection and Chemiluminescence	±1% of end-scale deflection	0.001 ppm	7 s	2 to 100 s selectable (range dependent)
Formaldehyde (HCHO)	High performance liquid chromatography (HPLC)	NA	0.01 ppm	1/3 full scale in less than 30 s	NA
Total Volatile Organic Compounds (TVOC)	Photo-ionization detection method	±20 ppb or 10% of reading	1 ppb (0-999 ppb); 0.01 ppm (0.01-9.99 ppm); 0.1 ppm (0.1-199.9 ppm)	<5 s	NA
Radon (Rn)	Solid state alpha detector	NA	Monitor: 0.4 counts/min/pCi/l; Sniffer: 0.2 counts/min/pCi/l	NA	NA
Airborne Bacteria Count (ABC)	Sampling with impactor and allow bacteria to grow on suitable agar medium	NA	NA	NA	NA
Room Temperature (T)	Thermistor	±0.6 ^oC	0.1 ^oC	120 s	Adjustable from 2 to 60 s
Relative Humidity (RH)	Polymer capacitor	±3% RH	0.1% RH	20 s	Adjustable from 2 to 60 s
Air Velocity (V)	Hot-wire anemometer	±3% of reading or ±0.015 m/s, whichever is greater	0.01 m/s	NA	1, 2, 5, 10, 15 and 20 s

NA = not applicable

Dataset A: IAQ in 422 sample offices

Table 4.3 shows a summary of the database of the 12 parameters for the 422 offices; the measured ranges, arithmetic means (AM), standard deviations (SD), geometric means (GM) and values of 95% confident interval (CI) of these parameters. They demonstrated that each of these parameters could be described by a geometric distribution ($p > 0.9$, Chi-square test). And Figure 4.1 shows the measurement results of the 12 parameters for the 422 offices. The levels of each parameter were plotted against the levels of the other 11 parameters, showing their associations.

Judging the IAQ of these offices using the 'Excellent' and 'Good' levels according to the HKEPD IAQ certification scheme as a reference, among the survey samples (422 offices), 414 offices could not achieve the 'Excellent' IAQ level while 201 could not achieve the 'Good' level. The fractions of offices in Hong Kong with unsatisfactory environments with respect to the two recommended classes of each parameter were also determined and shown in Table 4.3.

The environmental parameters contributed to the unsatisfactory indoor office environment, according to HKEPD classification, were ranked according to the individual pollutant failure rate $\hat{P}$, for both 'Excellent' and 'Good' levels, and shown in Figure 4.2. The top five contributors were TVOC, RSP, HCHO, ABC and CO_2 for 'Excellent' level; and TVOC, ABC, RH, HCHO and O_3 for 'Good' level. On the IAQ side, TVOC and ABC contributed most to the unsatisfactory rate as compared to the other seven parameters.

Substances of particular importance are known as organic compounds that originate in sources like paints, varnishes, solvents and preservatives in modern buildings. TVOC were the top most pollutant causing unsatisfactory IAQ in the surveyed offices (i.e. 74% and 16% failed in the ‘Excellent’ and ‘Good’ levels respectively). Formaldehyde (HCHO), which comes from new furniture or materials used in renovation work, was one of the parameters found to have exceeded the proposed IAQ objectives (58% failed in the ‘Excellent’ level and 6% failed in the ‘Good’ level).

An airborne bacteria count (ABC) in an indoor environment is a good indicator of the cleanliness of the MVAC system and one of the important parameters to evaluate IAQ. As shown in the database, ABC did not fulfil the IAQ criteria (i.e. 49% and 15% failed in the ‘Excellent’ and ‘Good’ levels respectively). This is a matter of concern because of the various human health and comfort implications associated as the MVAC system is also responsible for providing a path to transport micro-organisms from the locus of contamination to occupants in the vicinity of the buildings (Law et al. 2001, Seino et al. 2005). Since a large variety of biological particles are present in the count, the health effects of inhaling these particles might be significant. Their role in inducing illnesses through immune mechanisms, infectious processes, and direct toxicity was considered (Jones 1999).

On the thermal comfort side, relative humidity (RH) was the one contributed most to the unsatisfactory rate as compared to the other two parameters, room temperature (T) and air velocity (V). It should be noted that typical air-conditioning systems in Hong Kong are installed with air temperature control and diffusers according to the air diffusion performance requirements (Chow and Wong 1994, 1998), but generally without relative humidity control, e.g. terminal reheat coil or spray chamber. Also as recommended, the most effective ways to control indoor air pollutants in premises are source control and dilution by ventilation. Most developers and maintenance staff have adopted the approach of increasing fresh air quantity to enhance IAQ. However, it was shown that most existing air-conditioned systems had not yet been renovated to cater for the increased fresh air loads. In the measurements, some of the parameters seldom exceeded the recommended criteria, e.g. CO; and some contributed to a relatively low unsatisfactory rate, e.g. Rn and V.

Table 4.3: Survey results on 12 parameters (Sample size = 422 offices)

No.	Parameter (unit)	Criteria for		Sample average concentration (Standard deviation)	Geometric mean concentration (95% range)	Observed unsatisfactory rate for	
		Excellent	Good			Excellent, % (CI = 95%)	Good, % (CI = 95%)
1	CO_2 (ppm)	<800	<1,000	660 (159)	642 (409-1009)	18% (15-22%)	3% (1-4%)
2	CO ($\mu g\ m^{-3}$)	<2,000	<10,000	1002 (332)	942 (463-1919)	0.2% (0.0-0.7%)	<0.2%
3	RSP ($\mu g\ m^{-3}$)	<20	<180	33 (21)	27 (8-95)	65% (61-70%)	<0.2%
4	NO_2 ($\mu g\ m^{-3}$)	<40	<150	28 (16)	25 (9-70)	16% (12-19%)	<0.2%
5	O_3 ($\mu g\ m^{-3}$)	<50	<120	46 (40)	36 (7-197)	18% (15-22%)	5% (3-7%)
6	HCHO ($\mu g\ m^{-3}$)	<30	<100	54 (113)	32 (5-218)	58% (53-62%)	6% (4-9%)
7	TVOC ($\mu g\ m^{-3}$)	<200	<600	397 (341)	291 (55-1528)	74% (69-78%)	16% (12-19%)
8	Rn (Bq m^{-3})	<150	<200	52 (39)	40 (9-171)	2% (1-4%)	0.2% (0-0.7%)
9	ABC (CFU m^{-3})	<500	<1000	580 (392)	447 (96-2081)	49% (44-53%)	15% (12-19%)
10	T (°C)	20-25.5	<25.5	22 (2)	22 (18-26)	12% (9-15%)	2% (1-4%)
11	RH (%)	40-70	<70	59 (9)	59 (43-80)	14% (10-17%)	12% (9-15%)
12	V (ms^{-1})	<0.2	<0.3	0.09 (0.07)	0.06 (0.01-0.33)	7% (5-9%)	2% (1-4%)

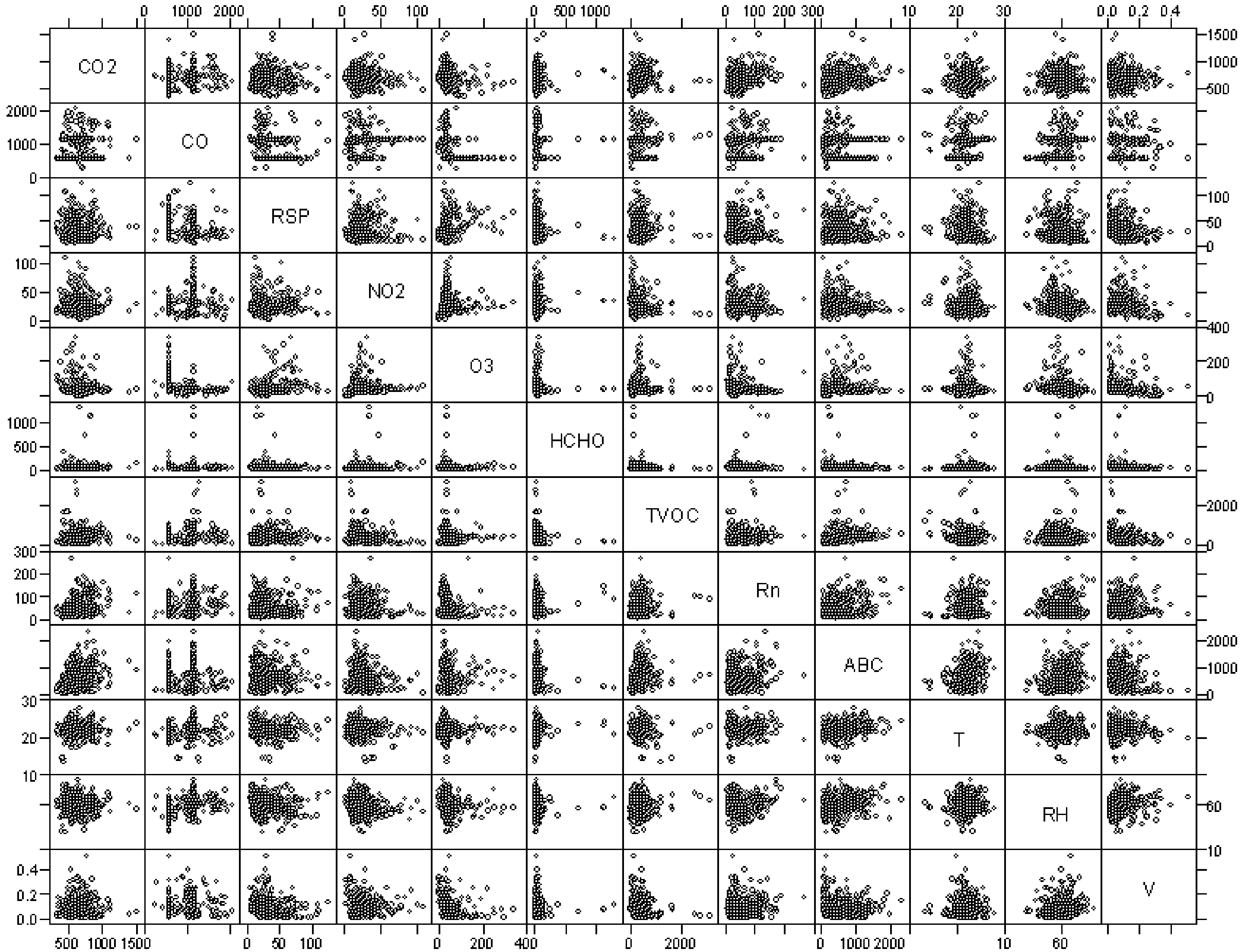
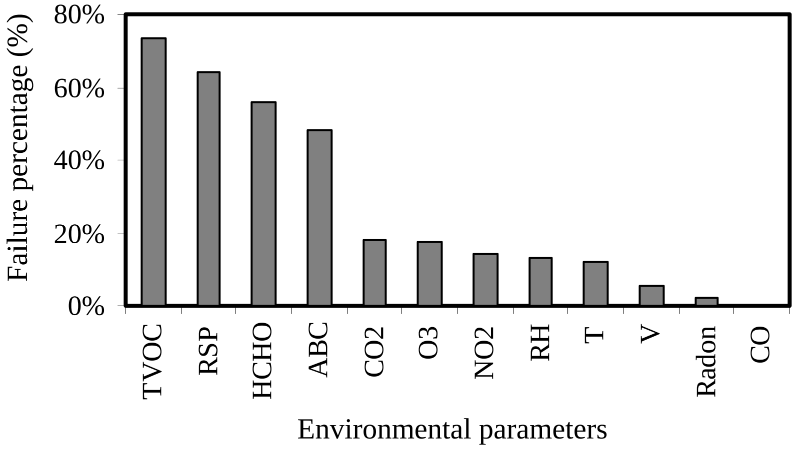
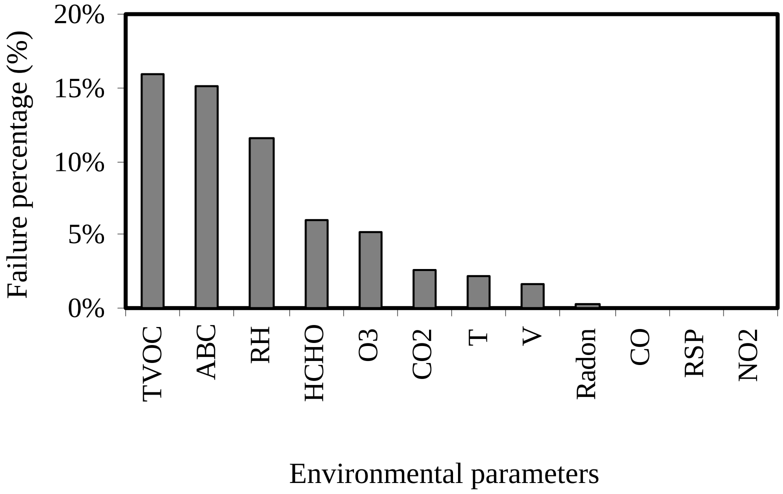


Figure 4.1: IAQ and thermal comfort parameters for Hong Kong offices



(a) Excellent



(b) Good

Figure 4.2: Contribution of assessment parameters to IAQ dissatisfaction for offices (Sample size = 422 offices)

Dataset B: IAQ in 103 Grade A offices

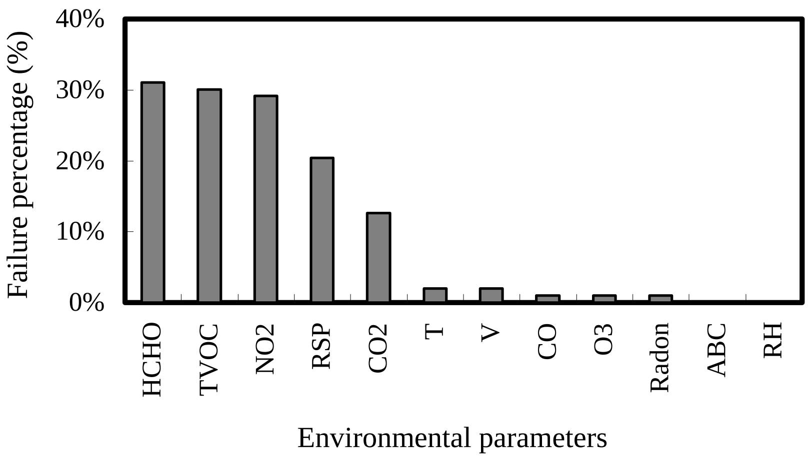
New information of another set of office samples was collected from the survey. Table 4.4 shows the measured levels of the 12 common indoor air parameters in the 103 Grade A offices; the measured ranges, arithmetic means (AM), standard deviations (SD), geometric means (GM) and geometric standard deviations (GSD) of these parameters. The mean levels of the nine common pollutants were lower than those measured for average offices from the 422 regional data.

Assessing the IAQ of these offices using the ‘Excellent’ and ‘Good’ levels in the HKEPD IAQ certification scheme as reference, among the 103 offices, 46 offices could not achieve the ‘Excellent’ IAQ level while 35 could not achieve the ‘Good’ level. The fractions of those Grade A offices with unsatisfactory environments with respect to the two recommended classes of each parameter were also determined and shown in Table 4.4. The pollutant levels of the samples did not exceed the HKEPD recommended ‘Good’ level values in general, except for excessive TVOC in few office samples. This surveyed group of Grade A offices shows different levels and contribution of assessment parameters to IAQ dissatisfaction, compare with the regional database of all offices.

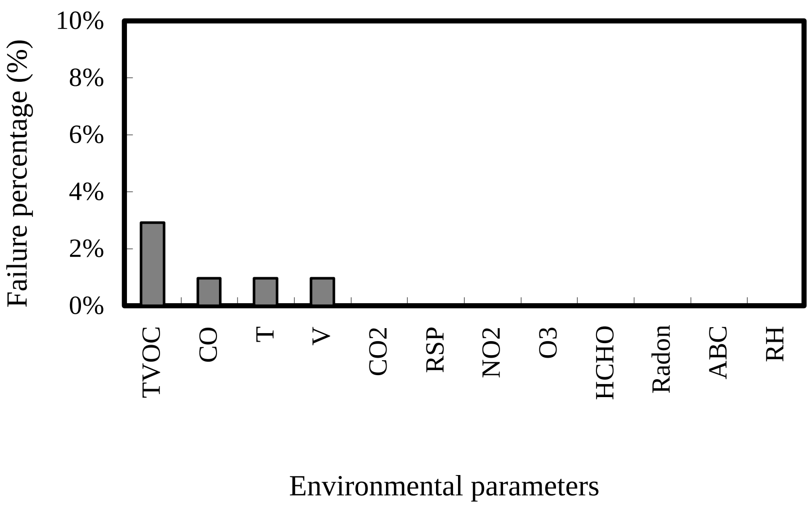
The individual pollutant failure rate was ranked, for both ‘Excellent’ and ‘Good’ levels, and shown in Figure 4.3. The top five contributors were HCHO, TVOC, NO_2, RSP, and CO_2 for ‘Excellent’ level; and for ‘Good’ level, TVOC contributed most to the unsatisfactory rate as compared to the other parameters. Within those top most contributors of the average offices in the region, ABC levels were comparatively lower in these Grade A offices which can be explained by better air-conditioning system cleanliness in those offices.

Table 4.4: Survey results on 12 parameters of Grade A offices (Sample size = 103 offices)

No.	Parameter (unit)	Range	Sample average concentration (Standard deviation)	Geometric mean concentration (Standard deviation)	Observed unsatisfactory rate for	
					Excellent, %	Good, %
1	CO_2 (ppm)	455-970	650 (115)	641 (1.2)	13%	<1%
2	CO (μg m^{-3})	0-1977	514 (488)	291 (4.2)	1%	1%
3	RSP (μg m^{-3})	6-38	16 (6)	15 (1.4)	20%	<1%
4	NO_2 (μg m^{-3})	4-94	25 (22)	14 (3.2)	29%	<1%
5	O_3 (μg m^{-3})	0-61	17 (9)	13 (2.8)	1%	<1%
6	HCHO (μg m^{-3})	3-92	21 (20)	13 (2.5)	31%	<1%
7	TVOC (μg m^{-3})	0-1318	198 (202)	141 (2.4)	30%	3%
8	Rn (Bq m^{-3})	1-153	22 (32)	12 (2.6)	1%	<1%
9	ABC (CFU m^{-3})	60-488	193 (93)	174 (1.6)	<1%	<1%
10	T (°C)	19.5-25.6	22.6(1.1)	22.5(1.1)	2%	1%
11	RH (%)	42-69	52(5)	51(1.1)	<1%	<1%
12	V (ms^{-1})	0.01-0.31	0.08(0.05)	0.07(1.85)	2%	1%



(a) Excellent



(b) Good

Figure 4.3: Contribution of assessment parameters to IAQ dissatisfaction for offices (Sample size = 103 offices)

4.3 Long-term pollutant concentration measurement

A long-term indoor pollutants measurement was conducted on an entire floor, chosen an in-use office of Hong Kong. The one-year CO_2 and radon measurement was conducted from the period of June 1998 to May 1999 in a building constructed in the early 1970s (Mui and Wong 2004, Mui et al. 2006). The building comprised three floors of podium and 51 floors of predominantly open-plan offices. It was served by a Variable Air Volume (VAV) system, and was divided into four main zones, each served by an independent air handling unit (AHU). The fresh air intakes and the primary air handling units were located on the mechanical floor, and the system was designed to supply 20% fresh air and 80% recirculated air mix. The mixed air would pass through the filter before entering the space. In this study, an entire floor of the building, served as an open-plan office, was selected. A long-term survey of the indoor air pollutant concentrations and ambient conditions in the building was conducted at a number of comparable spatial locations on the floor. All measurements were performed in the occupied period during working hours 0900 to 1700 for all working days throughout the year.

Radon measurement

In the open-plan office, the measurements of indoor radon transient levels were taken at a location in the office, the radon concentrations at that location was monitored continuously. The instrument used is the same type of radon monitor as in the regional survey, with the operation principle of electrostatic collection of alpha emitters on a solid state detector with spectroscopic analysis. In the continuous monitor mode, the instrument measures the EPA action level of 148 Bq m^{-3} in one hour with a standard deviation of 10%. The operating range of temperature is 0 ^{o}C to 40 ^{o}C and that of humidity is 0% to 80%. The instruments were calibrated prior to the measurement. To ensure the collected data is within acceptable accuracy, periodic checking and comparison of the monitoring devices and instruments are necessary. Within the period of study, a comparison test was performed with other calibrated instruments in order to ensure the reliability of the data.

CO_2 measurement

A total of 17 comparable spatial locations were selected to monitor the CO_2 concentrations in a year in order to maximize the sampling points in the office. The locations are as shown in Figure 4.4. The selections of the 17 measurement points were random and spread evenly over the office floor. They included open-plan workstations, individual rooms, conference rooms and also the reception area, their occupant loads were different. The details of the locations are summarized in Table 4.5, including also the locations of supply or return air diffusers.

A multipoint monitoring system, consisted of a multi-gas monitor with a multiplex-sampler and a multipoint sampling panel connected with rubber tubing, was used to collect the CO_2 concentrations at these locations in the office. Up to 6 locations could be measured simultaneously. The multi-gas monitor was calibrated with an accuracy of ±2 ppm for measuring a CO_2 concentration at 200 ppm. The detection limit for CO_2 was 3.4 ppm. For each sampling period (e.g. 3-4 days) throughout the year, the multiplex-sampler was scheduled to collect the concentrations at 6 of the 17 sampling locations. The sampling process was automatically controlled by a software to cover all the 17 locations, and the data was stored in a computer for further analysis.

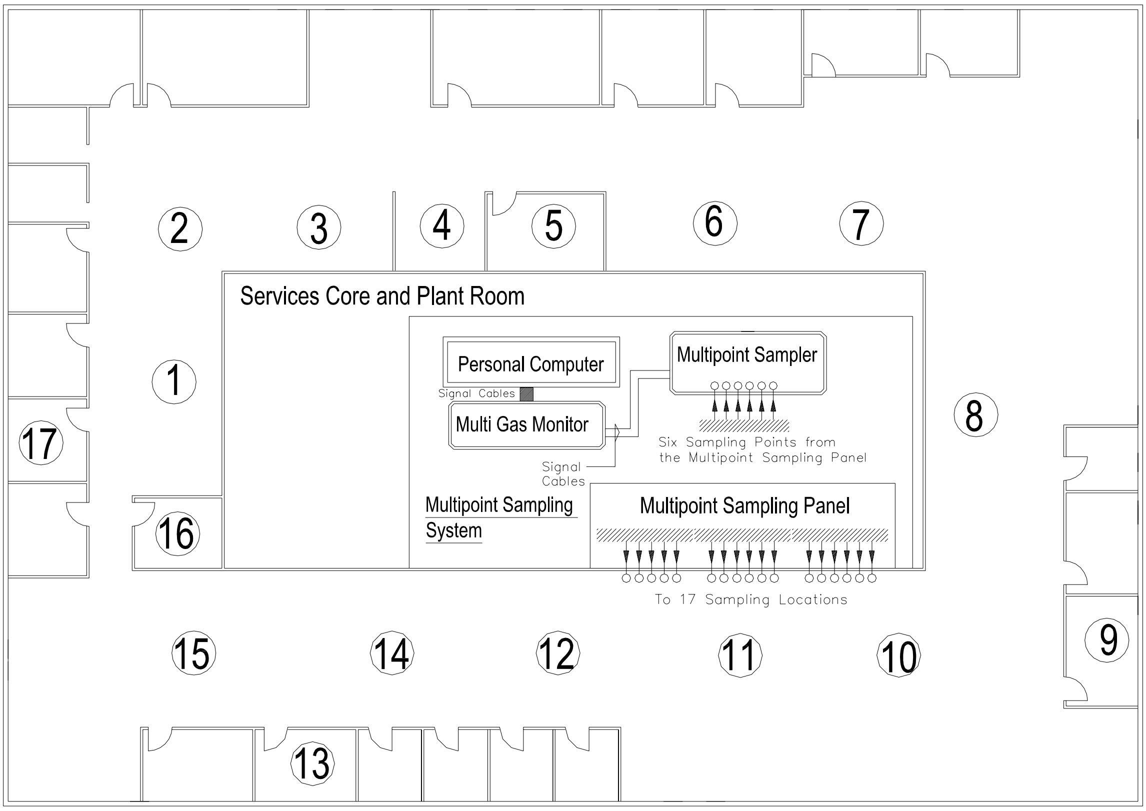


Figure 4.4: The office layout and sampling point locations

Table 4.5: Sampling locations for IAQ measurements

Point No.	Type of location	Characteristics of the workstation	
		Occupant load	Types of diffuser located above the workstation*
1	Open-plan	Low	SA
2	Open-plan	Low	SA and RA
3	Open-plan	Low	SA and RA
4	reception	varied (influenced by the staff and visitors)	SA and RA
5	conference room	varied (depends on the activities)	RA
6	Open-plan	average	SA and RA
7	Open-plan	average	SA and RA
8	Open-plan	high	SA and RA
9	single room	Low	SA and RA
10	Open-plan	high	SA and RA
11	Open-plan	high	SA and RA
12	Open-plan	high	SA and RA
13	single room	Low	SA and RA
14	Open-plan	varied (near the main entrance of the floor)	SA and RA
15	Open-plan	average	RA
16	conference room	varied (depends on the activities)	SA and RA
17	single room	Low	SA and RA

*SA = supply air grille; RA = return air grille

Variation characteristic of selected indoor air pollutants in an open-plan air-conditioned office

Data of the measured concentrations from the one-year measurement of the two selected pollutants were collected, formatted, and analysed for determining the long-term variations of pollutant concentrations, at one location for radon, and at 17 locations for CO_2 averages.

For the spatial variation of pollutant concentrations over an office floor, Figure 4.5 shows the sample-time average CO_2 concentrations at all 17 sampling locations described by a normal distribution ($p > 0.9$, Chi-square test). CO_2 concentrations within an office vary at different locations; their magnitude and variation can be used to study the significance when compared to the office sample-spatial average CO_2 concentration. The measurement period of one year was considered to be sufficient and the sample-time average CO_2 concentration $\langle \Phi \rangle$ was taken as the time-mean CO_2 concentration μ_τ at that location as shown in Figure 4.5. The mean and standard deviation of CO_2 concentration for the duration of the experiment at 17 locations in the open-plan office are summarized in Table 4.6.

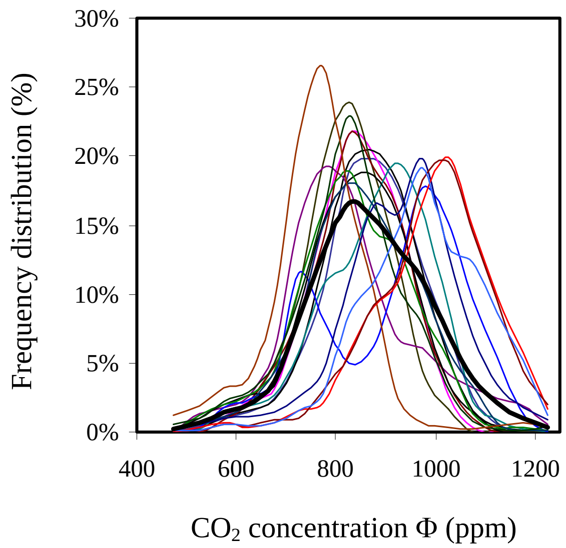


Figure 4.5: Frequency distribution of indoor CO_2 concentrations at 17 locations in the office during working hours (Sampling period τ = 1 year)

It was found that the standard deviations of CO_2 concentrations for the duration of the experiment varied between σ_τ = 89 ppm and 149 ppm, with the minimum and the maximum year-means of μ_τ = 766 ppm and 1012 ppm respectively. The sample-spatial average $\{\Phi\}$ and the standard deviation of CO_2 concentrations found in the office were 868 ppm and 135 ppm respectively (with r = 17; τ = 1 year). This average was taken as the spatial mean μ_{CO2} for the space, i.e. $\{\Phi\} \rightarrow \mu_{CO2}$, as the number of measurement points was 'sufficiently large', i.e. $r \rightarrow \infty$, i.e. μ_{CO2} = 868 ppm.

Table 4.6: Long-term average CO_2 concentrations at 17 sampling points

Point No.	Type of workstation	Mean μ_τ (ppm)	Standard deviation σ_τ (ppm)
1	open plan office	872	103
2	open plan office	841	95
3	open plan office	865	98
4	reception	821	89
5	conference room	853	176
6	open plan office	845	96
7	open plan office	880	111
8	open plan office	910	146
9	single room	840	111
10	open plan office	835	117
11	open plan office	852	115
12	open plan office	828	115
13	single room	766	105
14	open plan office	939	136
15	open plan office	1012	148
16	conference room	1007	147
17	single room	991	149

For the time variation of pollutant concentrations, Figure 4.6 shows the normalized radon and CO_2 concentrations in the office occupied zone during office hours 0900 to 1700 of the overall measurement period τ_p (day). The results demonstrated a 'sufficiently long' measurement period in obtaining the time-mean pollutant concentrations μ for the office using the average of all sampled concentrations. They also showed that the variation of the long-term average level $\langle \Phi_i \rangle$ was less than 5% for radon in a measurement period of $\tau_p \geq$ 185 days, and less than 2% for CO_2 in $\tau_p \geq 12$ days. A relatively long period was required for determining the former as there was a large fluctuation of radon concentration recorded in the office.

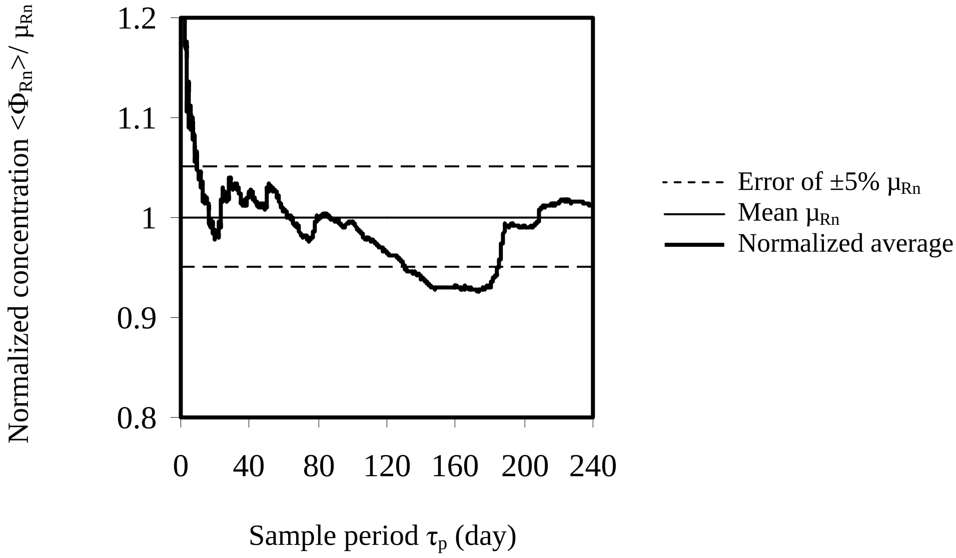
Figure 4.7 shows the cumulative frequency distributions of the measured radon and CO_2 concentration normalized with time-mean concentrations. The results for the two sessions of the occupied period τ (hr), i.e., session 1 from time 0900 to 1300, and session 2 from time 1300 to 1700, were compared. It was reported that, as expected, the radon concentration peaked in the morning session but the CO_2 concentration peaked in the afternoon. Figure 4.7 also shows that the sampled radon distribution skewed to the left and could be approximated by a log-normal distribution, however, CO_2 levels in the space would be better described by a normal distribution.

The average radon concentration in the morning (session 1) $\Phi_{\tau_{m1}}$ =87 Bq m^{-3} is higher than that in the afternoon (session 2) $\Phi_{\tau_{m2}}$ =116 Bq m^{-3}. Therefore, the mean radon concentration over the occupied period Φ_τ (Bq m^{-3}) should be between these two values. The radon concentration is approximated by a log-normal distribution, with mean of 98.4 Bq m^{-3} and the range indicated by ± a standard deviation of 60.8-159 Bq m^{-3}; or expressed by normal distribution with mean of 110.1 Bq m^{-3} and the range indicated by ± a standard deviation of 49-172 Bq m^{-3}. The sample-spatial average and the standard deviation of CO_2 concentrations found in the office were 868 ppm and 135 ppm respectively, with the average CO_2 concentration in the morning (session 1) $\Phi_{\tau_{m1}}$ =854 ppm lower than that in the afternoon (session 2) $\Phi_{\tau_{m2}}$ =885 ppm.

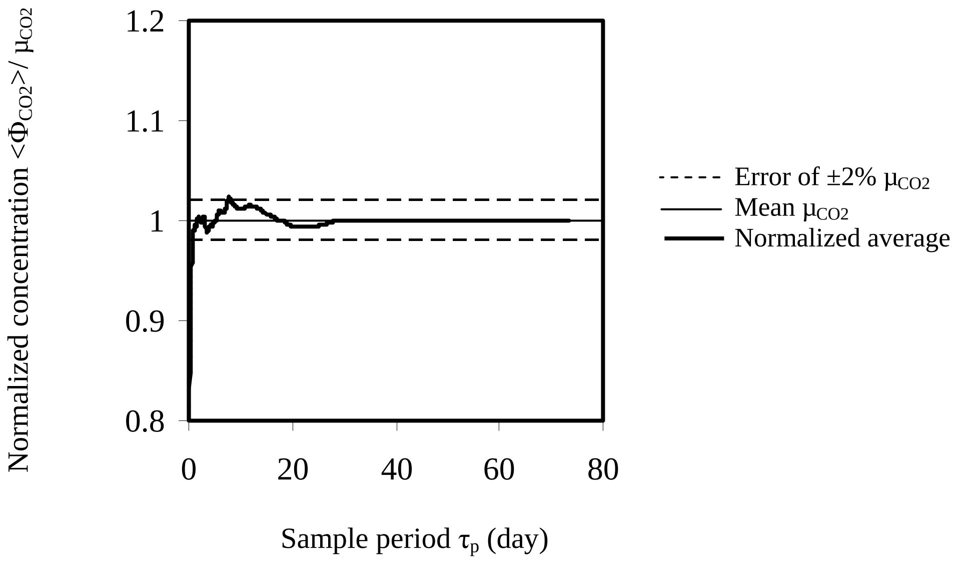
Figure 4.8 shows the average daily variations of pollutant concentrations in the office as a percentage of the maximum concentration measured in a day. It was reported that these variations for radon and CO_2 were 60% and 30% respectively. In the office, the characteristics of CO_2 built-up and radon decay were recorded during office hours and a 'dip' in the CO_2 concentration was observed between time 1300 and 1500.

The normalized pollutant concentration Φ_t can be correlated with an exponential built-up or decay curve ($p \leq 0.0001$, t-test), where Φ_{max} is the maximum pollutant concentration; λ is the effective ventilation rate for a pollutant; α is the fractional concentration of the pollutant in a steady state, i.e. $\lambda(t-t_0) \rightarrow \infty$; β is the fractional pollutant concentration that can be built-up or removed,

$$\Phi_t = \frac{\Phi}{\Phi_{max}} = \alpha + \beta e^{\lambda(t-t_0)} \qquad \text{… (4.1)}$$

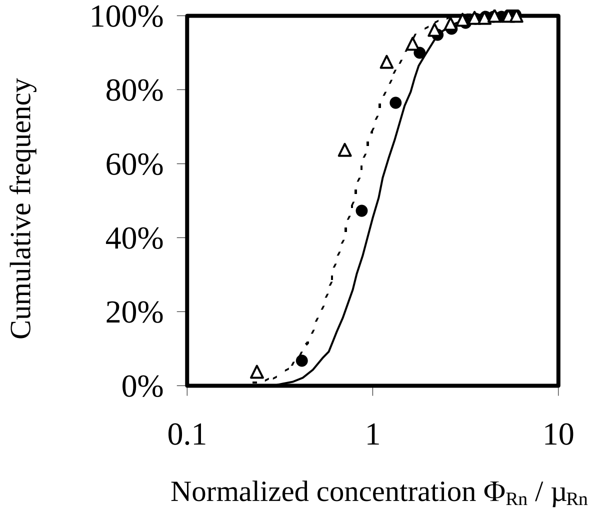


(a) Radon

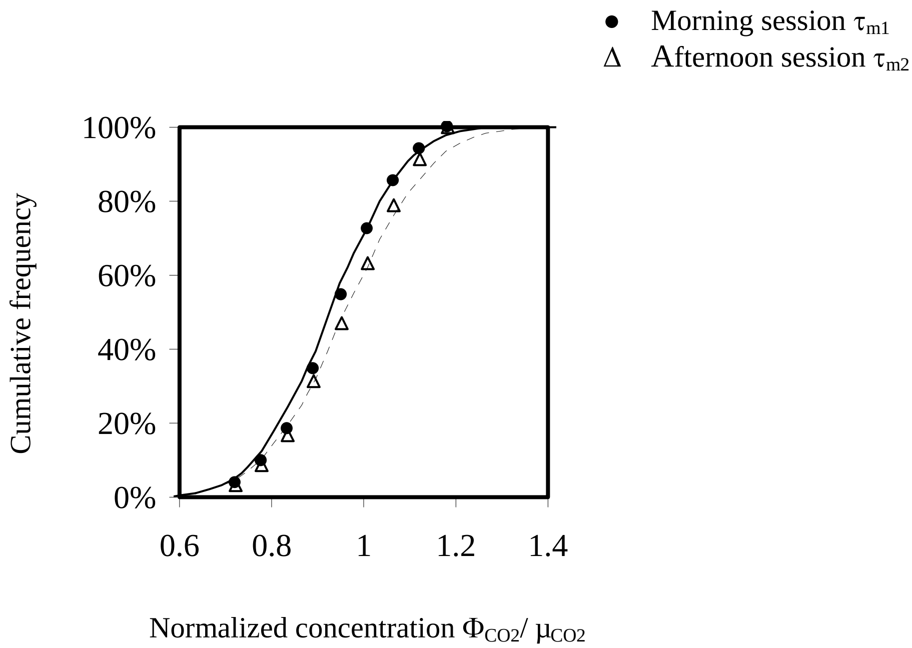


(b) CO_2

Figure 4.6: Sample average pollutant concentration in a sampling period τ_p



(a) Radon



(b) CO_2

Figure 4.7: Distribution of pollutant concentration

It was noted that the ventilation rate remained constant throughout the occupied period and no significant difference of λ for CO_2 built-up in both morning and afternoon sessions was found ($p \leq 0.001$, t-test). Probably, a drop in the number of occupants in the office at lunch hours (1300-1400) contributed to the drop in CO_2 concentration. Radon concentration was independent of the occupant load and its λ for the concentration decay was 0.55 ($p \leq 0.0001$, t-test). The result is obvious because the radon in a typical ventilated space could be diluted by a properly designed ventilation system (Chao and Hu 2004; Chow et al. 2002; Tso et al. 1994). The result also shows that the hypothetical background radon concentration for this site is 35 Bq m^{-3}. The result agrees with the previous measurement that the average outdoor radon level in Hong Kong ranges from 20 to 37 Bq m^{-3}, depending on the height of the sampling point and geological composition (Man and Yeung 1998).

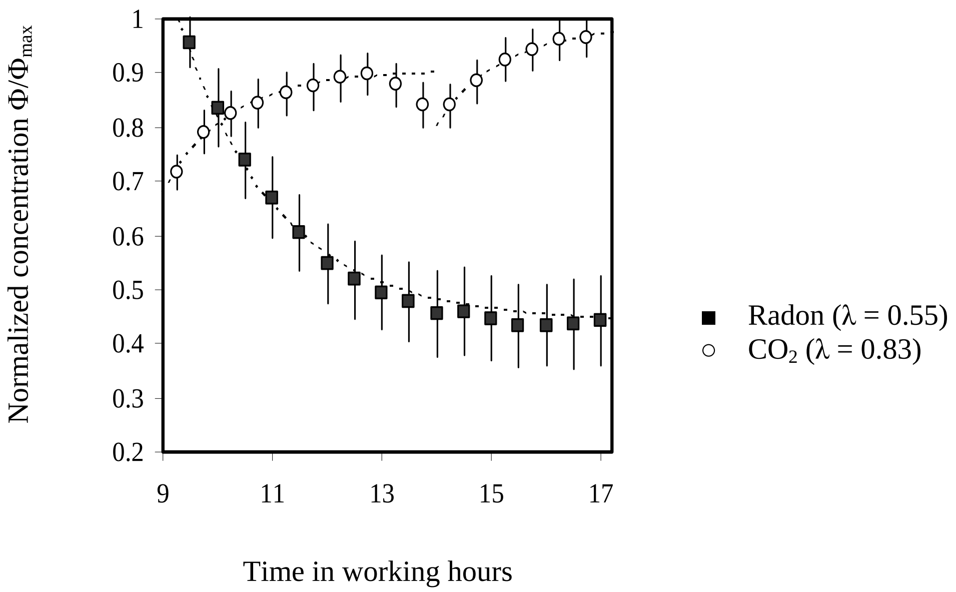


Figure 4.8: Pollutant concentration during working hours in an office

4.4 Interview survey on professional selection of sampling locations

To study the effects of professional choices of sampling locations in certain air-conditioned offices, a total of 19 professionals in the field of IAQ, including consulting engineers, designers, contractors of ventilation systems and specialists of IAQ assessment, were interviewed individually. Their details were recorded and summarized in Table 4.7. It was reported that the respondents had academic levels from higher diploma to PhD. About 60% of them had working experiences from 3 to 10 years. However, 63% claimed they were not familiar with the HKEPD IAQ certification scheme and only 26% had practical experience with it. This could be explained by the fact that since the launch of the scheme in 2003, only about 1% of the commercial premises (including offices, entrance halls, lobbies, club houses, food courts) have been certificated. For the 5 participants with the HKEPD IAQ assessment experience, 1 had a higher diploma, 2 had a bachelor degree and 2 had a master/PhD degree; for those without, 6 were higher diploma holders, 4 had a bachelor degree and 4 had a master/PhD degree. No significant difference in the academic background composition between these 2 groups was reported.

Considerations for the choice of 'representative' IAQ assessment locations were presented by the participants. It was reported that the top three criteria for the choice were occupant load at the sampling location, ventilation system arrangements and equipment set-up requirements. The practical 17 locations available, as shown in Figure 4.4, for IAQ measurements as indicated on the sitting plan of the selected office floor were then presented to the participants with a detailed air distribution layout. Further details of the building and its air-conditioning system arrangements and operation were available upon request. Each of the participants was asked to indicate whether the sampling locations were having CO_2 concentrations 'above' or 'below' the spatial average of the floor, and to decide the most ‘representative’ sampling location(s) for the spatial-average CO_2 concentration in an IAQ assessment.

Table 4.7: Respondents’ details

<table>
<tr><th colspan="6">Academic qualification</th></tr>
<tr><td colspan="2">Master degree or above</td><td colspan="2">Bachelor degree</td><td colspan="2">Higher diploma</td></tr>
<tr><td colspan="2">6 (31.5%)</td><td colspan="2">6 (31.5%)</td><td colspan="2">7 (37%)</td></tr>
<tr><th colspan="6">Working experience (years)</th></tr>
<tr><td>< 3</td><td>3-5</td><td colspan="2">6-10</td><td colspan="2">> 10</td></tr>
<tr><td>3 (16%)</td><td>7 (37%)</td><td colspan="2">5 (26%)</td><td colspan="2">4 (21%)</td></tr>
<tr><th colspan="6">Frequency in performing the HKEPD IAQ assessment</th></tr>
<tr><td colspan="2">Once per week</td><td colspan="2">Once per month</td><td colspan="2">Never</td></tr>
<tr><td colspan="2">3 (15.8%)</td><td colspan="2">2 (10.5%)</td><td colspan="2">14 (73.7%)</td></tr>
<tr><th colspan="6">Understanding of the HKEPD IAQ certification scheme</th></tr>
<tr><td>Very unfamiliar</td><td>Quite unfamiliar</td><td>Half and half</td><td>Quite familiar</td><td colspan="2">Very familiar</td></tr>
<tr><td>6</td><td>6</td><td>6</td><td>0</td><td colspan="2">1</td></tr>
</table>

Professional choices of sampling locations

A total of 52 counts of ‘representative’ sampling locations for the 17 assessment locations were made. The expected number of counts for each assessment location was about 3 and the expected number of choices from each participant was 2.7. Table 4.8 shows the number of assessment locations chosen by the participants, grouped according to their academic qualification and experience in the HKEPD IAQ assessment scheme. Interestingly, the group having the highest academic qualifications made significantly fewer choices (1.5 locations), in comparison with the one having bachelor degrees (4.2 locations) ($p \leq 0.0005$, t-test) or higher diplomas (2.6 locations) ($p \leq 0.02$, t-test). Significantly fewer choices (1.4 locations) were also reported for the group with the HKEPD IAQ assessment experience when compared to that without the experience (3.2 locations) ($p \leq 0.011$, t-test).

Table 4.8: Number of favourable locations for IAQ assessments

Academic qualification	**Experience in the HKEPD IAQ assessment?**				**Overall**	
	Yes		**No**			
	Average (SD)	*Sample size N*	*Average (SD)*	*Sample size N*	*Average (SD)*	*Sample size N*
Post-graduate degree	1 (0)	2	1.8 (1)	4	1.5 (0.8)	6
Bachelor degree	1 (0)	2	5.8 (4.9)	4	4.2 (4.5)	6
Higher diploma	3 (-*)	1	2.5 (1.4)	6	2.6 (1.3)	7
Overall	1.4 (0.9)	5	3.2 (3.1)	14	2.7 (2.8)	19

* Not applicable

The participants' favourable sampling locations were indicated by the total 'counts' of their votes on each location as 'representative'. The top three were location 12 (9 counts), location 6 (7 counts) and location 8 (6 counts); they were all open-plan workstations with constant 'average' or 'high' occupancy densities and located under both the supply and return air diffusers. The unfavourable positions reported were location 5 (0 count), and locations 13, 14, 15 and 17 (1 count each). Probably places like single workstation offices, conference rooms and workstations located near the main entrance of the floor associated with a transient or apparently 'low' occupant load might not be good in representing the spatial-average CO_2 concentration for the entire floor.

It was also reported that the average counts recorded for the 'representative' sampling locations having 'high', 'average', 'low' and 'varied' occupant loads were 5.3 (SD=3), 3.7 (SD=3.1), 2.3 (SD=1.4) and 1.5 (SD=1.3) respectively. A location with a 'low' ($p \leq 0.07$, t-test) or a 'varied' ($p \leq 0.05$, t-test) occupant load would be less 'favourable', and that was consistent with the participants' choice that occupant load was a primary consideration for a 'representative' sampling location of IAQ assessment.

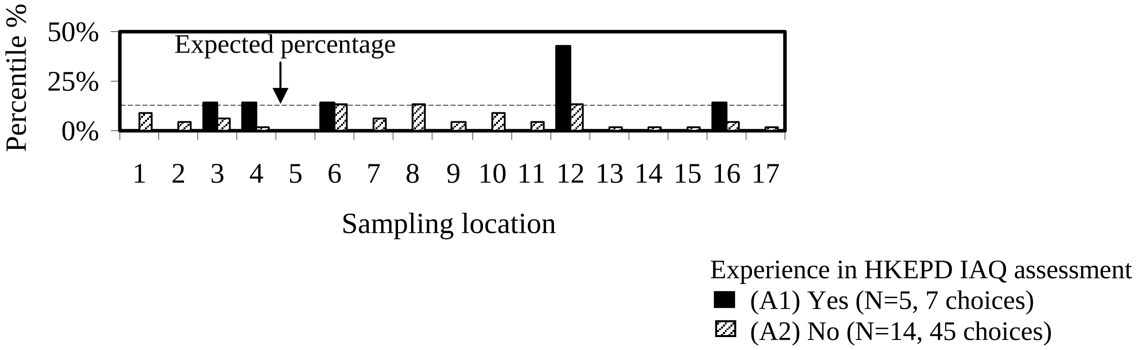
Experience in IAQ assessment and academic qualification

For studying their choices of sampling locations, the participants were categorized by their experience in the HKEPD IAQ assessment into two groups where group A1 had the experience while group A2 had not. Figure 4.9 shows the percentage of the locations chosen by both groups. The expected (average) percentage of the selected 'representatives' is shown by a dotted line. A percentage greater than the expected one indicated that the location would be more 'representative' for IAQ assessment as judged by the participants.

In group A1, 4 (out of 5) participants chose 1 'representative' sampling location only, of them 1 chose location 6 and 3 chose location 12 which indicated a favourable choice to this group. The other participant (who held a higher diploma) chose 3 other locations.

For group A2, their choices spread over the floor plan as in Figure 4.4. As shown in Table 4.7, each participant in this group made more choices: 4 participants chose 1 location, 3 chose 2, 2 chose 3, 4 chose 4 and the last one chose 13. There were 4 counts for location 1 and 6 counts each for locations 6, 8 and 12 respectively; and that implied that these 4 locations might be more favourable to this group. No significant difference of their choices of favourable/less favourable locations was found between groups A1 and A2 ($p \geq 0.4$, Chi-square test).

The participants were also categorized by their academic background into groups B1, B2 and B3 for having a master degree or above, a bachelor degree and a higher diploma respectively. The study showed that the group with more academic training would choose fewer sampling locations for an IAQ assessment. It was reported that group B1 chose 6 locations in total while groups B2 and B3 chose 13 and 14 locations respectively. They confined their choices of representative locations because they were properly equipped with better knowledge on the probable relationship between IAQ and the building or MVAC system design, and the balance between expenditure and assessment accuracies. Furthermore, the ratios of their favourable to less favourable locations for IAQ assessment were 6:3, 12:13 and 4:14 for B1, B2 and B3 respectively. A significant difference in their choices of favourable/less favourable locations was found between groups B1 and B3 ($p \leq 0.03$, Chi-square test), but not between groups B1 and B2 ($p \geq 0.3$, Chi-square test). There might be differences between the choices made by groups B2 and B3 ($p \leq 0.09$, Chi-square test).



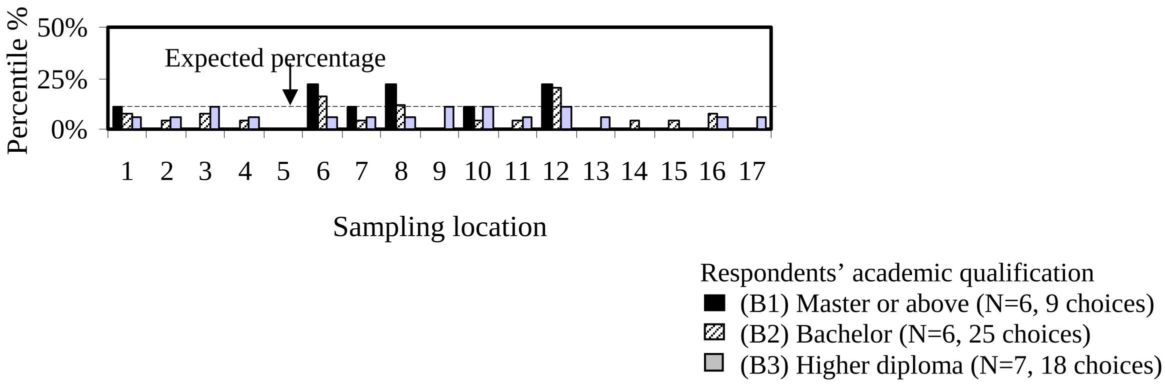


Figure 4.9: Respondents' choices of CO_2 sampling locations

4.5 Conclusion

This chapter formulated the database required for schemes evaluation, presented the methods and details of the surveys, and reported and discussed the measurement results. The database includes the existing available results of cross-sectional measurements at 422 offices on 12 indoor parameters as stated in the HKEPD IAQ certification scheme, and a one-year measurement of CO_2 and radon concentrations on an entire office floor at several comparable spatial locations. The surveys conducted in this study include an interview survey regarding the professional choice of sampling locations, and another cross-sectional survey on 12 indoor parameters in a different group of 103 Grade A offices in Hong Kong.

The regional survey results showed that for typical offices, TVOC, RSP and HCHO could be dominant in assessing ‘Excellent’ IAQ level, while TVOC, ABC, RH, HCHO and O_3 could be dominant in assessing ‘Good’ IAQ level. It was reported that the mean levels of the nine common pollutants among the 103 Grade A offices were lower than those measured for average offices from the 422 regional data. This surveyed group of Grade A offices shows different levels and contribution of assessment parameters to IAQ dissatisfaction, compare with the regional database of Hong Kong offices.

For the time variations of pollutant concentrations, the results demonstrated a ‘sufficiently long’ measurement period in obtaining the time-mean pollutant concentrations for the office, especially for radon which a large fluctuation in concentration were recorded. The frequency distributions of radon concentrations would be approximated by a log-normal distribution, and would be better described by a normal distribution for CO_2. For the average daily variations of pollutant concentration in the office, the characteristics of CO_2 built-up and radon decay were recorded during office hours and a ‘dip’ in the CO_2 concentration was observed between time 1300 and 1500.

The interview survey results on professional choices of sampling locations showed that among a number of probable sampling locations in the office, some would be more ‘favourable’ for IAQ assessment to the assessors. Results also showed that the choices of the assessment locations would be significantly influenced by the academic background of the assessors, but not their experience in the HKEPD IAQ assessment.

Chapter 5

Evaluation of the Assessment Protocol

5.1 Introduction

The proposed assessment tool was applied and analyzed using a structural database of indoor environmental parameters developed. It consists of longitudinal and cross-sectional measurements of the indoor air pollutant concentrations in air-conditioned offices in Hong Kong, as detailed in Chapter 4. The database provides measurement results of the corresponding indoor pollutant concentrations taken on working days for a year at comparable spatial locations of large spaces, and on air-conditioned offices over Hong Kong. These results were used to examine the feasibility and effectiveness of different assessment schemes in this study.

This chapter demonstrates the formulation and the analysis of the proposed assessment protocol, using the measurement results of the longitudinal and cross-sectional database. Choices of sampling parameters for a scheme are discussed and evaluated through some expressions of IAQ index. Deviations from the population mean are used as indicators for comparing the predictions made by various schemes. The confidence levels of the proposed assessment schemes are evaluated, and the fractional bias (FB) and the normalized mean square error (NMSE) are presented to show the goodness-of-fit of the schemes in obtaining the long-term sample average concentration.

5.2 Evaluation on sampling parameter selection

The IAQ assessment with reduced measurement parameters would reduce the efforts in IAQ monitoring, but suffered with the lost of assessment accuracy. In order to quantify the assessment accuracy of a number of measurement parameters essential for assessing an indoor environment, 8-h exposure levels of the listed 12 indoor environmental parameters in the IAQ certification scheme measured in the cross-sectional survey were referred (HKEPD 2003).

Choice of the failure occurrence density

The determined fractions of Hong Kong offices with unsatisfactory IAQ with respect to the two recommended classes were used to identify the dominant contributors for assessment parameter selection. The accuracy of the proposed schemes was evaluated.

The environmental parameters contributed to the unsatisfactory indoor office environment have been ranked according to the individual pollutant failure rate $\hat{P}_i$ (as determined by Equations 3.1 and 3.2). Assuming the occurrence of 'unsatisfaction' due to a parameter was independent, Figure 5.1 shows the cumulative unsatisfactory rates of the individual parameters with respect to the exposure limits of two IAQ classes. It was found that the top five contributors in terms of $\hat{P}_i$ contributed to 80% of the overall unsatisfactory rate. Hence, assessment with the top contributors would only be a good alternative for a cost-effective assessment of the unsatisfactory level of an indoor office environment.

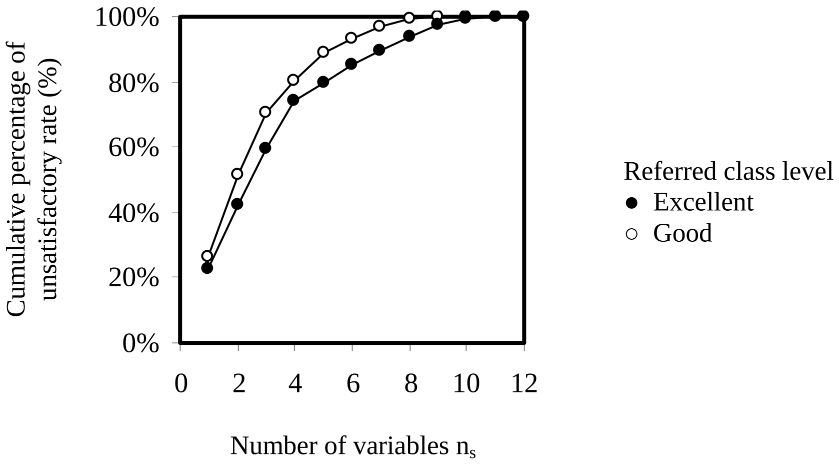


Figure 5.1: Cumulative percentage of environmental unsatisfactory rates using a number of measurement parameters

In the study, using the ranked parameter order (as in Figure 4.2), assessments of indoor environmental unsatisfactory rate for the criteria of 'Excellent' and 'Good' levels were conducted in all unsatisfactory offices. An assessment using different number of parameters selected from the list of the ranked parameters was evaluated with the measurement results.

The accuracy of the proposed assessment scheme of a number of dominant contributors only in assessing office IAQ was evaluated through comparing the assessed results between the proposed assessment scheme and the reference IAQ assessment of all 12 measured parameters in this case. The performance of the scheme was given by the confidence level ξ in assessing the environmental unsatisfactory rate using n_s parameters. The confidence level ξ is taken as the percentage of the number of unsatisfactory samples that can be identified by the scheme N_{μ_i} to the total number of unsatisfactory samples being assessed against all 12 parameters N.

The performance was assessed with respect to both ‘Excellent’ and ‘Good’ levels. The confidence level determined from the actual unsatisfactory counts in the measurement results is as shown in Figure 5.2. A rapid change of confidence level was observed at a number of assessing parameters. Taking the points of rapid change as a reference for discussion, i.e. n_s=3 and 5 for levels ‘Excellent’ and ‘Good’ respectively. The accuracy of the assessment scheme with the top three contributors was 96% (94% to 98% for CI=95%) from the measurements of TVOC, RSP and HCHO; and the accuracy was 93% (90% to 97% for CI=95%) from the measurements of TVOC, ABC, RH, HCHO and O_3.

As the assessment by the above two proposed schemes did not involve prediction of pollutant concentration by the model, analysis through fractional bias (FB) and the normalized mean square error (NMSE) were not applicable in this case.

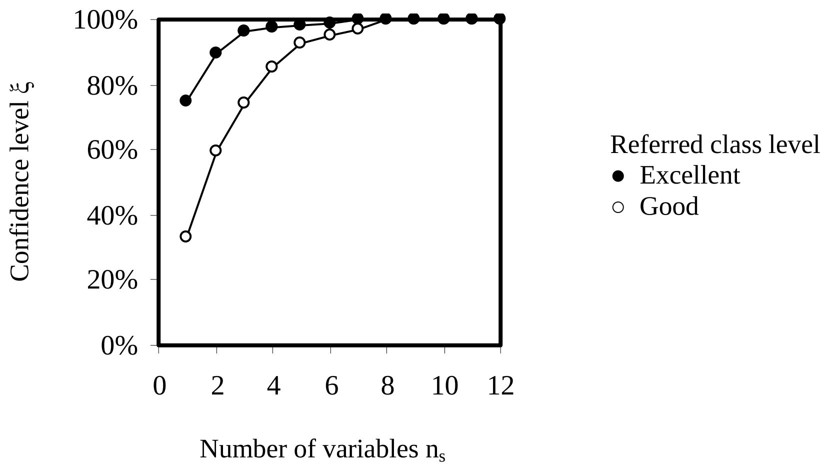


Figure 5.2: Confidence level of assessment scheme using n_s measurement parameters for environmental acceptance of offices

The above analysis demonstrated the use of collective results to determine the dominant contributors of unsatisfactory IAQ for offices in selecting representative parameters of a sampling scheme. A small number of dominant contributors of unsatisfactory IAQ in the surveyed offices were identified. In this way, the building owners can deal with the associated IAQ problems of a space quickly at a reduced measurement effort prior to any full scale assessment for detailed IAQ investigation, or obtaining a reference ranking (i.e. ‘Excellent’ or ‘Good’) described in the certification.

It was proposed that for typical offices, TVOC, RSP and HCHO could be dominant in assessing ‘Excellent’ IAQ level, while TVOC, ABC, RH, HCHO and O_3 could be dominant in assessing ‘Good’ IAQ level. Furthermore, the accuracy of the proposed scheme in assessing office IAQ was good enough to identify 96% and 93% of unacceptable offices against ‘Excellent’ level and ‘Good’ level respectively, comparing with the measurements of the 12 environmental parameters in the HKEPD IAQ certification scheme.

Choice of professional judgment

In selecting a set of representative parameters based on professional decision, the probable correlations among the measurement parameters were studied for judgment. The existing database of 422 offices was used to analyse the judged ‘representative’ parameters (out of the 12 common ones) of IAQ measurement and to derive mathematical expressions for the implementation of these representatives for an overall IAQ assessment.

The relationships among these 12 parameters were expressed by their correlations R and covariances as shown in Table 5.1(a). Significances of the correlations between any two of the parameters were examined by a t-test for the sample correlation coefficient R, with the null hypothesis of no correlation. Values of the 2-tail t-test and their corresponding p-values are shown in Table 5.1(b), where a p-value not larger than 5% would indicate a significant correlation, i.e. $p \leq 0.05$.

Sets of 'representative' parameters have been selected with several criteria. Firstly, the selected parameters must be literally typical enough as IAQ issues in an office; they are preferably able to represent the performance of the MVAC system in controlling IAQ through removal, dilution and source emission control. Secondly, these parameters must be independent to one another in the set but have significant correlations with other 9 parameters. This can be indicated by a p-value > 0.05 as shown in Table 5.1(b). Thirdly, priority is assigned to those parameters with high loading values L and can be easily measured.

A possible choice of the independent indoor pollutant set is RSP, CO_2 and TVOC, insignificant correlations are reported among them ($p > 0.2$, t-test). In a typical mechanically ventilated space, RSP is transported from outdoors. RSP level is closely related to filter efficiency of an air-conditioning system and the use of it could indicate the filtration performance. As some studies reported that RSP level would also be dependant on the indoor activities (Lee et al. 2002), inclusion of RSP could cover issues related to pollutants removal performance and activities in an office. Indoor CO_2 is generated by occupants and diluted by outdoor air and thus a good indicator for the ventilation of pollutants dilution and occupant load in the space (ASHRAE 2004, CEN 1998, Hoskins

2003, Möhle 2003). The results of this study showed that a low CO_2 concentration (i.e. a 'high' ventilation rate) would result in a high concentration of outdoor pollutants, e.g. O_3 ($p = 0.0307$, t-test). It should be noted that a high ventilation rate would dilute the levels of indoor radon emitted from concrete-based building materials in an office; and a significant positive correlation ($p < 0.0001$, t-test) obtained in this study confirmed it (Mui and Wong 2004). Finally, the inclusion of TVOC would be good for indicating those indoor pollutant emissions dominated by the building materials, finishing, and human activities, e.g. building renovation works (Hoskins 2003). This set of parameters could have a good representation including major system performances related to IAQ.

The loading value L of each parameter i, calculated from the correlation coefficient R_i (with respect to all other parameters) divided by the summation ΣR_i of all 12 parameters, is shown diagonally in Table 5.1(b). The results highlighted the 'relative importance' of the associated correlations among the parameters, their loadings from the largest to the smallest were: ABC, Rn, CO, RH, RSP, CO_2, TVOC, O_3, T, V, NO_2 and HCHO.

It is reported that from the data measured, about 70% of the sampled offices had CO concentrations below the detection limit of the instrument and hence the selection of CO should be less appropriate. For the parameter ABC, it needs rather 'expensive' measurement efforts in sampling, handling, and analyzing the assessment results, and it is not assigned with prime priority. Even though radon had significant correlations with ABC ($p < 0.0001$, t-test) and CO_2 ($p < 0.0001$, t-test), the pairs radon-ABC and radon-CO_2 were not chosen as CO_2 is generally selected as a surrogate indicator of IAQ which is common and easy to be measured. This further supports the pollutant set of RSP, CO_2 and TVOC would be an appropriate choice.

Table 5.1(a): Covariance and correlation matrix of the IAQ and thermal comfort parameters in offices[a]

Parameter i	CO_2	CO	RSP	NO_2	O_3	HCHO	TVOC	Radon	ABC	T	RH	V
CO_2	25203	1641	205.0	-104.8	-672.4	1882	1600	2374	15619	50.81	-61.78	-0.2837
CO	0.0311	110172	-2064	876.9	-4402	183.8	9452	2684	-1152	28.71	653.6	1.472
RSP	0.0618	-0.2976	436.4	9.116	223.3	-43.48	434.2	33.03	-159.8	-4.235	-33.01	-0.2898
NO_2	-0.0425	0.1702	0.0281	241.0	23.72	114.8	-1164	-42.01	-727.4	-2.866	-25.66	-0.0426
O_3	-0.1052	-0.3295	0.2655	0.0380	1620	-79.12	-135.6	-190.8	422.6	-1.812	-43.95	-0.3356
HCHO	0.1051	0.0049	-0.0184	0.0655	-0.0174	12728	-3644	544.9	-3671	21.21	-19.13	-0.3175
TVOC	0.0296	0.0835	0.0610	-0.2200	-0.0099	-0.0947	116211	1414	28998	-111.6	143.5	-4.827
Radon	0.3854	0.2084	0.0407	-0.0697	-0.1222	0.1245	0.1069	1506	2897	7.302	31.05	0.2557
ABC	0.2516	-0.0089	-0.0196	-0.1198	0.0268	-0.0832	0.2175	0.1909	152917	213.6	995.9	-2.334
T	0.1613	0.0436	-0.1022	-0.0931	-0.0227	0.0947	-0.1649	0.0948	0.2752	3.938	0.7226	0.0029
RH	-0.0425	0.2151	-0.1727	-0.1806	-0.1193	-0.0185	0.0460	0.0874	0.2782	0.0398	83.78	0.1170
V	-0.0259	0.0642	-0.2007	-0.0397	-0.1207	-0.0407	-0.2049	0.0954	-0.0864	0.0212	0.1850	0.0048

[a] Diagonal and upper entries are variances and covariances. Below are the correlations.

Table 5.1(b): Dependence test results for the parameter pairs[b]

Parameter i	CO_2	CO	RSP	NO_2	O_3	HCHO	TVOC	Radon	ABC	T	RH	V
CO_2	0.0840	0.6387	1.2695	0.8722	2.1685	2.1652	0.6063	8.5594	5.3275	3.3488	0.8722	0.5303
CO	0.5234	0.0985	6.3885	3.5394	7.1519	0.1006	1.7180	4.3660	0.1819	0.8942	4.5145	1.3180
RSP	0.2050	0.0000*	0.0858	0.5763	5.6447	0.3781	1.2519	0.8357	0.4010	2.1046	3.5922	4.1994
NO_2	0.3836	0.0004*	0.5647	0.0722	0.7787	1.3460	4.6213	1.4329	2.4737	1.9153	3.7630	0.8139
O_3	0.0307*	0.0000*	0.0000*	0.4366	0.0796	0.3572	0.2026	2.5225	0.5504	0.4650	2.4626	2.4912
HCHO	0.0309*	0.9199	0.7055	0.1790	0.7212	0.0452	1.9505	2.5707	1.7114	1.9504	0.3796	0.8354
TVOC	0.5447	0.0865	0.2113	0.0000*	0.8396	0.0518	0.0838	2.2034	4.5674	3.4266	0.9434	4.2909
Radon	0.0000*	0.0000*	0.4038	0.1526	0.0120*	0.0105*	0.0281*	0.1032	3.9854	1.9521	1.7984	1.9638
ABC	0.0000*	0.8558	0.6886	0.0138*	0.5823	0.0878	0.0000*	0.0001*	0.1054	5.8673	5.9367	1.7770
T	0.0009*	0.3717	0.0359*	0.0561	0.6422	0.0518	0.0007*	0.0516	0.0000*	0.0753	0.8160	0.4352
RH	0.3836	0.0000*	0.0004*	0.0002*	0.0142*	0.7044	0.3460	0.0728	0.0000*	0.4150	0.0937	3.8576
V	0.5962	0.1882	0.0000*	0.4162	0.0131*	0.4040	0.0000*	0.0502	0.0763	0.6636	0.0001*	0.0734

[b] Diagonal and upper entries are loading factors and t-test for the correlations. Below are p-values of the correlations. *Significant correlations.

The dependence of the other nine parameters i, namely CO, NO_2, O_3, HCHO, Rn, ABC, T, RH and V, on the above set (i.e. CO_2, RSP and TVOC) was examined by a statistic F-test and the corresponding p-values are shown in Table 5.2. Correlations for these parameters using CO_2, RSP and TVOC as the predictors were also determined from the following, where Φ_i is the measured value of a parameter i; Φ_{CO2}, Φ_{RSP}, and Φ_{TVOC}, are the measured levels of CO_2, RSP and TVOC respectively; $k_{i,0}$, $k_{i,1}$, $k_{i,2}$ and $k_{i,3}$ are the regression coefficients; ζ_i is the error term of i; $\langle\ \rangle$ is the average-operator for N data pairs and ε_i is the standard error of i.

$$\ln\Phi_i = k_{i,0} + k_{i,1}\ln\Phi_{CO2} + k_{i,2}\ln\Phi_{RSP} + k_{i,3}\ln\Phi_{TVOC} + \zeta_i;$$

$$\zeta_i = \int \frac{\exp\left(\frac{-(\ln\Phi_i)^2}{2\varepsilon_i^2}\right)}{\varepsilon_i\sqrt{2\pi}} d(\ln\Phi_i);\ \varepsilon_i^2 = \frac{1}{N-1}\sum_{j=1}^{N}\left(\ln\Phi_{ij} - \langle\ln\Phi_{ij}\rangle\right)^2 \qquad \ldots (5.1)$$

The confidence levels of the proposed measurement strategies were expressed with some statistical measures. For the sampling parameters suggested to be assessed, the goodness-of-fit for the correlations of the representative parameters and other parameters were expressed in terms of the regression coefficients, correlation coefficients, p-values, and relative residuals of the correlations as shown in Table 5.2. Significant correlations were found between the parameters and the independent indoor pollutant set ($p < 0.0001$, t-test, except for HCHO where $p = 0.0036$, t-test). The relative residual ω_i was the difference between the observed and predicted values normalized by the expected value of the parameter i. A smaller value shows that the residuals would be insignificant. Results show that they were insignificant ($\omega_i < 0.05$), except for the correlation with air movement V (i.e.

$\omega_{i=V} \geq 0.05$) where more parameters might be needed.

The correlations of parameters i are illustrated in Figure 5.3 with the probabilities of 0.05, 0.5 and 0.95 shown for the ranges of CO_2 from 400 to 1200 ppm, RSP from 10 to 120 μg m^{-3} and TVOC from 100 to 3000 μg m^{-3}. On visual inspection, these correlations reasonably covered the measured data points.

The goodness-of-fit for the correlations at $\zeta_i = 0$ were further examined by the values of FB and the NMSE for the correlations, with the results shown in Table 5.2. As a percentage to the expected values of the parameters i, except for air movement V (FB_V < 5%; $NMSE_V$ > 5%), the FBs and NMSEs were found to be varying from –0.7 to 0.4% and that indicated reasonable predictions would be obtained from the correlations.

With the above validity analysis of the model, the proposed set of 3 parameters namely CO_2, RSP and TVOC was evaluated as the ‘representative’ indicator for office IAQ. Their concentrations in an air-conditioned office could be measured by the proposed scheme to reasonably predict the other air pollutant concentrations at certain uncertainties.

Table 5.2: Proposed correlations

i	Para-meter, i	p-value of F-Test			Coefficients				Correlation coefficient	p-value	Residuals	Standard Error	FB_i	$NMSE_i$
		CO_2	RSP	TVOC	$C_{i,0}$	$C_{i,1}$	$C_{i,2}$	$C_{i,3}$	R		ω_i	ε_i		
1	**CO**	0.5021	0.0000	0.0306	7.8748	0	-0.2341	-0.0359	0.2862	2.1E-09	0.0014	0.3465	-0.0479	0.0027
2	**NO_2**	0.3725	0.5182	0.0000	4.4393	0	0	-0.1965	0.3141	4.1E-11	0.0314	0.5229	-0.1104	0.0381
3	**O_3**	0.0250	0.0000	0.6235	6.1024	-0.5500	0.3795	0	0.3035	1.9E-10	0.0177	0.7566	-0.1585	-0.4243
4	**HCHO**	0.0305	0.6059	0.0466	0.9962	0.6783	0	-0.2476	0.1416	0.0036	0.0110	1.0073	-0.4004	0.1950
5	**Rn**	0.0000	0.7060	0.0355	-3.7652	1.0915	0	0.1104	0.4032	6.3E-18	0.0153	0.6814	-0.2036	0.0448
6	**ABC**	0.0000	0.4462	0.0000	-2.8073	1.1802	0	0.2540	0.4042	5.1E-18	0.0015	0.7002	-0.1332	0.0161
7	**T**	0.0007	0.0018	0.0006	2.7092	0.0813	-0.0243	-0.0116	0.2815	4.0E-09	0.0453	0.0930	-0.0041	0.0010
8	**RH**	0.3769	0.0004	0.2326	4.2526	0	-0.0515	0	0.2115	1.2E-05	0.0167	0.1569	-0.0116	0.0015
9	**V**	0.5822	0.0000	0.0000	-0.8314	0	-0.2148	-0.1652	0.2839	2.9E-09	> 0.05	0.7897	-0.2578	0.0984

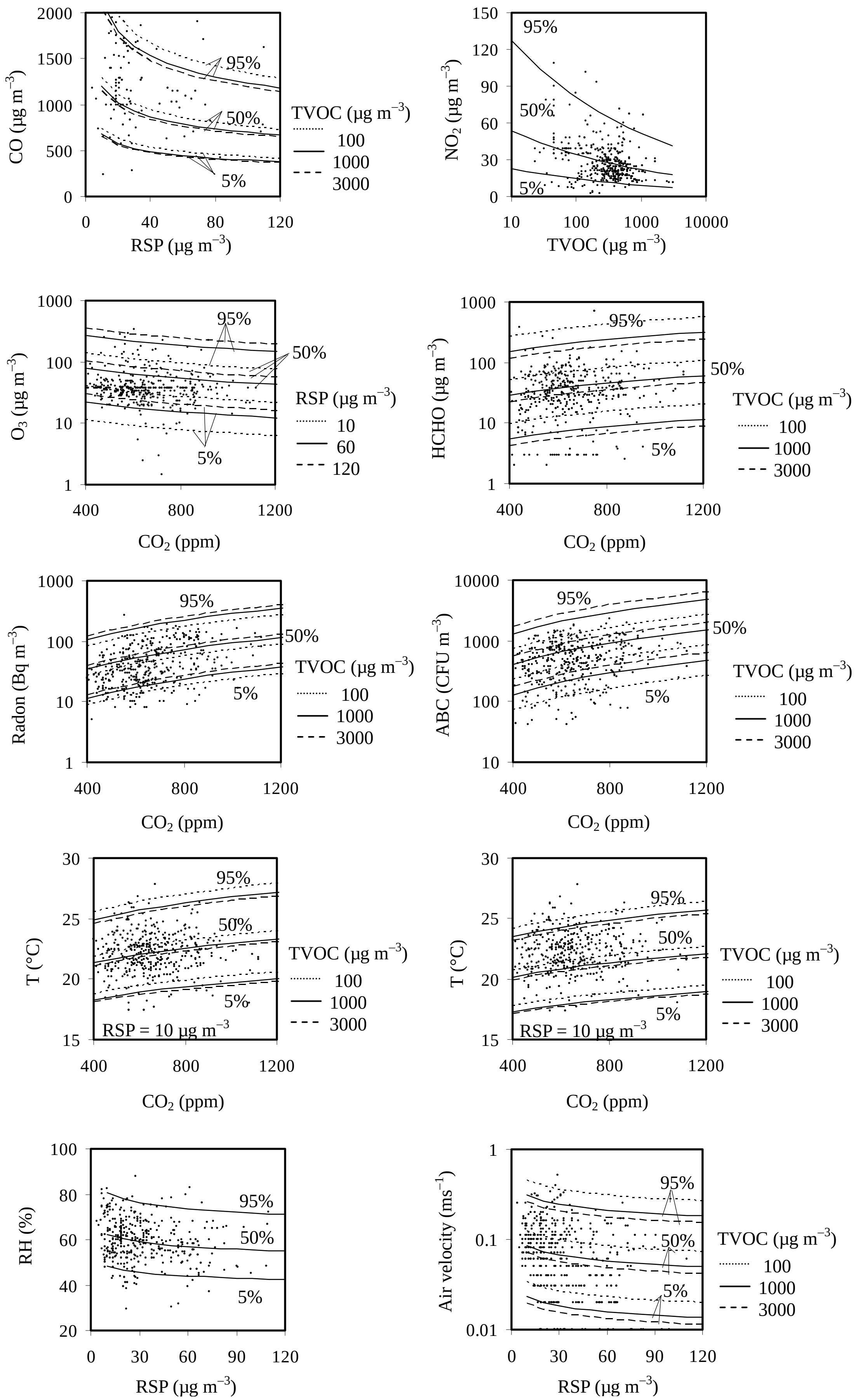


Figure 5.3: Correlations among parameters

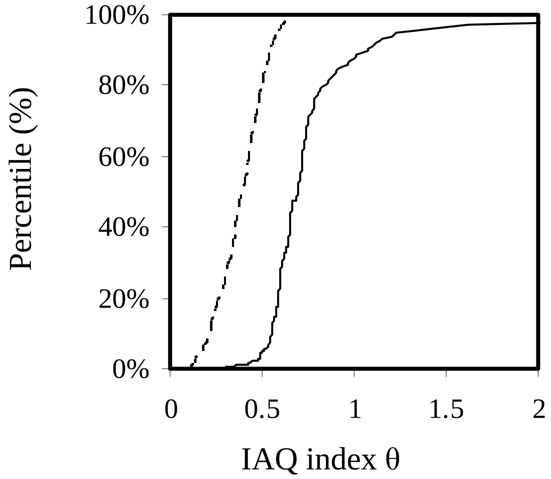
Performance evaluation on sampling schemes

In this study, two groups of representative pollutant choices were suggested for the composition of the IAQ index using expression in Equation 3.4. The first group was selected according to the failure occurrence density, where four dominant pollutants contribute to unsatisfactory IAQ were identified, they are TVOC, ABC, HCHO and O_3 (n_s = 4 for the index θ). And the second group was selected as judged typical to show the performance of IAQ control through dilution, removal, or source control, they are CO_2, RSP and TVOC (n_s = 3 for the index θ). Calculated indices from the two groups of representative parameters choices were both analyzed.

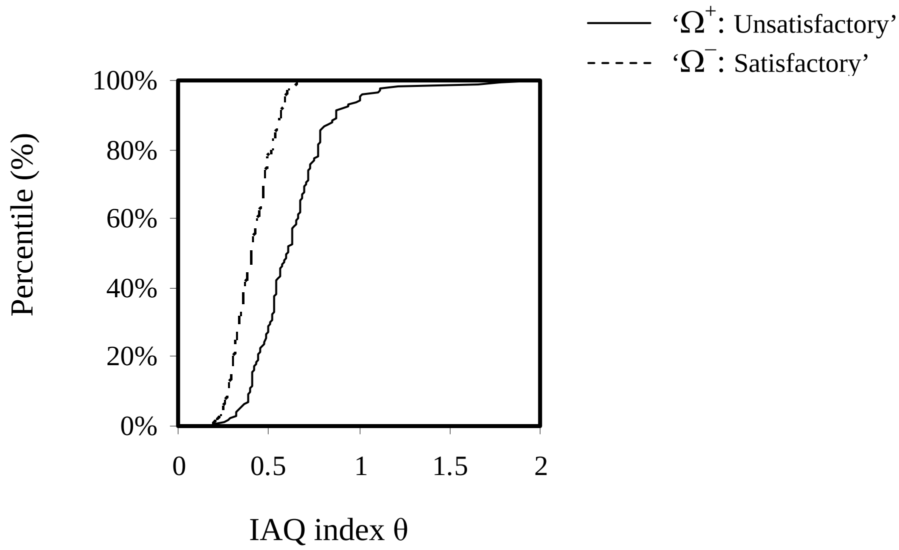
Figure 5.4 shows the IAQ index θ of the 422 samples, with measured TVOC, ABC, HCHO and O_3 (n_s = 4) or CO_2, RSP and TVOC (n_s = 3). They are classified into environment of satisfactory Ω^- and unsatisfactory Ω^+ IAQ respectively based on the reference assessment of 9 common air pollutants. It was reported that the range of IAQ index for the satisfactory and unsatisfactory offices were θ_4^- = 0.11-0.68 and θ_4^+ = 0.31-3.44, with averages $\overline{\theta}_4^-$ = 0.39 (standard deviation S_4^- = 0.13) and $\overline{\theta}_4^+$ = 0.78 (S_4^+ = 0.41), respectively for n_s=4. And the range were θ_3^- = 0.19-0.78 and θ_3^+ = 0.20-1.99, with averages $\overline{\theta}_3^-$ = 0.43 (S_3^- = 0.11) and $\overline{\theta}_3^+$ = 0.80 (S_3^+ = 0.25), respectively for n_s=3. In both cases, 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 in the offices of unsatisfactory IAQ ($p < 0.0001$, pair t-test). The IAQ index θ would be correlated to the assessed unsatisfactory from reference assessment by a logistic model, for a space having an unsatisfactory IAQ (event A) P(A) as ($p < 0.0001$),

$$P(A) = \frac{1}{1 + \exp(13.63 - 24.08\theta_4)} \quad ; \text{ for } n_s = 4 \qquad \dots (5.2)$$

$$P(A) = \frac{1}{1 + \exp(5.13 - 9.12\theta_3)} \quad ; \text{ for } n_s = 3 \qquad \dots (5.3)$$



(a) n_s = 4



(b) n_s = 3

Figure 5.4: IAQ index θ of Hong Kong classified into satisfactory and unsatisfactory IAQ

Establishing the screening level θ_{sc} for the screening test 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 $P(A) \geq 0.5$ as the 'high risk group', the corresponding screen levels θ_{sc} were 0.566 and 0.563 for $n_s = 4$ and $n_s = 3$ respectively.

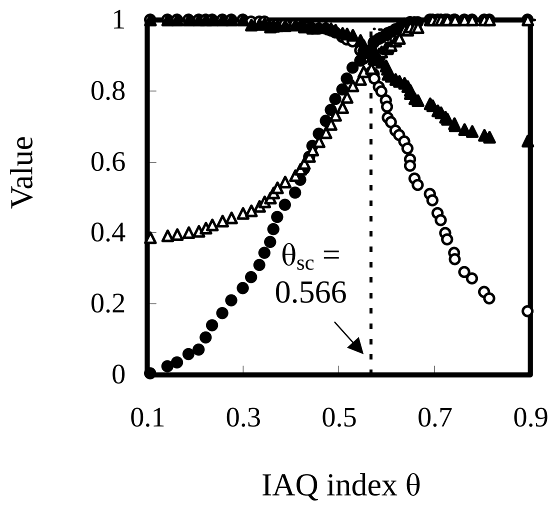
Table 5.3 shows the IAQ assessment results using the sampling scheme with screening by IAQ index for both $n_s = 4$ and $n_s = 3$ in some offices. The results showed a significant association between the predicted and assessed results ($p < 0.0001$, t-test), and that indicated that the test could identify the asymptomatic IAQ problems associated with the test samples. The association was further evaluated using Yule's Q statistics. Strong relationship (i.e. $Q \geq 0.75$) between the prediction and the observation was reported, Q = 0.97 for $n_s = 4$ and Q = 0.81 for $n_s = 3$.

The results showed that, for the assessment by the four dominant contributors at screening level $\theta_{sc} = 0.566$ for P(A) = 0.5, the test would correctly identify 87.1% IAQ problem present ($P_s = 0.871$) and 91.5% ($P_f = 0.915$) IAQ problem absent with the test samples passed. Among the test positive samples, 86.6% had IAQ problems ($P_+ = 0.866$) and for the test negative samples, 91.9% did not have IAQ problems ($P_- = 0.919$). For the assessment by the three selected representative pollutants, the test would identify 56.4% IAQ problem present and 88.0% problem absent. And, 74.8% of test positive samples had IAQ problems while 76.3% of test negative samples did not have IAQ problems. The proposed IAQ indices derived from the sampling schemes are feasible to describe the IAQ of some air-conditioned offices.

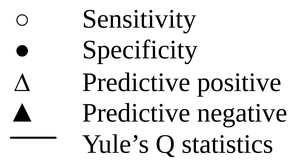
Table 5.3: Predicted unsatisfactory IAQ by the IAQ index at P(A) = 0.5

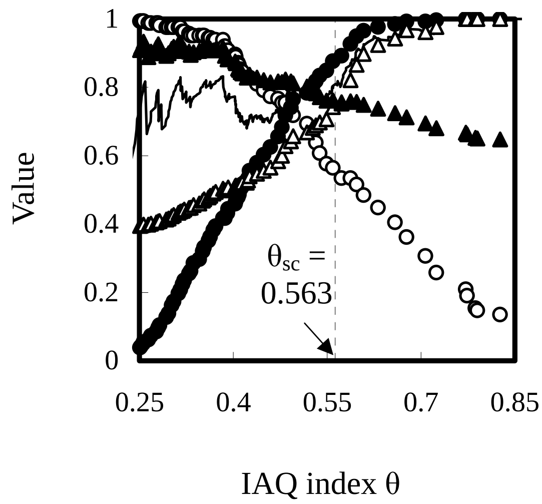
Assessed unsatisfactory IAQ	**Predicted unsatisfactory IAQ for n_s = 4 (n_s = 3)**		**Total counts**
	'No' P(A) < 0.5	**'Yes'** P(A) ≥ 0.5	
'Yes'	FN = 21 (71)	TP = 142 (92)	163
'No'	TN = 237 (228)	FP = 22 (31)	259
Total counts	258 (299)	164 (123)	422

Figure 5.5 shows the sensitivity, specificity, predictive values and the corresponding Yule's Q statistics of the test by the proposed schemes at various screening levels θ_{sc}. The screening level selected will affect the sensitivity, specificity and predictive values of the test. For both schemes, expectedly, as sensitivity increases, it is less likely that a test sample with a negative result would have an IAQ problem and therefore the predictive negative value increases. Conversely, as the specificity increases, it is less likely that a sample with a positive result would be free from the IAQ problem and hence the predictive positive value increases.



(a) n_s = 4





(b) n_s = 3

Figure 5.5: Sensitivity, specificity, predictive values and Yule's Q statistics at various screening levels θ_{sc}

5.3 Evaluation on sampling times of a scheme

In order to interpret the sampling results with the choice of different measurement time and periods, a database of year-round measurement recorded profiles and fluctuations of pollutant concentrations was used for evaluation. The one-year CO_2 and radon measurement of an open-plan office during working days demonstrated a 'sufficiently long' measurement period in obtaining the time-mean pollutant concentrations for the in-use office.

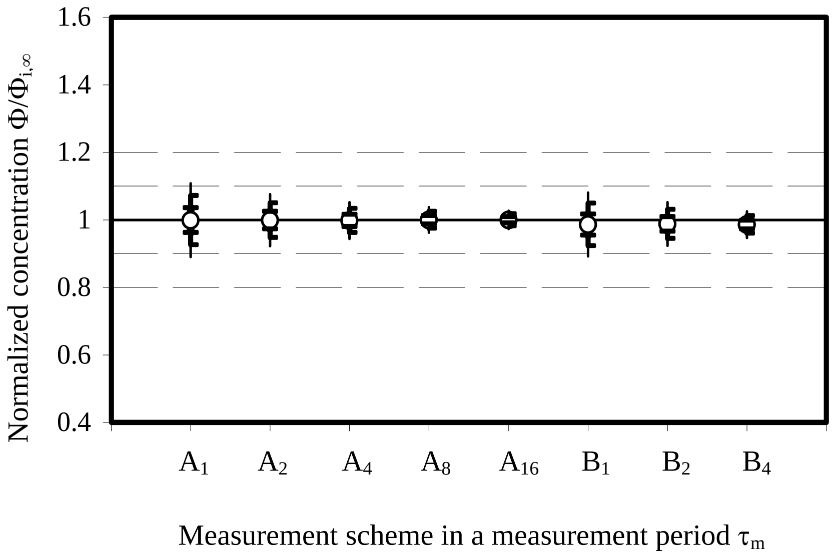
It was reported that, as expected, radon concentration peak measured in the morning session while CO_2 concentration peak in the afternoon. In the office, the characteristics of CO_2 built-up and radon decay were recorded during office hours and a 'dip' in the CO_2 concentration was observed between time 1300 and 1500. Studying this two pollutant levels variation covered the time variation characteristics of occupants related and building related pollutants. For other pollutants where their present and change in concentration are random in time, assume their concentrations are normally distributed over a period of time, concentrations profiles were generated from the Monte-Carlo simulations for different cases of distribution. Three example cases, i.e. standard deviation σ equals to 0.1, 0.3 and 0.5 of the time-mean concentration, were demonstrated. The simulated concentrations profiles of the three cases were used for analyzing the accuracies with different schemes applied.

A measurement period of 8 hours by continuous sampling (i.e. Scheme A of 8h measurement, or denoted as 'A_8') is adopted in the current practice and, in this study, the measurement results of Scheme A_8 were used as a 'base case' for comparison with the measurement time required τ_m (h) for a sample mean Φ_A or Φ_B obtained by the two schemes. The average concentration from the alternative scheme (denoted as 'Scheme B') proposed, was determined from the average of two random measurement samples, one from each of the two time-equal sessions.

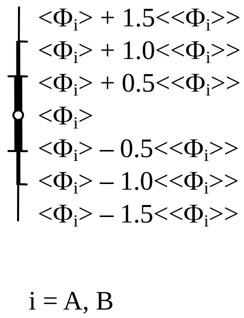
The normalized sample means are shown in Figure 5.6, with τ_m = 1, 2, 4 and 8 hours using Scheme A (denoted as A_1, A_2, A_4 and A_8), and τ_m = 1, 2 and 4 hours using Scheme B (denoted as B_1, B_2 and B_4) for pollutants with (a) random variation, (b) decay (radon as example), or (c) built-up (CO_2 as example) characteristics in concentrations. It is noted that the results of Scheme A_8 is the base case for comparison. Calculations were repeated for τ_m = 16 in Scheme A (denoted as A_{16}) to illustrate the effects of extending the measurement time for comparison with the alternative scheme. The pollutant concentrations on two consecutive working days were used to compute the mean for A_{16}. The probable range of sample means shown is determined from the average and standard deviation of the sample means for Schemes A and B, with a constant k_j of set error limits ±0.5, ±1 and ±1.5, in a total measurement time τ_m (h),

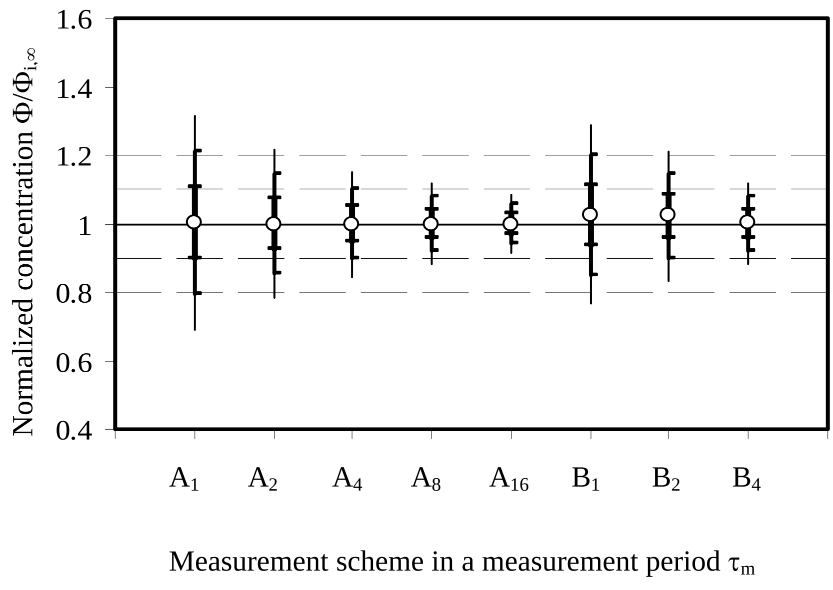
$$\Phi_{i,\tau_m,j} = \langle\Phi_{i,\tau_m}\rangle + k_j\langle\langle\Phi_{i,\tau_m}\rangle\rangle \quad ; \; k_j = j/2 - 2\,; \; j = 1, 2, \ldots, 7 \qquad \ldots (5.4)$$

The calculated sample means were compared to the long-term average pollutant concentration $\Phi_{i,\infty}$. The surveyed results showed that the long-term average concentrations for radon and CO_2 were 110.1 Bq m^{-3} and 868 ppm respectively; with error limits of 20% and 30% deviation from the means of radon, and 10% and 20% deviation from those of CO_2 as shown in Figures 5.6(b) and (c). The accuracy of the schemes can be assessed by the deviation of the sample means from the long-term average values. As expected, for all the three types of daily pollutant concentration variation characteristics, a longer sampling period would reduce the probable error using the same sampling scheme. The results also showed that similar deviations were found in Scheme B, with a reduced measurement time required as compared with the base case Scheme A_8.

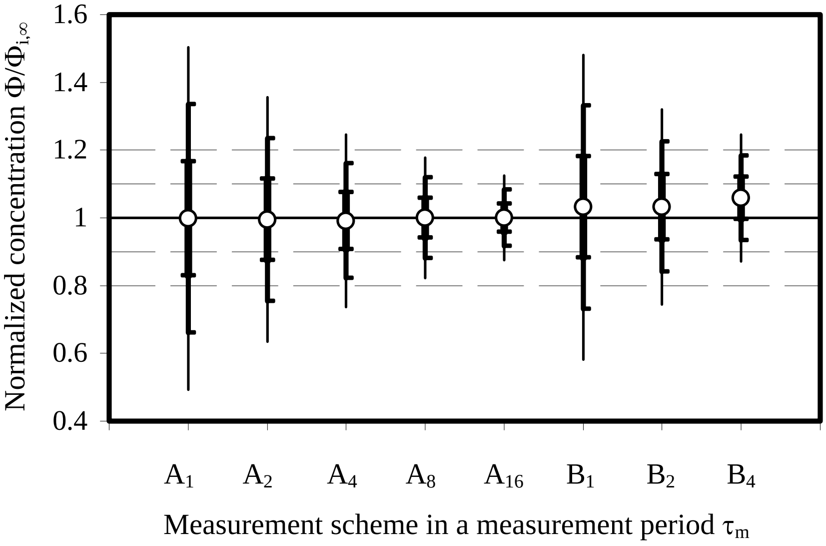


(i) $\sigma = 0.1\Phi_{i,\infty}$



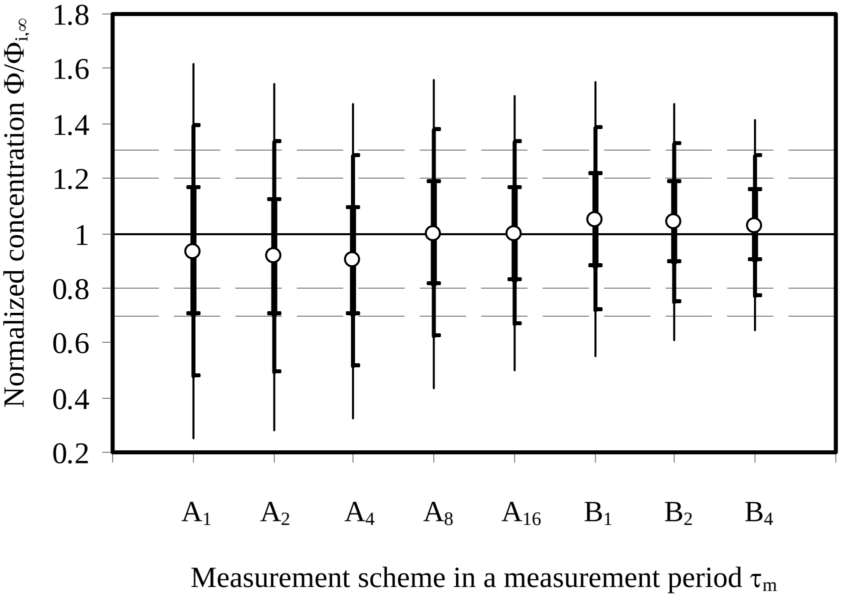


(ii) $\sigma = 0.3\Phi_{i,\infty}$

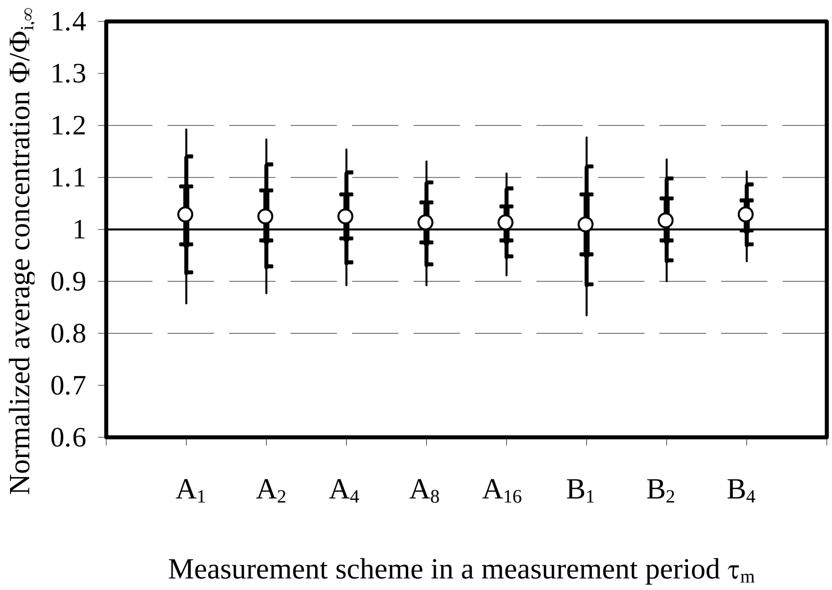


(iii) $\sigma = 0.5\Phi_{i,\infty}$

(a) Random variation



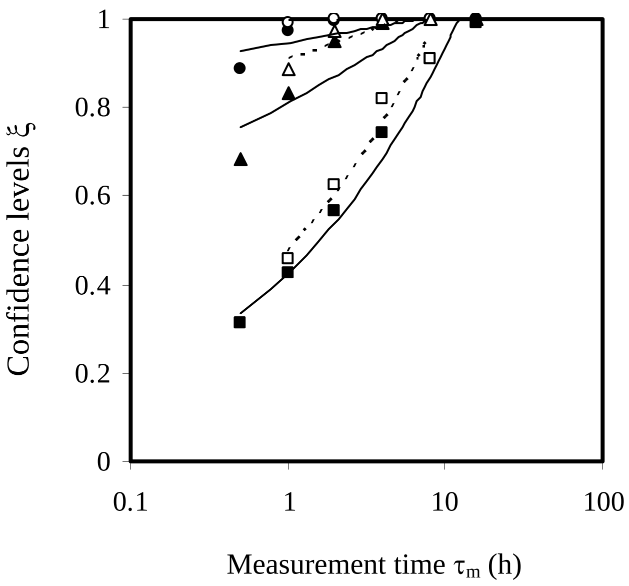
(b) Decay



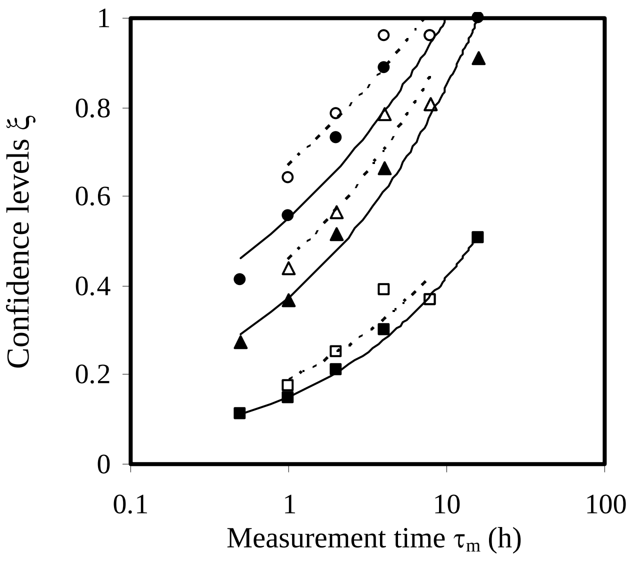
(c) Built-up

Figure 5.6: Sample means of pollutant concentration determined by Schemes A and B

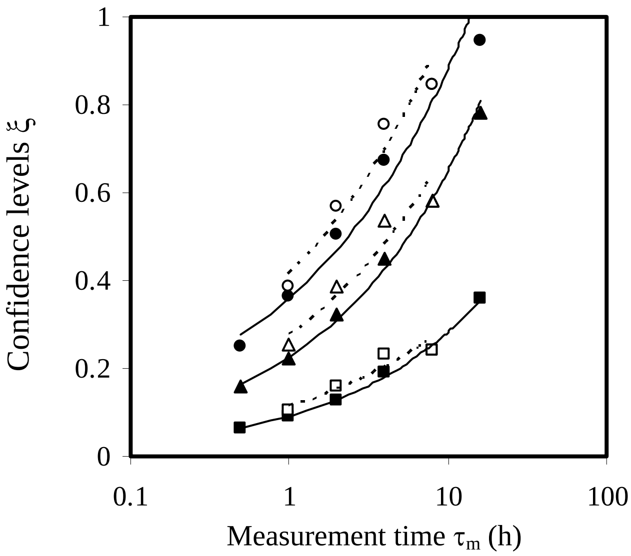
The accuracy of the proposed scheme can be further evaluated by expressing the number of sample means N_{μ_i} that fall within the probable error limits of the average concentration determined by the scheme as a percentage of the total number of samples made by the scheme N. This percentage can also be interpreted as the confidence level that the sampled average 'represents'. Figure 5.7 shows the confidence levels $\xi_{\tau_m,i}$ for the predictions at the average probable errors E, 4% to 10% for random and built-up cases and 10% to 30% for decay, deviated from the long-term average values, average confidence levels $\bar{\xi}_i$ over all sampling locations for the example pollutant CO_2 for built-up are shown. The results showed that the sampling period required $\tau_{m,i}$ in determining the average pollutant concentrations in the occupied period for the ventilated space could be reduced by applying Scheme B as compared with Scheme A, at the same confidence level.



(i) $\sigma = 0.1\Phi_{i,\infty}$



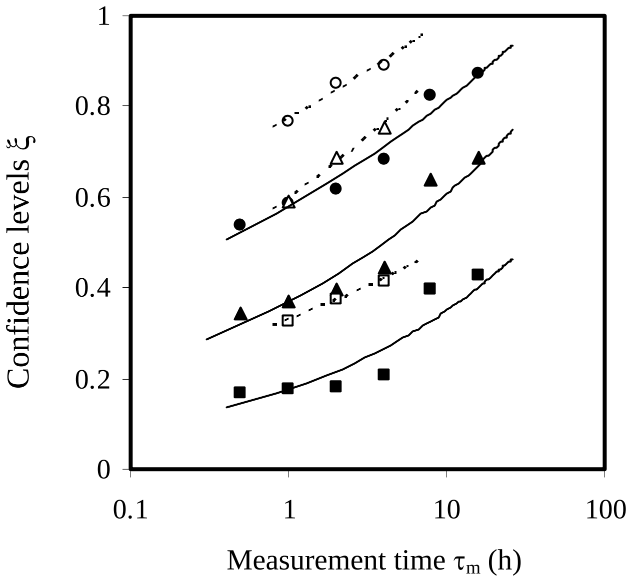
(ii) $\sigma = 0.3\Phi_{i,\infty}$



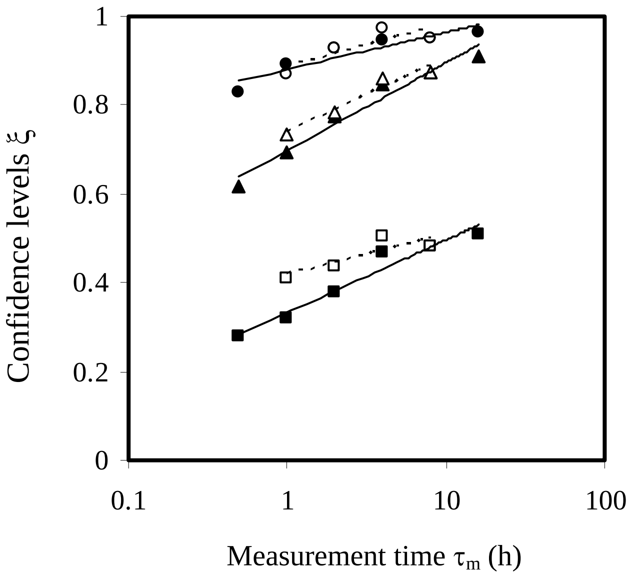
(iii) $\sigma = 0.5\Phi_{i,\infty}$

(a) Random variation

Error limit E			Scheme	
Random	Decay	Built-up	A	B
0.04	0.1	0.04	■	□
0.10	0.2	0.10	▲	Δ
0.16	0.3	0.16	●	○



(b) Decay



(c) Built-up

Figure 5.7: Average confidence levels $\bar{\xi}$ at different probable errors E deviated from long-term average

The goodness-of-fit for the proposed assessment scheme in obtaining the long-term sample average concentration $\Phi_{i,\infty}$ was further checked by the FB and the NMSE. Table 5.4 compared the FB and NMSE values of the two schemes with sampling time less than 8 hours, to the reference scheme of A_8. Adopting Scheme B would generally give a better prediction of the long-term sample average than Scheme A at the same measuring period. Accuracy improved with Scheme B when compared to A_8 in the cases of random variation or decay in pollutant concentrations.

Table 5.4: FB and NMSE values of assessment with different schemes for the three different pollutant variation characteristics

Scheme	Random						Decay		Built-up	
	$\sigma = 0.1\Phi_{i,\infty}$		$\sigma = 0.3\Phi_{i,\infty}$		$\sigma = 0.5\Phi_{i,\infty}$					
	FB	NMSE	FB	NMSE	FB	NMSE	FB	NMSE	FB	NMSE
$A_{\tau<8}$	-0.0021	0.0050	-0.0151	0.0701	-0.0361	0.3958	-0.1443	0.1687	0.0122	0.0175
A_8	0.0013	0.0004	0.0074	0.0066	0.0163	0.0127	-0.0477	0.0845	0.0048	0.0121
$B_{\tau<8}$	-0.0161	0.0038	0.0111	0.0193	0.0314	0.0586	0.0051	0.0603	0.0089	0.0173

At the same probable errors E, the required sampling period for Scheme B at certain confidence levels was correlated with the measurement period required for Scheme A as shown in Figure 5.8. Good correlations between $\tau_{m,B}$ and $\tau_{m,A}$ at the same confidence level were obtained with Pearson's correlation coefficients R from 0.93 to 0.98 ($p \le 0.0001$, t-test). It confirmed that the required measurement period would be reduced when the alternative scheme was applied at the same confidence level as in Scheme A.

$$\tau_{m,B} = \begin{cases} 0.44\tau_{m,A}^{1.24} \\ 0.52\tau_{m,A}^{1.42} \\ 0.39\tau_{m,A}^{1.28} \end{cases} ; \begin{cases} \text{Random} \\ \text{Decay} \\ \text{Built-up} \end{cases} \qquad \dots (5.5)$$

At certain confidence levels, the potential reductions in the required measurement period of the proposed scheme for assessing indoor pollutants concentration with random variations or built-up characteristics (CO_2 level) could be up to 30%, as compared with an 8-hour continuous one, and a 20% less than that for assessing pollutants that decay within a working day (radon level).

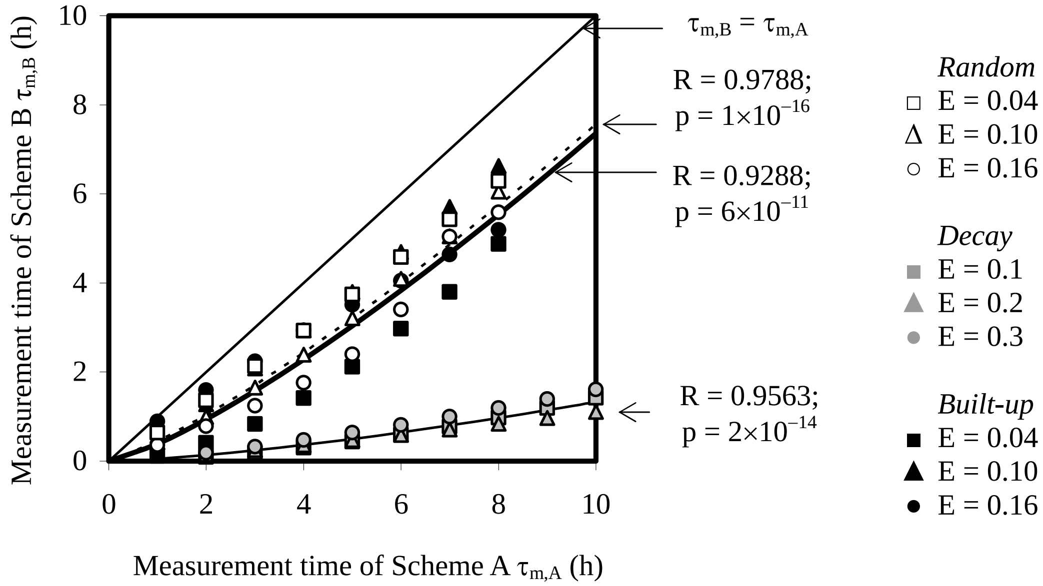


Figure 5.8: Measurement time required for Schemes A and B, at the same confidence level

5.4 Evaluation on sampling point density and location of a scheme

The sampling location selection in a large indoor space would contribute to the assessment results of the spatial average pollutant concentration. Measuring the spatial dependence of pollutant concentrations in an indoor environment is useful for pollutant monitoring and exposure assessment. CO_2 concentration was selected as an IAQ indicator to investigate the probable errors and measurement efforts in different sampling schemes regarding the sampling point density and the sampling location(s). CO_2 concentrations within an office vary at different locations; their magnitude and variation can be used to study the significance when compared to the office sample-spatial average CO_2 concentration.

In the study, the probable measurement errors with r random sampling locations for IAQ assessment at a sampling point density were expressed by the number of sample averages which fell within the probable error limits of the sample-spatial average concentration. The confidence level ξ_r of the scheme with various number of sampling locations r selected randomly can be evaluated by expressing the number of sample means that fell within the probable error limits of the average concentration determined by the scheme as a percentage of the total number of samples made.

Scheme confidence level with various sampling point density

The confidence level ξ_r of the measured concentration from r points at certain probable errors E is determined from the 'portion' of the sample average within the set error limits ±E, in comparison with the total number of r-combination N_r, where N_{μ_i} is defined as the combinations having sample-spatial average concentrations within the set error limits ±E.

The confidence levels ξ_r related to the proposed sampling point density A_s were evaluated. The confidence level for the measurements, with the error limits |E| set at 1%, 2%, 3%, 4% and 5%, deviated from the spatial mean CO_2 concentration at various A_s (equivalent to 2 to 12 measurement points in the office), is shown in Figure 5.9. With the results for |E| from 0.01 to 0.05 and a step change of 0.002, a regression equation for determining the probability of a measured CO_2 concentration with a sampling point density A_s fell within the set error limit (1 – |E|) = 0.95 to 0.99 in a large space is given by,

$$\xi_r = \left(k_1 + k_2|E| + k_3|E|^2 + k_4|E|^3 + k_5|E|^4\right)A_s^{k_6+k_7|E|} \quad ; \begin{cases} 100 \le A_s \\ 0.01 \le |E| \le 0.05 \\ 0 \le \xi_r \le 1 \end{cases} \quad \ldots (5.6)$$

with a correlation coefficient R = 0.998 ($p < 0.0001$, t-test), and the constants k_i as,

$$k_i = \begin{bmatrix} 7.3133 \times 10^{-2} \\ 870.35 \\ -34807 \\ 503009 \\ -2574098 \\ -0.68131 \\ 8.6175 \end{bmatrix}$$

This shows a strong correlation between the sampling point density A_s and the probability of obtaining the measured quantity at certain confidence levels. Increasing number of sampling points in the space could significantly increase the confidence level in determining the average concentration in the occupied period, as shown in Figure 5.9. The results showed that the probability required in determining the IAQ in the occupied period for the ventilated space could be increased from 70% to 90% within the 5% error set limit when the number of sampling points (A_s = 250 m^2) was doubled to the one recommended in the HKPED certification scheme (A_s = 500 m^2). Likewise, a lower probability (from 70% to 60%) of obtaining the measurement concentration at the claimed confidence levels (5% error set limit) would result from a 50% reduction in measurement points (A_s = 1000 m^2) as shown.

The goodness-of-fit for the schemes with various sampling point densities in obtaining the long-term sample average concentration $\Phi_{i,\infty}$ of a pollutant i were further checked by the

FB and the NMSE. The recommended density of A_s = 500 m^2 would give FB and NMSE values as 0.0124 and 0.0023 respectively. Doubling the number of sampling points (A_s = 250 m^2) would change the FB and NMSE values as 0.0132 and 0.0011, while reducing the number of sampling points by half (A_s = 1000 m^2) would give FB and NMSE values as 0.0109 and 0.0048. A smaller NMSE shows that the better model output agrees with the observations from more sampling points.

From the results, reducing the number of sampling points required for an IAQ measurement by 50% would decrease the probability of obtaining the sample-spatial average concentration at the same confidence level by 10% only. This shows that assessing the space with reduced sampling points would also be a possible way for cost-effective assessment. Based on the results obtained and taking the measurement uncertainties into account, various parties can decide on the manpower and resources required for their sampling strategies.

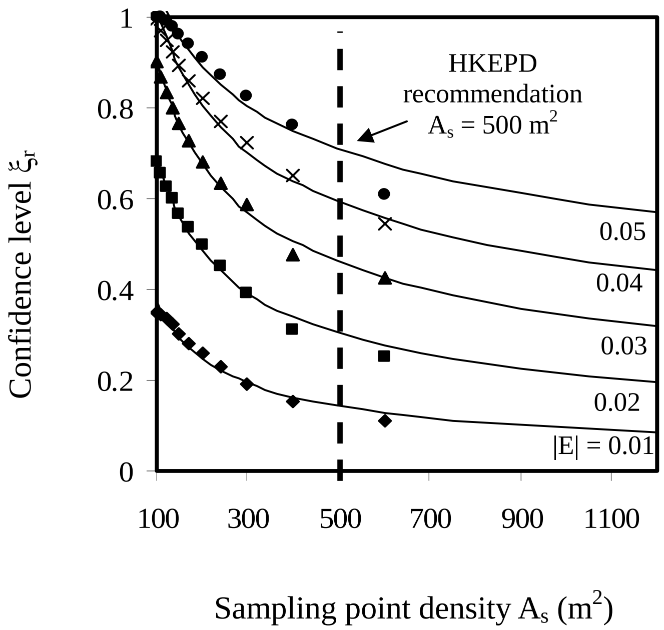
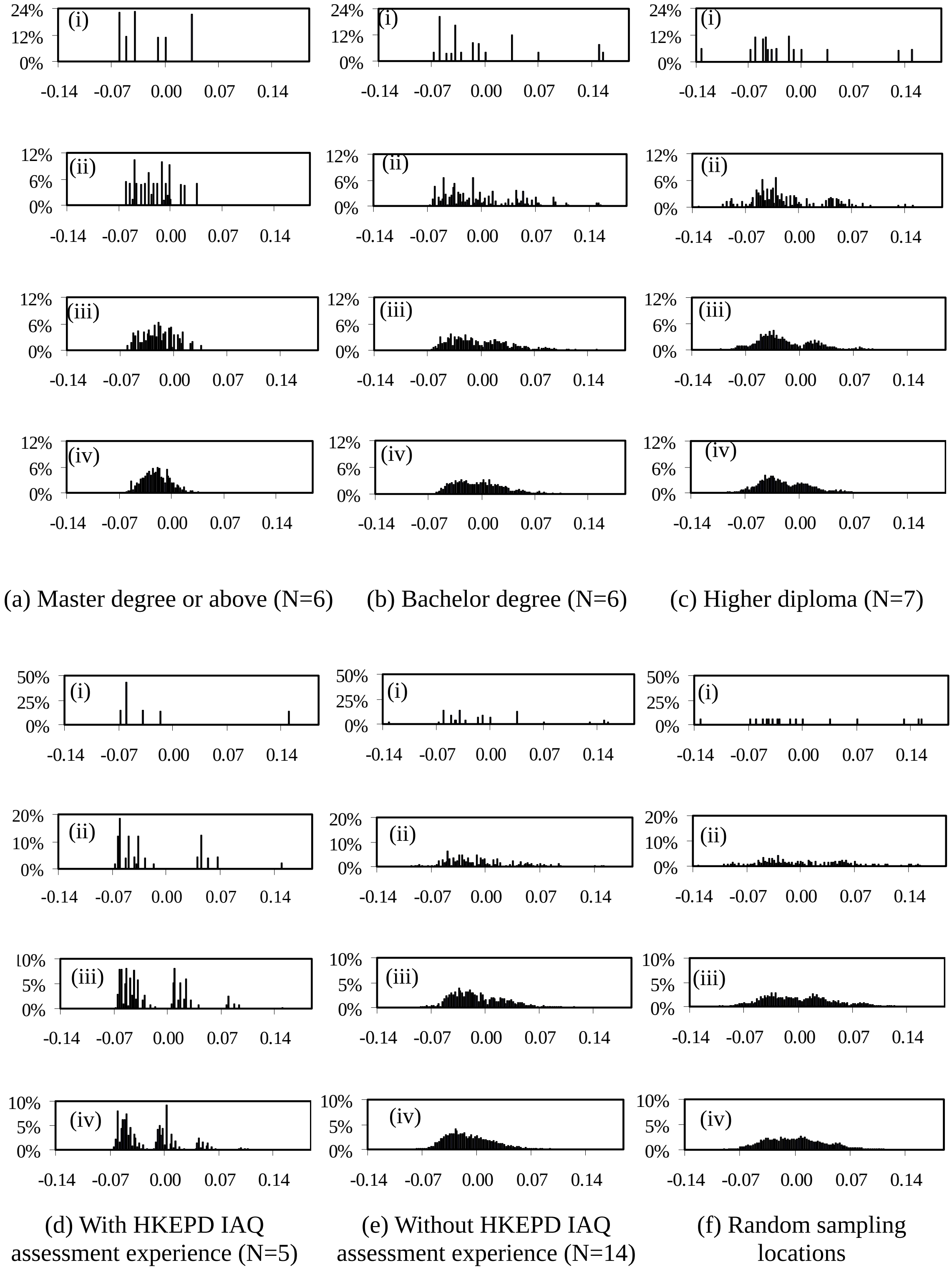


Figure 5.9: Confidence level by different sampling point densities and set error limits

Scheme confidence level with professional selection of sampling locations

With the professional selection preference expressed in the interview survey, IAQ assessment for the average CO_2 concentrations was made according to the assessors' choices of sampling locations, with the number of sampling locations r = 1, 2, 3 and 4 for sampling point densities of 1200 m^2, 600 m^2, 400 m^2 and 300 m^2 per point (i.e. cases i, ii, iii and iv) respectively. The density functions of the normalized errors of the sample-spatial average concentration, compared with the spatial mean, are shown in Figures 5.10(a) to (e). For those scenarios with more than one set of probable sampling locations according to the assessors' choices, the normalized errors were evaluated by the Monte Carlo simulations. In the simulation, the density functions for each location selected were based on the assessors' choices frequency (as shown in Figure 4.9). Comparing with the results obtained at some randomly picked sampling locations (Figure 5.10(f)), the assessors' choices were found to have significant effects on the measurement results. In particular, group B1 (i.e. with the highest academic qualification), which made more consistent choices than the other two groups (B2 and B3), gave a more concentrated distribution especially when the number of sampling points was increased. As the figures shown, however, differences between groups B2 and B3 were less significant.

For the group with experience in the HKEPD IAQ assessment (A1), their common choice of location 12, which had a sample-time average CO_2 concentration lower than the spatial mean, dominated the resultant density functions: a considerable portion of the assessed concentrations skewed to the left and lied beyond some arbitrary error limit envelopes, e.g. E = 1-9%. And that posed a greater probable error to the IAQ assessment results. Nevertheless, the assessed CO_2 concentrations made by the groups A1 and A2 against the arbitrary set error limits had no significant difference ($p \geq 0.09$, t-test).



x-axis: Normalized error
y-axis: Percentile (%)

(i) A_s = 1200 m^2
(ii) A_s = 600 m^2
(iii) A_s = 400 m^2
(iv) A_s = 300 m^2

Figure 5.10: Normalized error distributions of the IAQ assessment results

In the study, the probable measurement errors with the professional choice of 'representative' sampling locations for IAQ assessment at a sampling point density were further evaluated and expressed by the number of sample averages which fell within the probable error limits of the sample-spatial average concentration. The confidence level ξ_r of the assessed concentrations at the chosen location(s) r within the probable errors E of ±1% to ±5% from the spatial mean CO_2 concentration $\mu_{\Re}$ were evaluated and the results are shown in Figure 5.11. Probabilities for the randomly selected assessment locations were shown together for comparison. With the expert choices, it was found that the assessment results would provide a significant improvement in the assessment accuracy at coarse sampling point densities, e.g. 600 m^2, 400 m^2, 300 m^2 and 200 m^2 for r = 2, 3, 4, with an engineering acceptable error limit E = ±5% as shown in the figure. Interestingly, with or without the expert judgment, there would be no significant difference regarding the measurement accuracy between the location choices for error limits from ±1% to ±3%. The results also showed that the benefit of the above accuracy improvement would be diminished if more sampling locations were used in the assessment.

As the choice of IAQ assessment locations would be dependent on the academic background of the participants, the accuracy of the IAQ assessment results were evaluated for the participants according to their academic background, i.e. groups B1, B2 and B3. Taking an arbitrary set error limit of ±5% as a reference, the probabilities of the assessment results for these groups within the limit were shown in Figure 5.12. Results for all participants together and for the random assessment locations were shown for comparison.

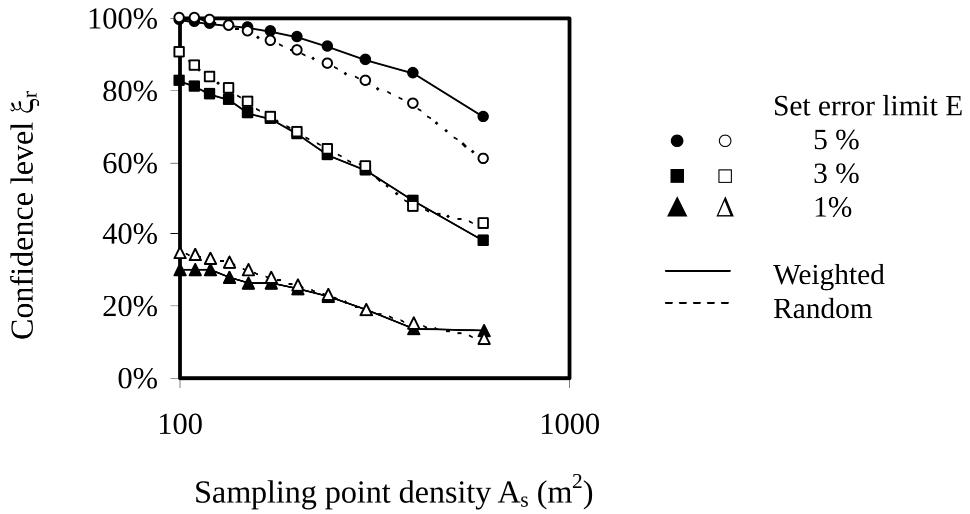


Figure 5.11: Confidence level of the IAQ assessment results at different sampling point densities

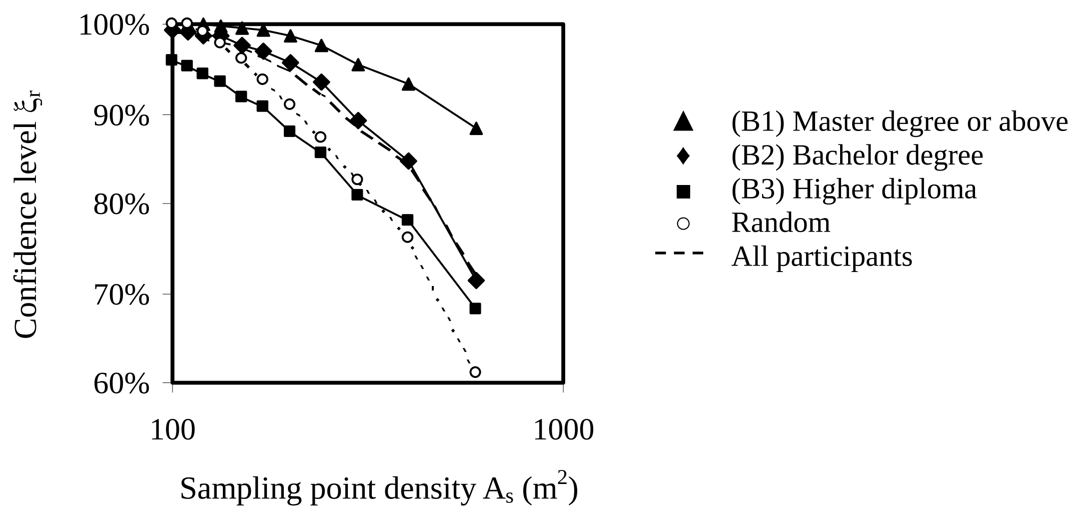


Figure 5.12: Confidence level of the IAQ assessment results against the participants' choices of sampling points

For coarse sampling point densities A_s = 300-600 m^2 in Figure 5.12, the assessment results from group B3's choices were found to be similar to those from the random assessment locations; while those from choices made by groups B1 and B2 would be more accurate as their probabilities were found higher. At A_s = 600 m^2, the probability of getting an assessment result within E = ±5% increased from 0.61 for a randomly selected assessment location to 0.89, 0.71 and 0.69 for a location chosen by experts with a master degree or above, a bachelor degree and a higher diploma respectively. It was observed that the assessment accuracy would be improved with the assessors' academic level.

5.5 Flexibility in choice of sampling time period and sampling point density

When assessing an IAQ parameter, accuracy of a sampling could be quantified as the combination of the uncertainties associated with different sampling periods and sampling point densities when compared with the long-term average pollutant level over a space. The confidence level ξ' of an assessment result obtained from a sampling period of τ_m (h) on r points would be expressed as,

$$\xi' = \xi_{\tau_m} \xi_r \qquad \ldots (5.7)$$

Based on the one-year CO_2 measurement results, the confidence levels of adopting a sampling point density A_s of 500m^2 and an 8-hour continuous measurement are 71% and 58% respectively. Therefore, conducting an IAQ assessment that follows the sampling schemes recommended by HKEPD would result in a confidence level ξ' of 41% of the yearly spatial average. Taking the confidence level of 41% as the "acceptable" uncertainty in current practice, alternative IAQ sampling schemes which would provide the same confidence level as HKEPD recommendation but with different combinations of sampling point densities and sampling periods were derived as shown in Figure 5.13. It shows a concession between the number of sampling points chosen and the duration of the measurement needed. As extending the sampling period beyond 8 hours will not reflect the usual exposure of the occupants to pollutants during office hours, only sampling schemes using a shorter sampling period are shown. It was reported that measurements with the number of sampling points increased would significantly reduce the corresponding sampling period required, this would be obvious when the confidence level is higher. To maintain the same confidence level, for example, if the sampling point density A_s is doubled from 250 m^2 to 500 m^2 per measurement point (i.e. the value recommended in the HKEPD certification scheme), then the sampling period required will be reduced from 8 hours to 3 hours.

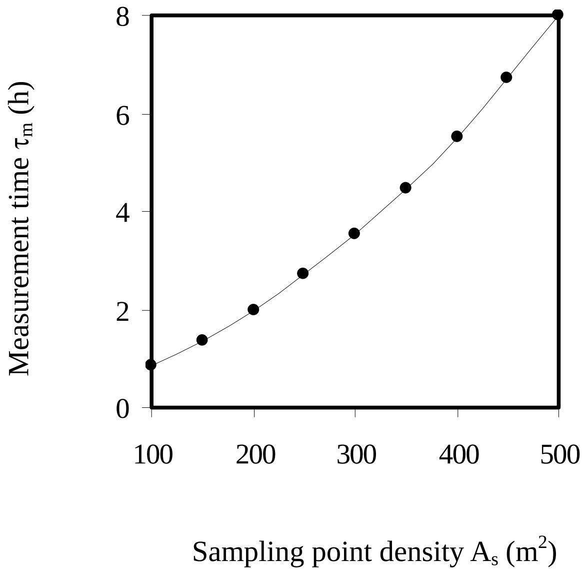


Figure 5.13: Alternative sampling schemes for IAQ assessment

Figure 5.14 illustrates the application examples of the three alternative schemes taken from Figure 5.13 with the ‘acceptable’ uncertainty associated with the current practice: point A, measurement period τ_m = 5.5 h at a sampling point density A_s = 400 m^2 per measurement point, point B, τ_m = 3.5 h at A_s = 300 m^2, and point C, τ_m = 2 h at A_s = 200 m^2. Over four typical working days in the office, the probable errors $|E|_{sch}$ deviated from the long-term sample average concentration for the three schemes were evaluated and compared with the probable errors $|E|_{ref}$ of the HKEPD recommended scheme. In particular, the probable errors were calculated by the number of sampled means that fell within the probable error limits of the long-term sample-spatial average concentration as a percentage of the total number of sample measurements made on that particular working day. Calculations were repeated for the sampled means obtained by the example schemes or by the recommended sampling period of 8 hours at a sampling point density of 500 m^2. The results showed that the probable errors ranged from 0.5% to 7% with an average of about 5%. The results reasonably agreed with the set error limit $|E|$ = 5% deviation from the long-term average. Adopting the example alternative schemes with a shorter sampling period but more sampling points would also provide the “acceptable” confidence level adopted in current practice.

Therefore, there is probable flexibility in choices between the number of sampling points and the duration of the measurement needed according to the “acceptable” uncertainty as recommended from reference sampling method. It provided scheme options that all parties could decide for the best resources allocation.

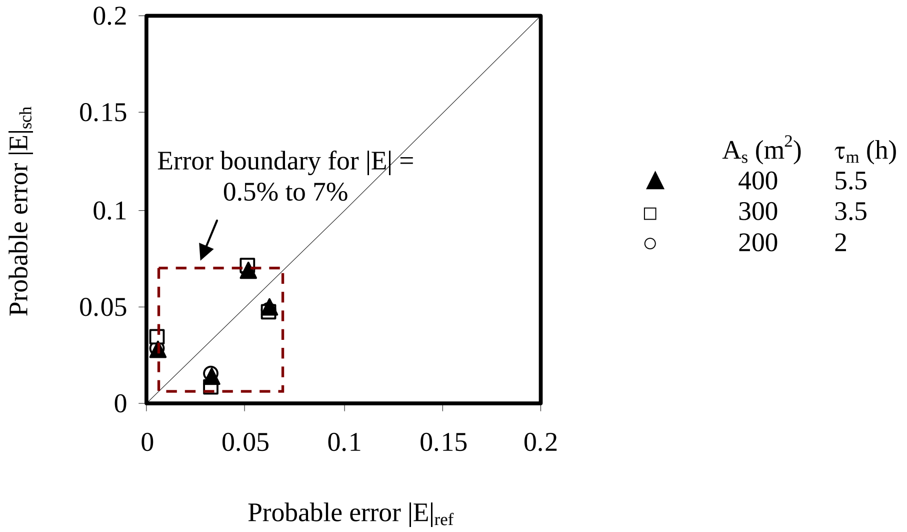


Figure 5.14: Probable errors of alternative sampling schemes

5.6 Conclusion

The objectives of this study are to develop a practical IAQ monitoring and assessment protocol for promoting better IAQ of air-conditioned offices in subtropical climates. As the bases of the protocol, IAQ assessment results of selected representative pollutant levels should be obtained from sampling schemes at acceptable assessment uncertainties regarding sampling locations and times. This chapter evaluated various sampling schemes and demonstrated their applicabilities. It discussed the formulation and the analysis of the proposed assessment protocol using the database of a comprehensive cross-sectional survey on common indoor air parameters and the long-term measurement on CO_2 and radon in air-conditioned offices of Hong Kong, as reported in Chapter 4.

The probable errors deviated from the population mean was used as indicators for comparing the predictions of various schemes. The confidence levels were evaluated and the goodness-of-fit for the proposed assessment schemes in obtaining representative assessment results were presented with the fractional bias (FB) and the normalized mean square error (NMSE).

Regarding the choice of assessment parameters, it was shown that selecting representative parameters by identifying a small number of dominant contributors of unsatisfactory IAQ would provide acceptable accuracy with reduced measurement effort. The accuracy of the proposed scheme in assessing office IAQ was good enough to identify over 90% of unacceptable offices against, comparing with the reference assessment scheme in Hong Kong. Concurrently, reasonable predictions could be made by another proposed model with assessed carbon dioxide (CO_2), respirable suspended particulates (RSP), and total volatile organic compounds (TVOC) levels. These three parameters were judged to be indicative for the performance of IAQ control through dilution, removal, or source control respectively.

Presenting the assessment results of the proposed two sets of representative parameters with the IAQ index, the performance of the assessment for office IAQ was evaluated through the application of a screening test. The performances were expressed in terms of the test sensitivity, specificity and predictive values compared with the reference IAQ assessment. With a screening level set at the probability of unsatisfactory IAQ be 0.5, the test would provide over 70% correct IAQ problem identification.

Furthermore, the uncertainties of various sampling schemes were analysed using the year-round longitudinal measurement results. For a representative parameter, the required measurement period by a proposed scheme of two random sample averages from two time-equal sessions with an opposite reverse time sequence within the occupied period would have potential reductions up to 30% for CO_2 and 50% for radon, as compared to the 8-hour continuous sampling at the same confidence level and error limits. Furthermore, reducing the number of sampling points by 50% would decrease the probability of obtaining the sample-spatial average concentration at the same confidence level by 10% only.

Comparing with the random choices of sampling locations, the assessment accuracy with the expert choices of 'representative' sampling locations were significantly improved for coarse sampling point densities at an engineering acceptable error limit of ±5% deviated from the sample-spatial average CO_2 concentration. It was reported that the location choices and assessment accuracy would be significantly influenced by the academic background of the assessors. An assessor group with higher academic level would make a choice leaning towards more accurate assessment results.

Detailed uncertainties of IAQ assessment and proper training of IAQ assessors are required for usable assessment results. This study provided a template for further investigations into the uncertainties of IAQ assessment results involving professional choice of sampling locations. With these uncertainties quantified, policymakers could decide on the manpower and resources required for the sampling strategies and the inappropriate level of reliance on the assessment results could be avoided.

With the validity of the assessment schemes verified, and taken uncertainties into account, this simplified protocol provides an easy tool for performing IAQ monitoring in offices and will be useful for determining appropriate mitigation measures in a cost-effective way.

Chapter 6

Feasibility of accuracy improvement with the epistemic approach

6.1 Introduction

In the previous chapters, the formulation of an assessment protocol for IAQ measurement has been discussed in terms of the accuracy of the assessment schemes, and the trade-off between measurement efforts and accuracies. As the schemes are not promising to give the true exposure concentration, possibilities of accuracy improvement with limited further measurement efforts by using additional information are evaluated. The use of the information relies on the applications of mathematical treatments for improving the level of beliefs or reducing the measurement efforts required for current assessment.

This chapter explains the proposed idea of applying the epistemic assessment for judging IAQ acceptance and regional IAQ monitoring, followed with example applications for feasibility demonstrations.

6.2 Basic ideas

In view of the technical difficulties in applications of the schemes in the protocol, a more effective and efficient assessment can be developed. It would provide better understanding on how to interpret the assessed results from the schemes to judge the IAQ acceptance of the space, and the use of already available information to improve present understanding.

IAQ assessment result is knowledge on the space; judgment of acceptance would be made from a belief based on evidence. Source of evidence sometimes includes more than the assessments from current measurement, but also prior knowledge on the probable IAQ level of the space. The prior knowledge can be the past assessment records at that space, the probable levels of similar space type in the region, and the level of belief based on the accuracy of an assessment scheme.

It is believed that prior knowledge of IAQ satisfaction in the form of the regional survey of similar type of spaces with updated assessment information may help judge the acceptance of the currently assessed space through a Bayesian approach. Accordingly, before an intensive IAQ assessment, preliminary measurements at some locations would give an understanding of the general IAQ and hence evidence of IAQ acceptance of an office is to be assessed.

When assessing the IAQ of a space, measurement errors of the sampling methods can lead to a bias in the exposure-effect relationship. Refinements of assessment methods are required so that a cost-effective, representative, and user-friendly procedure can be developed for the practitioners with the uncertainties of the measured quantities also quantified. Therefore, this study demonstrates the use of an epistemic approach in assessing the acceptable IAQ of an office with respect to certain exposure limits of indoor pollutant level by a sample test regarding a pollutant with pre-measurement knowledge of the IAQ. The prior knowledge on pollutant level distributions of offices in the region, in this case, is used to account together with the probable errors of the adopted sampling schemes to work out the posterior probability by Bayesian' theorem for evaluating the acceptance of IAQ against an action level of remedy.

Furthermore, long-term and comprehensive measurements of air pollutant levels may not be a good approach to the monitoring of regional indoor air pollution levels in terms of intensive resources involved. Assessment results with limited samples, however, may be deficient in representing personal exposures. Uncertainties resulting from sampling variations can be improved with statistical methods. A rapid estimate of the office failure rate using the epistemic assessment is applicable to a timely and cost-effective decision on the mitigation actions of IAQ control. This requires prior knowledge of the office probable failure rate and the current assessment results. The likelihood of unsatisfactory for a pollutant level from observation of a fewer number of samples from a survey would update the “prior” knowledge of the air pollutant concentration distributions and thus the unsatisfactory probability from the regional survey of other similar spaces.

6.3 Epistemic assessments for IAQ acceptance

In assessing the acceptance of IAQ, an office having an average indoor air pollutant level in the occupied period higher than a certain set limit is considered as ‘unacceptable’, and appropriate remedial actions must be taken. As discussed in Chapter 5, different sampling schemes adopted associate with different levels of uncertainties as compared with the long-term average of the assessing parameters. Apart from the existing commonly adopted 8-h continuous sampling, alternative sampling schemes of short-term measurement in assessing average indoor pollutant levels of Hong Kong offices are proposed in this study. During the IAQ assessment, a sample average pollutant level Φ_{sch} (i.e. a test value) with a set concentration limit Φ^* over certain exposure time is used to evaluate the acceptance of the environment. A negative test outcome ($\Phi_{sch} \leq \Phi^*$) indicates a space of an ‘acceptable’ pollutant level while a positive test outcome ($\Phi_{sch} > \Phi^*$) indicates otherwise. If the space is 'unacceptable' (event A) and the test would come back positive (event B), then the probability of a positive test given an 'unacceptable' environment is P(B|A). Since the test results are subject to uncertainties, a test might give a false positive in an 'acceptable' environment, i.e. $P(B \mid \overline{A})$. Hence, the probability of having an 'unacceptable' environment $P(A \mid B)$ given a positive test P(B) can be determined by a conditional probability, where P(A) is the 'prior' probability of event A before the test is conducted,

$$P(A \mid B) = \frac{P(A)P(B \mid A)}{P(B)} \qquad \dots (6.1)$$

Prior knowledge of office IAQ

IAQ test result of an assessed office is used as the 'prior knowledge' of the office for further assessment. Repeated positive test results would indicate an 'unsatisfactory' IAQ and repeated negative test results would confirm the acceptance. For an office without any 'prior' IAQ assessment, results of other similar offices from the same region are used as a reference for the 'prior' knowledge in the epistemic assessment. The failure rate P(A) of the offices, i.e. the fraction of offices in a region (e.g. a district or a city) having long-term pollutant levels Φ_i above the set limit Φ^*, can be expressed by a density function of pollutant levels $\hat{\Phi}_i$ obtained from measurements in all similar spaces i over the region,

$$P(A) = 1 - \int_{-\infty}^{\Phi^*} \hat{\Phi}_i \, d\Phi_i \qquad \dots (6.2)$$

Uncertainties of sampling schemes

Accuracy of results from sampling schemes is closely related to the test value Φ_{sch} gained from a relatively 'short-term' sampling of up to 8 hours. Since indoor pollutant levels are transient, the probable sample average pollutant levels produced by a sampling scheme on any sampling day over a 'longer-term' measurement period, e.g. one year, would be described by certain distribution function $\hat{\Phi}_{sch} \sim \hat{\Phi}_{sch}(\mu_{sch}, \sigma_{sch})$, where μ_{sch} and σ_{sch} are the mean and standard deviation of the measured average pollutant levels respectively. With the criterion of an acceptance from the sample result, the probability $P(B \mid A)$ would be given by,

$$P(B \mid A) = 1 - \int_{-\infty}^{\Phi^*} \hat{\Phi}_{sch}\, d\Phi_{sch} \qquad \ldots (6.3)$$

Uncertainties of a sampling scheme affect the confidence of a test result. At an arbitrary allowable probability of 'false positive', the test pollutant levels required with respect to the uncertainties of a sampling scheme can be expressed as Φ^- for ensured satisfactory environment and Φ^+ for ensured unsatisfactory environment. The test result is noted positive ('+') for $\Phi_{sch} \geq \Phi^+$, or negative ('−') for $\Phi_{sch} \leq \Phi^-$. The positive test results at a test pollutant concentration $\Phi_{sch} \geq \Phi^+$ indicate 'unsatisfactory' while negative test results $\Phi_{sch} \leq \Phi^-$ confirm the acceptability. For an assessed office with a test result $\Phi^- < \Phi_{sch} < \Phi^+$ at certain probability of acceptance, further tests are required to 'confirm' the acceptance.

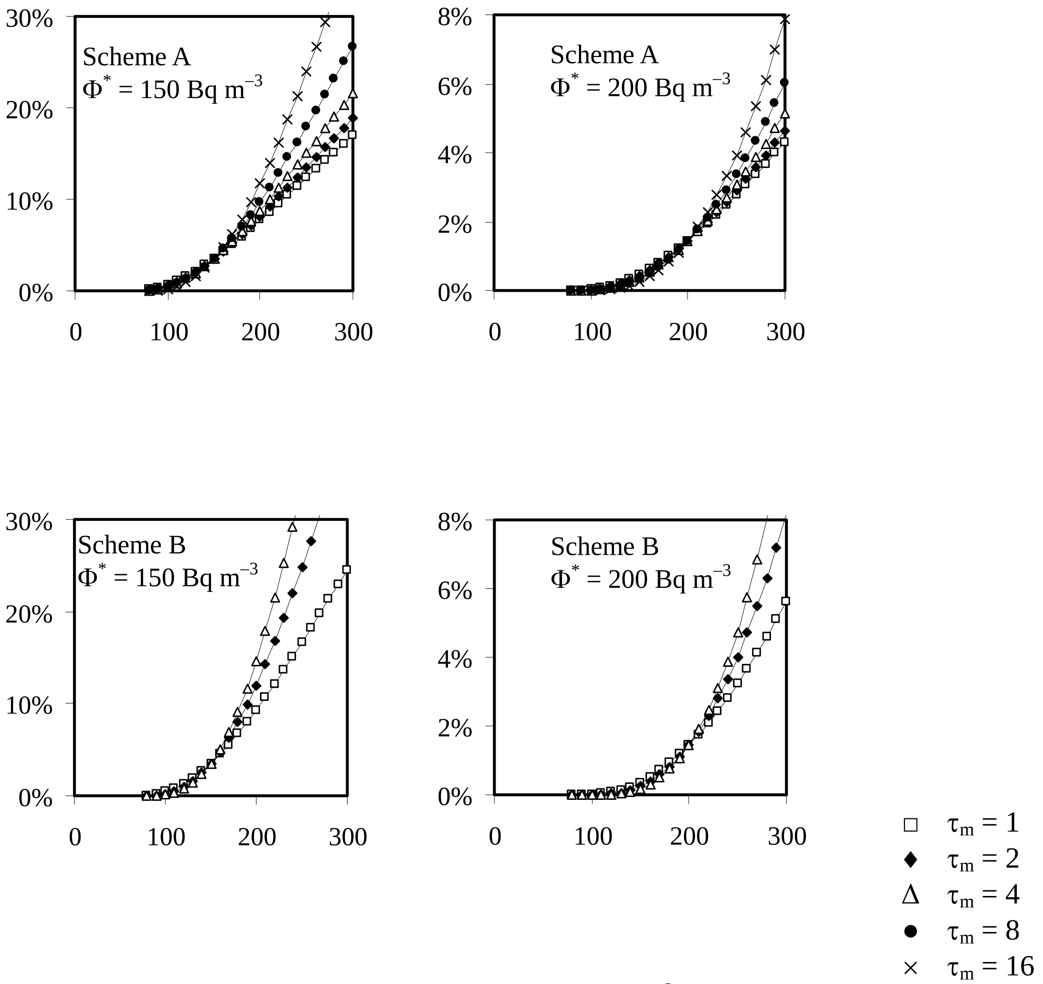
Application examples

For demonstration, application of the epistemic approach to radon level assessment is performed in this study as an example. The prior understanding of pollutant level acceptance, the previous cross-sectional assessment results discussed in earlier chapters are referred to, radon levels of 216 office samples from the regional survey database are taken for analysis.

The distribution of radon concentrations at the occupied zones of the 216 offices during office hours is approximated by a geometric distribution function, with the geometric mean radon level of 37.2 Bq m^{-3} and 68% range of radon levels from 17.3 Bq m^{-3} to 80.3 Bq m^{-3}. It is reported that 96.5% and 98.6% of the office samples would be satisfactory with an action radon level of 150 Bq m^{-3} and 200 Bq m^{-3} respectively. As the distribution is taken as the radon levels in Hong Kong office environment in this study, with Equation (6.2), the probabilities of having an ‘unacceptable’ environment P(A) at radon levels 150 Bq m^{-3} and 200 Bq m^{-3} are 0.035 and 0.014 respectively.

Judgment about an acceptable IAQ regarding the indoor radon level in an office is based on the test results. Apart from the 8-hour continuous measurement (Scheme A_8), alternative sampling scheme of two random samples in two equal sampling periods of 2 hours (Scheme B) is adopted in this study.

With the uncertainties of the sampling schemes, in terms of uncertainty ratio $\varepsilon = \sigma_{sch} / \mu_{sch}$, the acceptance probabilities of an office environment with a test radon level are determined by Equation (6.1). At a measurement time used to assess the acceptable radon level, Figure 6.1 shows the probabilities of acceptance with a test radon level Φ_{sch} (Bq m^{-3}) concerning an unacceptable radon level (Φ^* = 150 Bq m^{-3} or 200 Bq m^{-3}). In the figure, the probability of ‘unsatisfactory’ (indicated by the Y-axis) is increased as the difference between the test value and the unacceptable radon level ($\Phi_{sch} - \Phi^*$) increases. The results also indicated that the measurement schemes and the sampling time have some effects on the result uncertainty. It confirms that a longer sampling period would reduce the probability of ‘false positive’.



X-axis: Tested radon concentration Φ_{sch} (Bq m^{-3})
Y-axis: Probability of ‘unsatisfactory’ given a positive test P(A|B)

Figure 6.1: Probabilities of an office having an ‘unacceptable’ radon level

For an office with an unknown radon level, the regional distribution of radon levels of offices are considered, and P(A) of 0.035 and 0.014 would be assumed. Figure 6.2 illustrates the test radon levels Φ^- and Φ^+ required with respect to the uncertainties of a sampling scheme at an arbitrary allowable probability of 'false positive' at 0.6%, 0.8%, 1% and 1.2%, for the action levels of 150 Bq m^{-3} and 200 Bq m^{-3}. The uncertainties of some sampling schemes adopted in practice are shown for illustration.

The result showed that for a sampling method having a higher uncertainty, a lower test value would be required in order to ascertain acceptance, and to confirm an unacceptable environment with a higher test value. For example, at an allowable probability of 'false positive' of 1%, a test result of 180 Bq m^{-3} given by Scheme A_8 (8 hours continuous measurement) cannot certify the space with unacceptable radon level at the set concentration limit $\Phi^* = 150$ Bq m^{-3}, while the same test result given by Scheme B_4 (two random samples in two equal sampling periods of 2 hours) would confirm unsatisfactory environment.

For an assessed office with a test result at certain probability of acceptance, further tests can be conducted to 'confirm' the acceptance. Figure 6.3 shows an example probability of unsatisfactory for an office in Hong Kong with a number of repeated tests N_{sch}, using example sampling schemes of typically low and high uncertainty ratio $\varepsilon = 0.2$ and 0.6. The probability using current practice is shown for comparison. The results showed that repeated positive test results at a test radon concentration Φ_{sch} would indicate 'unsatisfactory' while negative test results would confirm the acceptability. This is obvious as seasonal variations of radon level in a typical office environment were encountered (Man et al. 1994, Pang and Pun 1994). Repeated measurements can be useful to certify an indoor environment with an acceptable radon level as illustrated in this study. Concerning efforts of measurements, however, preliminary tests using sampling schemes with higher uncertainty can be considered.

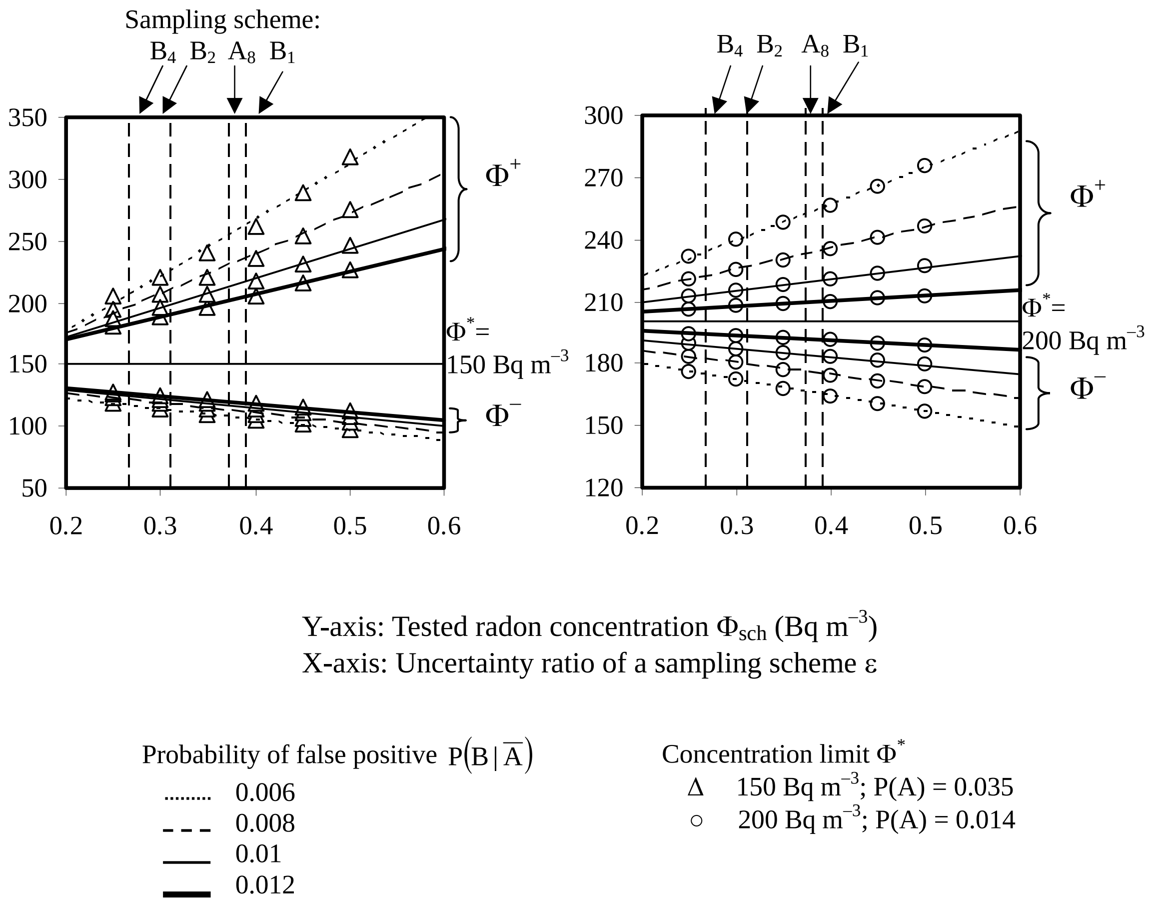


Figure 6.2: Maximum test values for indoor radon levels Φ^*

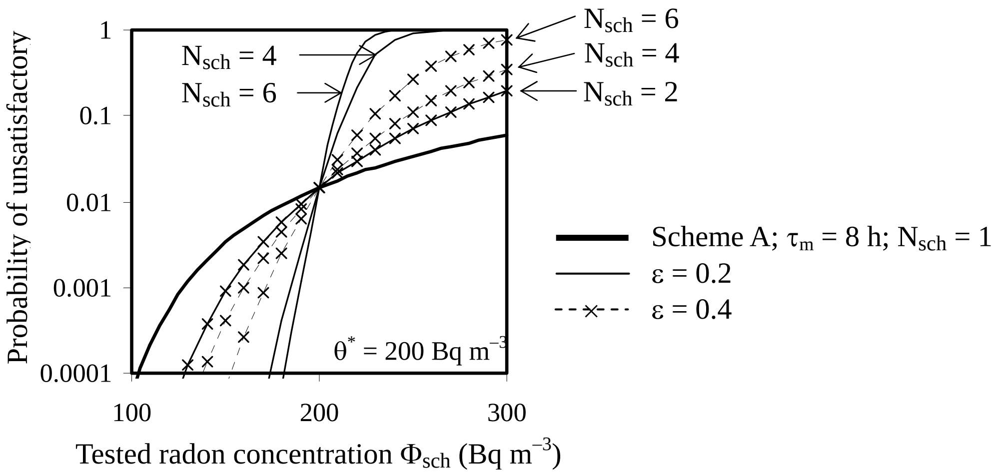


Figure 6.3: Probability of unsatisfactory with repeated tests at a radon concentration Φ_{sch}; at an unsatisfactory radon level 200 Bq m^{-3} for an office in Hong Kong

6.4 Epistemic assessments for regional IAQ monitoring

In an epistemic assessment, the IAQ assessment results of other similar offices over a region can be used to formulate the ‘prior’ knowledge. A regional survey of indoor pollutant levels requires considerable efforts and the results are very useful in understanding the overall picture of regional IAQ.

Measurement of a few samples is deficient in representing the overall environmental conditions for the population, however, in practical measurements, only a finite number of samples can be assessed in a given time frame, with a balance of measurement effort and accuracy. The measured radon distribution $\tilde{\Phi}_N$ of N samples from the population would be taken as ‘the distribution’ for offices in a region $\tilde{\Phi}_\infty$ if N is ‘sufficiently’ large. The ‘failure probability’ with respect to a set concentration limit Φ^* would be approximated by, where $\hat{\Phi}_N$ are pollutant levels among offices approximated by a geometric distribution, with μ_N and σ_N are geometric sample mean and sample standard deviation from i samples.

$$P(A)\Big|_{\infty}^{\Phi^*} \approx P(A)\Big|_{N}^{\Phi^*} = 1 - \int_{-\infty}^{\Phi^*} \hat{\Phi}_N \, d\Phi_N \; ; \qquad \begin{cases} \hat{\Phi}_N(\mu_N, \sigma_N) \approx \hat{\Phi}_\infty \\ N >> 0 \end{cases} \qquad \ldots (6.4)$$

For continuous monitoring of the office IAQ in the region, further smaller-scale regional measurements (denoted as the ‘second survey’) can be conducted with a ‘smaller’ sample size $N_s < N$. It is suggested to apply the idea of Bayesian statistics to improve the accuracy of the approximated failure probability $P(A)|_\infty$ from a survey distribution $\hat{\Phi}_{N_s}$ with ‘fewer’ samples available in the earlier stage of an intensive regional survey study. The distribution $\hat{\Phi}_{N_s}$ is ‘corrected’ by a ‘sample correction factor’ φ, where μ_{N_s} and σ_{N_s} are the estimated average and standard deviation of the pollutant concentrations from the second survey of smaller size, $\overline{\Phi}_{N_s}$ and s_{N_s} are the sampled average pollutant concentration and its sampled standard deviation from the second survey, μ_N and σ_N are the population mean concentration and the standard deviation from the first detailed regional survey, w_{N_s} and w_N are the weighting factors for the two survey quantities,

$$\hat{\Phi}_{N_s} = f\left(\mu_{N_s}, \sigma_{N_s}\right); \quad \sigma_{N_s} = \varphi s_{N_s}, \ \mu_{N_s} = \frac{w_{N_s}\overline{\Phi}_{N_s} + w_N \mu_N}{w_{N_s} + w_N},$$

$$w_{N_s} = \frac{N_s}{s_{N_s}^2}, \ w_N = \frac{1}{\sigma_N^2} \qquad \ldots (6.5)$$

Apart from a new assessment without any prior mean that the survey average would be taken as the mean, however, it was suggested that for an unbiased estimate of the population standard deviations, a constant sample correction factor φ, irrespective to the set concentration limits Φ^*, can be taken as (Andersen et al. 2001),

$$\varphi \approx \varphi_k = \sqrt{\frac{N_s - 1}{2}} \frac{\Gamma\left(\frac{N_s - 1}{2}\right)}{\Gamma\left(\frac{N_s}{2}\right)}; \qquad \ldots (6.6)$$

The validity of the constant sample correction factor φ_k for IAQ assessment would be examined with measurement results obtained from large-scale measurements over a region. With the distribution of measured average pollutant concentrations of N offices $\Omega = \left[\langle\Phi_1\rangle, \langle\Phi_2\rangle, \ldots \langle\Phi_N\rangle\right]$ in a region, the pollutant levels of N_s offices can be randomly sampled from survey database Ω in order to evaluate the distribution function $\hat{\Phi}_{N_s}$. The sample correction factors φ against certain concentration limits Φ^* would be determined from anyone of the arbitrarily selected N_s samples from N offices by equating the two probable failure rates from samples N_s and N, i.e. $P(A)\big|_{N_s}^{\Phi^*} = P(A)\big|_{N}^{\Phi^*}$ and, $\sigma_{N_s} = \varphi s_{N_s}$. It is noted that a total of N_s-combinations C(N, N_s) would be encountered and the sample correction factors can be described by certain distribution function $\hat{\varphi}_{N_s}$. For a very large N of normally distributed concentrations, the expected sample correction factor would be approximated by the constant sample correction factor $\varphi_{N_s} \approx \varphi_k$.

Analysis with existing database

As demonstration, data from the two cross-sectional measurements of indoor radon levels are used to evaluate the proposed method in this study. The measurement results from the regional survey of 422 air-conditioned offices in Hong Kong have been selected and divided into two datasets. Radon levels at 216 offices reported in the previous section are taken as the first district survey with their geographical locations summarized in Figure 6.4. A primitive caution has been applied to ensure that the selection was random enough to represent the overall situation of Hong Kong - all the 216 samples were selected in a way that they covered all the regions for office development on the largest peninsula of Hong Kong. The second district survey was taken at 97 offices in the local commercial area, where high-class and quality environments were provided. The offices mainly locate on two major islands of Hong Kong as shown in Figure 6.4. With the proposed sample correction factor φ from the first survey for office radon level assessment in the region, this database is used to determine the failure probabilities of workplace IAQ in the city centre. It is acknowledged that building age has some effects on the sources of pollution. Nevertheless, the sampling premises in this study were selected with a building age of 5 to 10 years such that their respective building styles, materials used and periods after construction did not vary much.

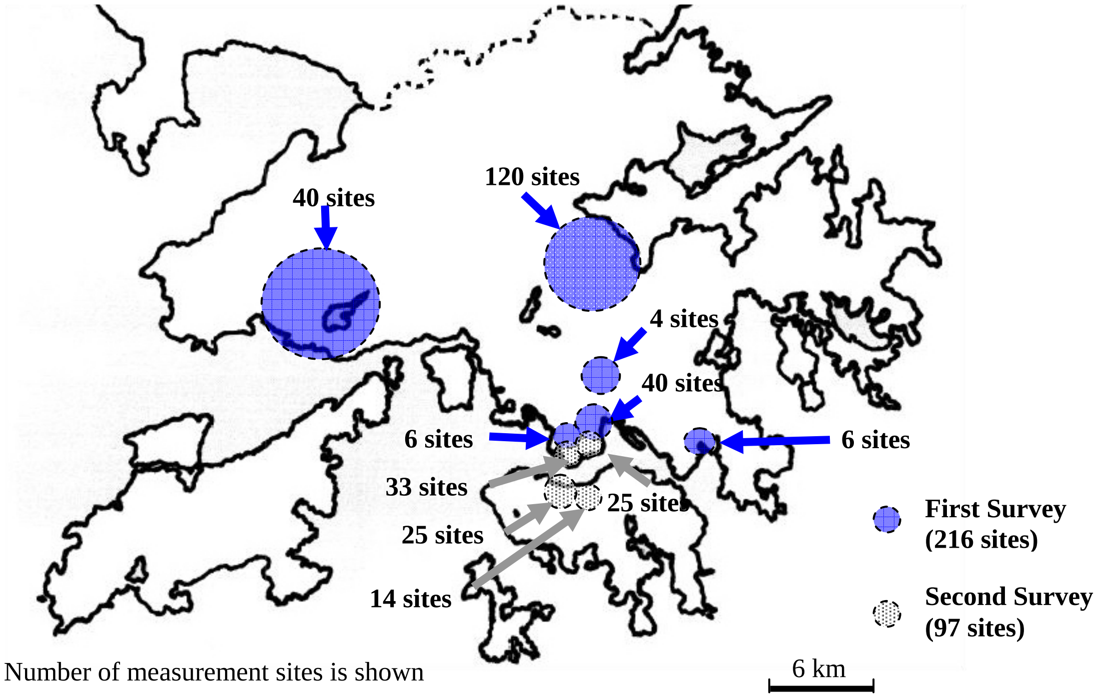


Figure 6.4: Measurement locations in Hong Kong (Latitude: 22.0° (22° 30' 0"); Longitude: 114.17° (114° 10' 1")

Approximate pollutant level profiles

As shown in Figure 6.5, the average radon concentrations of 'small-size' samples from N_s = 5 to 100 were approximated by geometric distributions and compared with the mean of all samples N = 216. As expected, when sample size N_s increases, the variance decreases and hence $\overline{\Phi}_{N_s} \rightarrow \mu_N$. The expected value of any sample size N_s is very close to the mean concentration μ_N. For example, the probabilities of the measured average concentrations fall within the acceptable error limits of μ_N±10%, i.e. 33.5-41.0 Bq m^{-3}, with sample size N_s = 5, 10, 25, 50 and 100 are 0.2329, 0.3269, 0.5167, 0.7077 and 0.9197 respectively.

Figure 6.6 shows the sample correction factors φ of sample sizes N_s = 20 to 100 for the set radon concentration limits Φ^* = 150 Bq m^{-3} and Φ^* = 200 Bq m^{-3}. Figure 6.7 shows the expected values of φ approximated by the Monte-Carlo simulations (with 100,000 trials). The process was: (1) the sample mean and sample variance were calculated from N_s random samples among the 216 surveyed samples; (2) under each set radon concentration limit Φ^*, the failure probabilities $P(\Phi<\Phi^*)_{N_s}$ was determined, and then by equating $P(\Phi<\Phi^*)_{N_s}$ and $P(\Phi<\Phi^*)_N$, φ was calculated; and (3) by repeating (1) and (2) 100,000 times, the likelihood function for $\varphi(N_s)$ was obtained and the maximum likelihood of φ could be determined. Expectedly, as sample size N_s increased, φ approaches unity with the probable error reduced. In the figure, the unbiased estimator φ_k of the population standard deviations for normal distribution is shown for comparison.

The results showed that the sample correction factors φ under the two set limits reasonably agreed with the estimator φ_k. As the average radon concentrations, especially with 'small-sized' samples, would not be perfectly log-normally distributed and the sample correction factors required in order that $P(\Phi<\Phi^*)_{N_s}$ would match $P(\Phi<\Phi^*)_N$ were dependent on the set limits, improved estimates on the failure probability P could be obtained by considering these set limits.

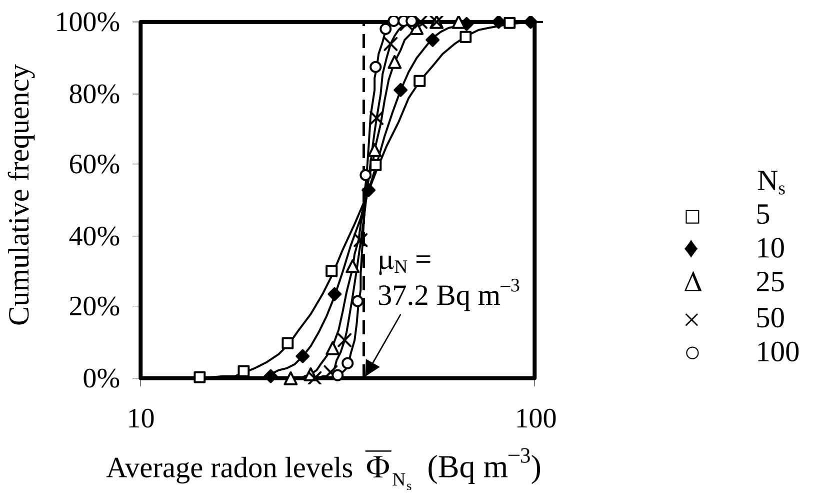


Figure 6.5: Average indoor radon concentrations with sample size N_s

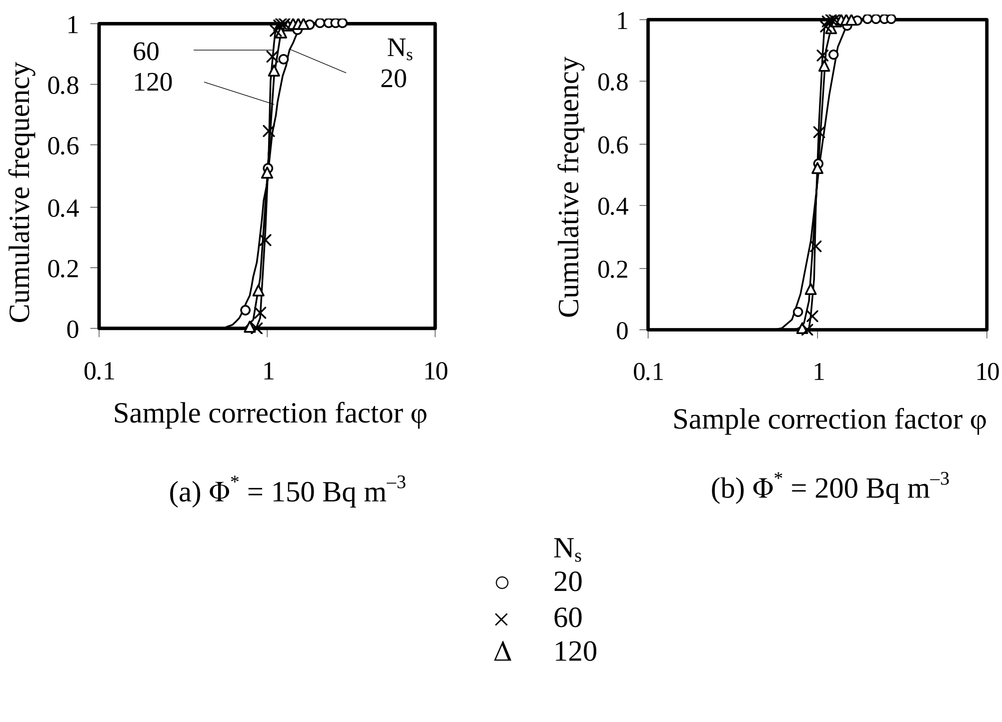


Figure 6.6: Likelihood function of sample correction factor φ

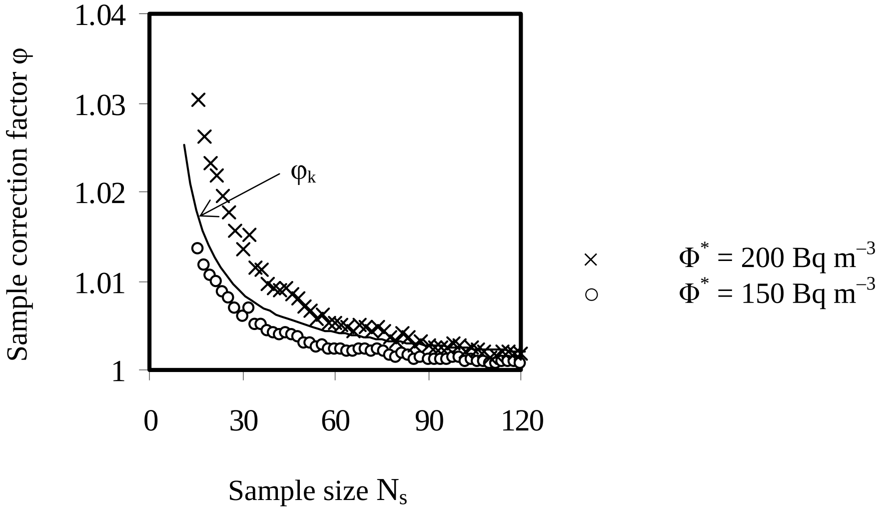


Figure 6.7: Sample correction factor φ of a sample size N_s

Figure 6.8 shows the failure probability P estimated under the set concentration limits (150 and 200 Bq m^{-3}) with random samples of N_s = 20 to 120 from the database (N=216) by applying φ for 100,000 trails. The averages and the 68% ranges of the predicted P are summarized in Table 6.1; the latter decreases with larger sample size. Predictions without φ and with $\varphi = \varphi_k$ are shown for comparison. When compared with the 'true' values from all samples, as expected, the predictions with φ and φ_k applied yield an improved accuracy.

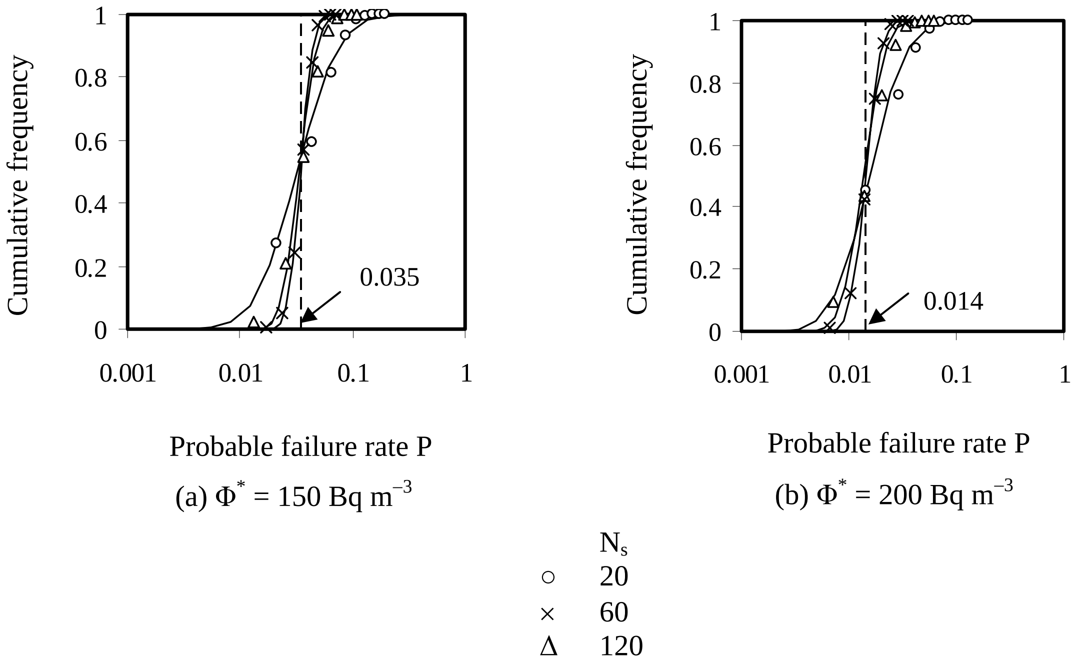


Figure 6.8: Failure probabilities P with set radon concentration limits Φ^* = 150 Bq m^{-3} and 200 Bq m^{-3}

Table 6.1: Failure probability of an office environment exceeding a radon concentration limit (N=216)

Sample size N_s	P at $\Phi^* = 150$ Bq m^{-3}		P at $\Phi^* = 200$ Bq m^{-3}	
	Average	68% range	Average	68% range
		No correction factor applied (i.e. $\varphi = 1$)		
20	0.0291	0.0113 to 0.0747 (–68% to 114%)	0.0113	0.0034 to 0.0377 (–76% to 170%)
60	0.0336	0.0223 to 0.0506 (–36% to 45%)	0.0136	0.0081 to 0.0230 (–42% to 65%)
120	0.0347	0.0278 to 0.0431 (–21% to 23%)	0.0142	0.0107 to 0.0188 (–24% to 35%)
		$\varphi = \varphi_k$		
20	0.0308	0.0122 to 0.0774 (–65% to 121%)	0.0122	0.0037 to 0.0397 (–74% to 184%)
60	0.0341	0.0227 to 0.0513 (–35% to 47%)	0.0140	0.0083 to 0.0235 (–41% to 69%)
120	0.0350	0.0281 to 0.0435 (–20% to 25%)	0.0144	0.0109 to 0.0190 (–22% to 36%)
		$\varphi = \varphi(N_s)$		
20	0.0304	0.0120 to 0.0767 (–66% to 119%)	0.0129	0.0041 to 0.041 (–71% to 193%)
60	0.0339	0.0275 to 0.0510 (–35% to 46%)	0.0141	0.0084 to 0.0237 (–40% to 69%)
120	0.0348	0.0279 to 0.0433 (–20% to 24%)	0.0144	0.0109 to 0.0190 (–22% to 36%)

( ) is the percentage error of P comparing with the 'true' mean P_N calculated from all 216 samples under the two set limits, i.e. P(Φ<150) = 0.035; P(Φ<200) = 0.014.

Application examples

It is expensive to conduct an extensive regional survey for all offices in the city centre. In practical measurements, the sample size of each district in the city centre could be small for establishing results with high confidence level. Therefore, the developed model with the sample correction factor defined is used to estimate the regional failure probabilities with a set radon concentration limit $\Phi^* = 150$ Bq m^{-3} for offices in different districts of the city centre. Table 6.2 summarises the observations and predictions of four districts (A-D) in the city centre of Hong Kong from the second survey. Differences in failure probabilities of office IAQ have been reported in these districts. The model estimates showed a reasonable consistency with the observed failure probabilities.

The observed failure probability is determined by the actual count of offices with unsatisfactory IAQ divided by the total number of samples as shown in Table 6.2. Its resolution is dependent on the sample size. Since the sample size in each of the districts is small, large uncertainty is expected. Indeed, no failure has been reported in some of the districts and the probable observed failure probabilities for these districts are $\leq 1/(1+N_s)$ and half of $1/(1+N_s)$ as shown.

The predicted failure probability estimated by equating the two from samples N_s and N is shown for comparison. The predicted district failure probabilities P are shown in Figure 6.9 against the observed rates. The results show a good agreement between them, the latter fall within the 95% confidence level of the former. Hence, the proposed constant sample correction factor is applicable to prior knowledge determination for a relatively small sample size over a district in the city centre.

Table 6.2: Observed and predicted failure probabilities for offices in the city centre of Hong Kong

District	Sample size N_s	Failure probability P at $\Phi^* = 150$ Bq m^{-3}	
		Observed (CI = 95%)	Predicted (CI = 95%)
A	25	≤ 0.04 (0-0.11)	0.06 (0.03-0.10)
B	14	≤ 0.07 (0-0.20)	0.03 (0.01-0.07)
C	33	≤ 0.03 (0-0.09)	0.02 (0.01-0.03)
D	25	0.04 (0-0.12)	0.08 (0.05-0.12)

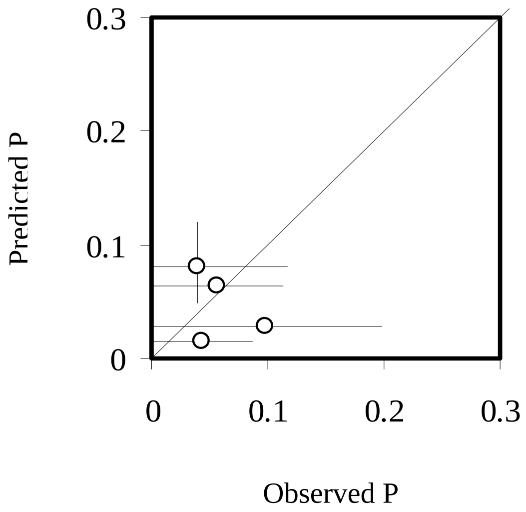


Figure 6.9: Failure probabilities of office IAQ in four districts of Hong Kong (Φ^* = 150 Bq m^{-3})

6.5 Conclusion

In view of the technical difficulties in applications of the schemes in the protocol, this chapter has proposed and discussed the possibility of a more effective and efficient assessment with limited further measurement efforts, through applications of mathematical treatments on already available information. Application of the epistemic assessment with prior knowledge for judging the IAQ acceptance and assisting regional IAQ monitoring was discussed, with example applications on indoor radon levels monitoring in Hong Kong for feasibility demonstrations.

The epistemic assessment approach, with the prior knowledge and a sample test result, is proposed to assess the acceptance against an action pollutant level of an office. This method can be applied to the offices for follow-up tests of acceptance, with the certainty of test results determined for judgmental purposes. Results from a longitudinal and a cross-sectional measurement of indoor radon concentrations in offices in Hong Kong, presented in previous chapters, were used to quantify the prior knowledge on indoor radon level distributions of an office. The results indicated that both measurement schemes and sampling time have effects on the result uncertainty. It was observed that a longer sampling period reduce the unacceptable probability.

At an arbitrary allowable probability of ‘false positive’, the test radon levels required with respect to the uncertainties of a sampling scheme at the action level of 150 Bq m^{-3} and 200 Bq m^{-3} were shown for illustration. For a sampling method having a higher uncertainty, a lower test value would be required in order to ascertain an acceptable indoor radon level, and to confirm an unacceptable environment with a higher test value.

Apart from assessment on a space, epistemic approach can also be applied in regional pollutant levels assessment. The existing IAQ assessment results of other similar offices over a region are used to formulate the ‘prior’ knowledge and be useful in understanding the overall picture of regional IAQ in current monitoring. Using the sample size and corresponding sample correction factor as defined, accompanied with estimation of the uncertainties associated, a fraction of local offices above certain set limit of radon concentration could be predicted from measurements of small samples (e.g. 10% of the target sample size) by the newly developed statistical model. Comparison between model predictions and actual measurements indicated that the model could be used for mapping indoor radon of Hong Kong offices.

With the proposed epistemic assessment approach, the accuracies of the sampling methods were taken into account in an assessment, justified assessment results can be obtained from limited further measurement with the help of prior understanding. It would be useful to policymakers for making appropriate decision with effective use of resources and manpower.

Chapter 7

IAQ benchmarking for air-conditioned offices

7.1 Introduction

When performing IAQ assessment on a space, apart from a number of technical difficulties in implementation such as the choice of representative parameters, sampling time period, sampling point density and influence of professional judgment on measurement uncertainty, the interpretation of the assessment results posed a barrier of understanding to the general public for promoting the IAQ care of the indoor environment.

On top of assessing the IAQ acceptance, a simple and readily understandable IAQ benchmark of the relative performance of an office environment offers incentive of promoting IAQ. This chapter discusses the feasibility of presenting the office IAQ by a 5-star rating system using the IAQ index as the benchmarking parameter, which assesses only the concentrations of some selected representative indoor air pollutants.

7.2 Benchmarking with IAQ index

This study proposes an 'IAQ index θ' determined from the average fractional dose against the exposure limits of a number of 'representative' air pollutants for IAQ assessment. This index value can give a qualitative indication of IAQ overall in the assessed environment with respect to the acceptable exposure levels.

Choices of a number of air pollutants as assessment parameters for an IAQ assessment were investigated in pervious chapters. An assessment can be conducted with only some parameters which dominant to the IAQ dissatisfaction or representative in showing the overall IAQ satisfaction at an acceptable probable inaccuracy. It was noted that the dominant contributors of unsatisfactory IAQ identified would not be identical among all offices in the region and would also change in time, which is less preferred to be selected as the bases for benchmarking.

Using the factor analysis for the nine common air pollutants and three thermal comfort parameters in air-conditioned offices in Hong Kong, it was reported in previous chapters that three out of nine common air pollutants could be selected as 'most representative' for the overall satisfactory IAQ. Insignificant correlations were found among RSP, CO_2 and TVOC, but significant correlations with other common air pollutants. In a typical mechanically ventilated space, they cover issues related to system performance in pollutant removal, dilution and source control. Therefore, RSP, CO_2 and TVOC would be the 'three representatives' equally rated for the overall IAQ acceptance among the nine common air pollutants found in Hong Kong air-conditioned offices.

An IAQ index θ in equation below, determined from the fractional dose Φ_i'' of these representative air pollutants $n_s = 1 \ldots 3$, i.e. CO_2, RSP and TVOC, to the exposure limits of IAQ acceptance Φ_i^* in assessing the IAQ satisfactory level for indoor environment, was proposed as the benchmarking parameters, where, Φ_i is the assessed average representative pollutant level over the exposure time period.

$$\theta = \frac{1}{3}\sum_{i=1}^{3}\Phi_i'' \;;\; \Phi_i'' = \frac{\Phi_i}{\Phi_i^*} \qquad \ldots (7.1)$$

A high value of θ would indicate that the environment is associated with a high probability of unsatisfactory IAQ.

Taking θ_i as an indicative measure of IAQ for an office indoor environment i from N samples, and $\hat{\theta}$ as the distribution of IAQ indices for all indoor environments of the same type over a region, the IAQ benchmark B_i for i-th environment is expressed by,

$$B_i = \int_{-\infty}^{\theta_i} \hat{\theta}\, d\theta;\ \hat{\theta} \sim \hat{\theta}(\mu_\theta, \sigma_\theta) \qquad \ldots (7.2)$$

Among all spaces in the region, an indoor environment with $B_i \leq 1\%$ indicates that it has the 'best' IAQ, i.e., this environment has the lowest exposure concentrations of the air pollutants contributed to the index among the database of the index; while with $B_i = 100\%$, it has the 'worst' IAQ.

7.3 5-Star benchmarking system

For simplicity, this study proposed a 5-Star rating IAQ benchmarking system because the star ratings have been widely adopted in daily applications, such as financial analysis and hotel rating. The system is deemed familiar to the public. Follow the criteria proposed for performance assessed by a continuous benchmarking parameter by Blume (1998), the benchmarking system assigns 1 star to the top 10% samples of IAQ benchmarking value ($B_i \geq 0.9$), 2 stars to the next 22.5% ($0.675 \leq B_i < 0.9$), 3 stars to the next 35% ($0.325 \leq B_i < 0.675$), 4 stars to the next 22.5% ($0.1 \leq B_i < 0.325$) and 5 stars to the bottom 10%

(B_i<0.1), as shown in Figure 7.1, where B_j is the integral of a benchmarking parameter, known as the IAQ index θ_i of the office sample i from all offices in Hong Kong, $\hat{\theta}$ is the distribution of IAQ indices for all offices over a region with estimators of mean μ_θ and standard deviation σ_θ of the IAQ index.

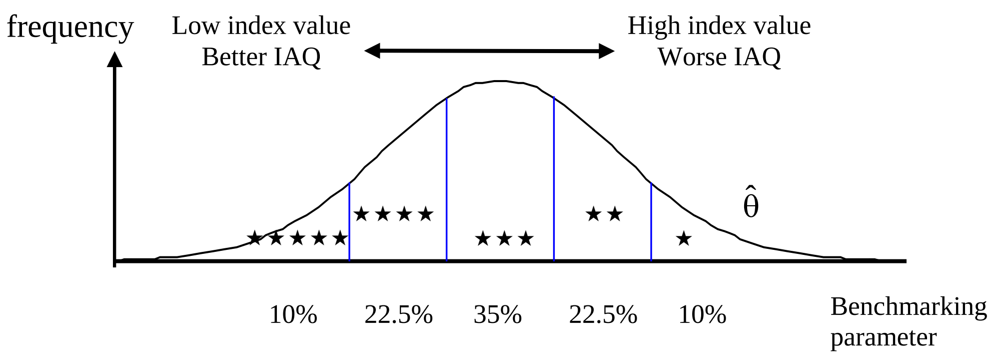


Figure 7.1: 5-Star Benchmark

7.4 Comparison with the existing IAQ ranks

To evaluate the ability of the proposed benchmarking system with IAQ index in distinguishing offices with different IAQ ranking, the benchmarks are compared with the IAQ labels ('Excellent office', 'Good office' and 'Unclassified office') classified based on the existing HKEPD certification scheme.

Taking the pollutant level criteria for labelling 'Good' in the certification scheme as the exposure limits (HKEPD 2003), Figure 7.2 shows the IAQ index θ determined from the CO_2, RSP and TVOC measured in the 525 office samples from the two regional IAQ surveys (422 samples from the first survey database and 103 samples from the second survey conducted in this study). The samples were classified by the existing IAQ labels from nine common indoor pollutants into offices of ‘Excellent’ IAQ Ω_E, ‘Good’ IAQ Ω_G, and ‘Unclassified’ IAQ Ω_U, with frequency of 10%, 58% and 32% respectively. It was reported that for ‘Excellent’ IAQ offices, the range of θ was 0.19-0.39 ($\mu_E = 0.29$, $\sigma_E = 0.05$); while for ‘Good’ IAQ and ‘Unclassified’ IAQ were 0.19-0.73 ($\mu_G = 0.42$, $\sigma_G = 0.11$) and 0.21-1.99 ($\mu_U = 0.64$, $\sigma_U = 0.25$) respectively. The expected values of θ determined for ‘Excellent’ IAQ offices were significantly lower ($p < 0.0001$, t-test) than that in the group of ‘Good’ IAQ, and that for the ‘Unclassified’ IAQ group were also significantly different from the ones in the ‘Good’ IAQ groups ($p < 0.0001$, t-test). The proposed IAQ index by the three representative parameters can distinguish offices with different IAQ labels.

Figure 7.3 shows the corresponding benchmarks B_i of certain IAQ index θ determined from the regional profiles of office environment $\hat{\theta}$. It was reported that the range of IAQ index θ was between 0.91 and 1.99 ($\mu = 0.47$, $\sigma = 0.20$). For benchmarks of offices with the proposed IAQ index to distinguish offices of different IAQ labels, the benchmark levels would be set at the corresponding frequency of the three groups obtained from the ‘full’ assessment for the 525 offices. The first 10% would be labelled as ‘Excellent’ IAQ with an IAQ index $\theta \leq 0.28$, the next 58% as ‘Good’ IAQ with an index $0.53 \leq \theta < 0.28$, and the last 32% as ‘Unclassified’ with an IAQ index $\theta > 0.53$ respectively.

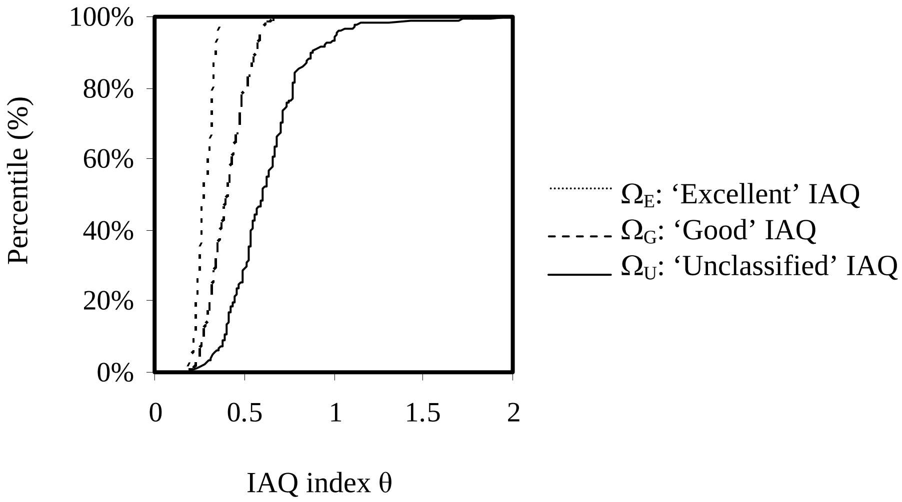


Figure 7.2: IAQ index θ of 525 Hong Kong air-conditioned offices classified with 'Excellent', 'Good', and 'Unclassified' IAQ labels

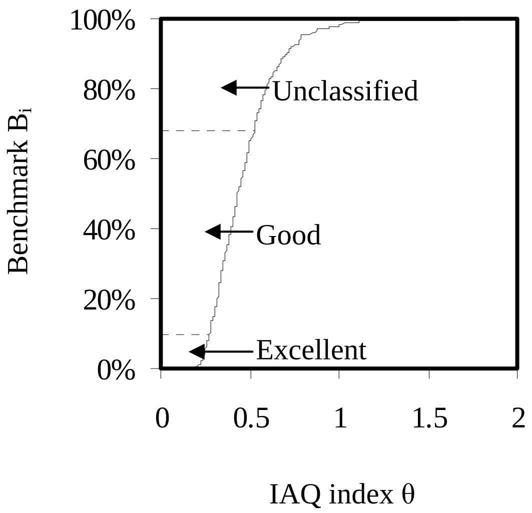


Figure 7.3: Benchmarks of Hong Kong air-conditioned offices IAQ

Using the above IAQ index levels of each label for judgment, Table 7.1 illustrates the comparison of the proposed benchmarks with the existing IAQ labels in the 525 offices. The proposed benchmarks by IAQ indices correctly identify 24 ‘Excellent’ IAQ offices, 224 ‘Good’ IAQ and 113 ‘Unclassified’ offices, which are equivalent to 46%, 73%, and 68% of the sample in the group respectively. Overall, the proposed benchmark was effective in labelling 69% of the assessed offices in our sample cases. Taking the assessment uncertainties into account, the significant association between the predicted and assessed results showed that benchmarking by the IAQ index was cost-effective and feasibly justified for identifying the levels of IAQ, with appropriate benchmarking levels set.

Table 7.1: Comparison of assessed and predicted IAQ labels

Assessed label	Predicted label (counts)			
	Excellent	Good	Unclassified	Total counts
Excellent	24	28	0	52
Good	26	224	56	306
Unclassified	3	51	113	167
Total counts	53	303	169	525

7.5 5-Star IAQ benchmarking system in Hong Kong offices

Figure 7.4 shows the IAQ index θ measured in the Hong Kong offices and the corresponding benchmarks B_i using the 5-star rating system, determined as: 5 stars for offices with IAQ index $\theta \leq 0.30$, 4 stars for offices with $0.30<\theta\leq 0.40$, 3 stars for offices with $0.40<\theta\leq 0.54$, 2 stars for offices with $0.54<\theta\leq 0.72$, and 1 star for offices with $\theta>0.72$.

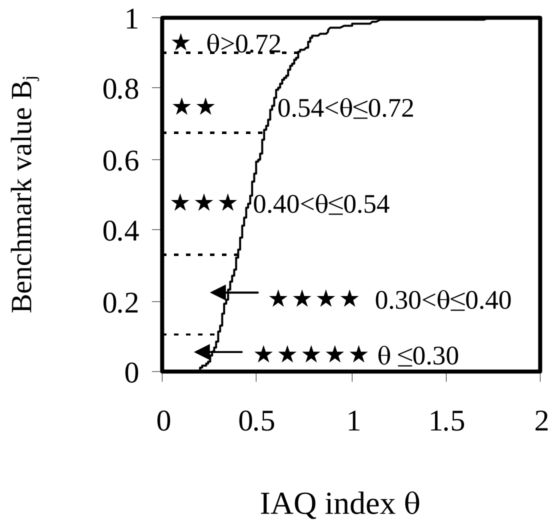


Figure 7.4: Benchmarks of IAQ

To show the application of the IAQ benchmarks system, IAQ benchmarks at the two surveyed offices groups in Hong Kong were evaluated in two directions, and followed with full IAQ assessments of 8-hour average concentration of six more common air pollutants, including carbon monoxide, nitrogen dioxide, ozone, formaldehyde, radon and airborne bacteria count. The star ratings of these two groups were compared collectively to demonstrate the feasibility of the proposed benchmarking system for IAQ.

Group (1) For the 422 offices from the first survey, the exposure concentrations in offices of 1-star and 5-star ratings were compared to illustrate the performance of benchmarking office IAQ.

Group (2) All the 103 samples in the second survey are Grade A offices; in which are provided the luxury designed and well maintained centralized air-conditioning systems among the office stocks. A better IAQ compared with group (1) is expected.

Table 7.2 shows the comparison of the measured levels of the nine common indoor air pollutants in the 5-star offices and 1-star offices benchmarked from the 422 samples, the first three are the parameters for benchmarking. Among the 42 offices of each of the two groups, using the HKEPD's requirements on the nine common pollutants as reference (HKEPD 2003), only four (equivalent to 9.5%) 5-star offices are considered to have unsatisfactory IAQ, but for 1-star offices, 41 (equivalent to 97.6%) offices in the group have pollutant level(s) exceeding the HKEPD recommended maximum. In the 1-star office group, TVOC and ABC contributed to the major unsatisfactory cases, and the level of these two pollutants are significantly higher than that in 5-star offices ($p < 0.0001$, t-test). The benchmarks also reflected the differences in levels of CO_2 and RSP of the two groups, 5-star offices are having significantly lower levels ($p < 0.0001$, t-test). For the other five pollutants, the mean levels in both groups are similar and lower than the recommended maximum.

Table 7.2: IAQ of 5-star and 1-star offices in Hong Kong

No.	Air pollutant	HKEPD recommended maximum level	5-star offices			1-star offices		
			AM	ASD	Observed unsatisfactory rate (%)	AM	ASD	Observed unsatisfactory rate (%)
1	CO_2 (ppm)	1000	538	105	0%	714	206	5%
2	RSP (μg m^{-3})	180	18	8	0%	40	19	0%
3	TVOC (μg m^{-3})	600	88	51	0%	1112	560	93%
4	CO (μg m^{-3})	10000	1059	239	0%	1076	346	0%
5	NO_2 (μg m^{-3})	150	40	22	0%	22	12	0%
6	O_3 (μg m^{-3})	120	46	22	0%	43	34	5%
7	HCHO (μg m^{-3})	100	44	49	7%	38	24	0%
8	Rn (Bq m^{-3})	200	32	17	0%	56	36	0%
9	ABC (CFU m^{-3})	1000	301	241	2%	707	389	19%

For the measured levels of the nine common indoor air pollutants in the 103 Grade A offices. As reported in Chapter 4, the mean levels of the nine common pollutants are lower, compared with the regional data. The pollutant levels of all the samples do not exceed the HKEPD recommended maximum values in general, except for TVOC in some samples.

The range of IAQ index θ of the 103 Grade A offices is between 0.19 and 1.03, with mean and standard deviation of 0.36 and 0.13 respectively, which are significantly lower than those of the general offices in the region ($p < 0.0001$, t-test). Compared with the benchmark levels, 37 and 40 offices out of the 103 offices would be awarded 5 stars and 4 stars respectively, which contributed to 74% of the total samples. 20 of the remaining would be awarded 3 stars, and 4 and 2 of them would be awarded 2 stars and 1 star respectively. Figure 7.5 shows the distribution pattern of the awarded IAQ star ratings with 95% confidence intervals of these Grade A offices, together with that of the typical offices for comparison. The results showed that the distribution pattern of those Grade A offices was significantly different from the typical offices in Group (1) ($p < 0.0001$, Chi-square test). The expected frequency of the samples with star ratings 5 and 4 for Grade A offices was higher. Grade A offices would attribute with better IAQ among air-conditioned offices in Hong Kong as with better management in maintenance and cleaning of air-conditioning systems. Results showed that these already graded the best offices which can be awarded more stars in the benchmarking system. The proposed IAQ benchmarks would be effective in distinguishing IAQ satisfactory and indication of IAQ in some air-conditioned offices.

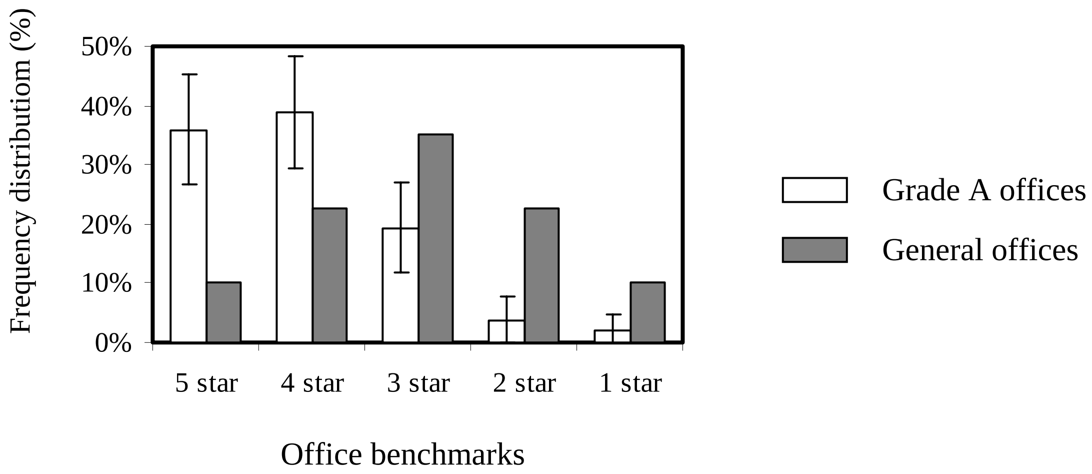


Figure 7.5: Distribution patterns of the IAQ benchmarks

7.6 Conclusion

With proper assessment schemes defined, a simple indication of relative performance would help promoting good IAQ to the general public. Nine common indoor air pollutants were used to assess IAQ for many offices in Hong Kong and this database was available for reviewing the assessment strategy. This chapter proposed and analysed the feasibility of a 5-star IAQ benchmarking system using the IAQ index as a benchmarking parameter.

Choices of a number of air pollutants as IAQ assessment parameters investigated in pervious chapters were used for compiling the IAQ index, assessing only three ‘representative’ pollutants, i.e. RSP, CO_2 and TVOC, was proposed. With the regional cross-sectional measurement at 525 offices in Hong Kong, the significant association found between the predicted and assessed results showed that benchmarking by the IAQ index would be feasibly justified for distinguishing offices of different IAQ levels as identified by comprehensive IAQ assessment.

The application of the proposed 5-star rating IAQ benchmark system in labelling office IAQ was demonstrated in the 5-star and 1-star groups, and the Grade A offices group which are expected with better IAQ, with follow-up measurement on the other six pollutant levels. The results showed that the overall IAQ unsatisfactory rate in 1-star offices were 98%, while it is only 10% for offices awarded 5-star rating. It was also shown that the distribution patterns of the awarded IAQ star ratings of those already better graded Grade A offices were significantly different from the typical offices. The proposed benchmark would be a useful tool for policymakers, building owners and professionals as a screening assessment for IAQ in air-conditioned offices and to make decisions on resources and manpower management for IAQ investigations elsewhere in order to achieve the best IAQ control.

Chapter 8

Conclusion

This thesis proposed a flexible and practical IAQ monitoring and assessment protocol for air-conditioned offices. This protocol offers choices of sampling schemes of assessment parameters, sampling locations and times in assessing IAQ for the statutory control at the acceptable measurement accuracy. The protocol also promotes the IAQ by presenting the assessment results with a simple benchmark so that occupants can easily realize the relative environmental performance in the offices and active participation in the IAQ award would become possible.

There is an increasing awareness of IAQ as people are spending more time indoors, where population's exposure to a wide range of air pollutants has posed a significant health concern. IAQ is a complex issue resulting from various factors of the indoor environment. In order to quantify IAQ, different ways have been suggested and adopted in literature. Performing IAQ monitoring and assessment is critically significant for understanding the exposures and characterizing risks from a particular indoor air pollutant source, where, for each parameter there is a need to define when, how often, for how long and where measurements should be made. Different criteria have been set in the form of regulations or guidelines in different places, however, technical difficulties in implementation were reported owing to their complexity. Measurement strategy is of the greatest importance to ensure that the maximum useful information with the minimum of resource utilization is obtained. Protocols must be developed and validated to provide alternatives for IAQ sampling strategies with quantified assessment efforts and uncertainties, which indicated the needs of this study.

A comprehensive cross-sectional IAQ survey on common assessment parameters from a long-term measurement in Hong Kong air-conditioned offices was used as a reference to study the probable relationships among assessment parameters, choices of measurement periods, locations and measurement uncertainties. The assessment results provide understandings on the IAQ in air-conditioned offices of Hong Kong and the information is useful for the development of IAQ assessment protocol. A structural database was developed through the review of existing data and measurements performed in this study, which includes a one-year measurement of CO_2 and radon concentrations on a large office floor at several comparable spatial locations, and two cross-sectional measurements at a total of 525 offices on 12 indoor parameters as stated in the HKEPD IAQ certification scheme.

Regarding the choice of assessment parameters, with the database of 12 IAQ parameters from a cross-sectional survey in 422 offices, probable choices of representative parameters were evaluated with two considerations: (1) parameters had significant contribution to IAQ dissatisfaction; (2) parameters surrogated to air pollutant control system performance. For (1), the top contributors of unsatisfactory IAQ were TVOC, RSP and HCHO for offices ranked ‘Excellent’ and TVOC, ABC, RH, HCHO and O_3 for those ranked ‘Good’ in Hong Kong. The assessment scheme with the top three or five contributors in assessing office IAQ could identify up to 96% and 93% of unacceptable offices against the criteria for ‘Excellent’ and ‘Good’ offices respectively. For (2), a set of three parameters namely CO_2, RSP and TVOC (out of the 12 parameters stated in the certification scheme) was proposed for IAQ assessment in offices. The set was judged to be representative in indicating the performance of IAQ control system regarding dilution, removal, or source emission control respectively. Their concentrations in an air-conditioned office could be measured to surrogate the probable unsatisfactory IAQ due to the other 9 unmeasured parameters.

The uncertainties due to the choices of sampling time and sampling period for assessing the exposure level to a transient assessment parameter of the daily and seasonal variations have been evaluated. Apart from the assumption of randomly fluctuated assessment parameter level in the existing sampling scheme, parameter variation characteristics of build-up and decay in a day for determining the exposure level were considered. The evaluation based on the database of the year-round longitudinal measurement results in radon and CO_2 concentrations in air-conditioned offices, which characterized all types of variation as possible. The uncertainties of various sampling schemes were analysed based on the pollutants. The parameter variation characteristics were useful in saving the sampling effort at certain acceptable uncertainties. It was reported that in air-conditioned offices, for an acceptable uncertainty compatible to an 8-hour continuous sampling scheme, the required measurement period of a proposed sampling scheme of two random samples average from two time-equal sessions with an opposite reverse time sequence within the occupied period could be potentially reduced up to 30%.

Furthermore, for analyzing the spatial dependence of pollutant concentrations in an indoor environment for pollutant monitoring and assessment, CO_2 concentrations was selected as an IAQ indicator to investigate the probable errors and measurement efforts in different sampling schemes regarding the sampling point density and the sampling location(s). CO_2 concentrations within an office varied at different locations; their magnitude and variation can be used to study the significance when compared to the office sample-spatial average

CO_2 concentration. With random choices of sampling locations in an air-conditioned office, a reduction of sampling points required for an IAQ measurement by 50% would decrease the probability of obtaining the sample-spatial average concentration at the same confidence level by 10% only. It was also reported that the expert choices of 'representative' sampling locations significantly improved the assessment accuracy for coarse sampling point densities at certain engineering acceptable error limits. Trained assessors of strong academic backgrounds could select representative sampling locations and result in an improved assessment accuracy compared with the random location choices.

In view of the technical difficulties in applications of the schemes in the protocol, a more effective and efficient assessment with applications of mathematical treatments on already available information has been proposed. Application of the epistemic assessment with prior knowledge for judging IAQ acceptance and regional IAQ monitoring was discussed, and it was demonstrated feasible through example application on indoor radon levels monitoring in Hong Kong.

The assessment results of air-conditioned offices in Hong Kong with the proposed assessment scheme were presented by a benchmark of relative IAQ. The overall IAQ in the assessed environment with respect to the acceptable exposure levels was quantified by the IAQ index, derived from the selected representative sampling parameters. Finally, a simple IAQ index was proposed as a benchmarking parameter for distinguishing the relative performance of IAQ, presented in a widely adopted star rating system. To show the application, IAQ benchmarks at another group of offices in Hong Kong were evaluated as examples, being followed with reference to the IAQ assessments of the 8-h average concentrations of nine common indoor air pollutants, the IAQ benchmark system was demonstrated to be an effective indication of IAQ in air-conditioned offices. This proposed benchmark could be useful for a quick illustration of IAQ performance and can be used in promoting IAQ with quantitative assessment criterion for air-conditioned offices in Hong Kong or similar environment elsewhere.

Although the IAQ monitoring approach with continuous measuring of all indoor air pollutants would be good in identifying the needs for the mitigation of IAQ problems, it had significant resources impact and showed to be not practical for implementation in the general community in a city of subtropical climates, like Hong Kong. This study outlined procedures in setting up an IAQ assessment protocol and quantified the required assessment parameters, sampling time and location at acceptable assessment uncertainties for air-conditioned office buildings in Hong Kong. The assessment results were presented by a simple relative benchmark of IAQ.

The proposed assessment protocol is developed to indicate an environment of acceptable IAQ for occupants regarding some regulatory control exposure limits of concerned air pollutants, but not preliminarily intended to investigate the specific IAQ related health concerns or to replace the existing HKEPD system. The performance of the proposed protocol was evaluated and validated with IAQ measurement results of the common indoor air pollutant concentrations in Hong Kong. Taking the assessment uncertainties into account, this study provided a useful reference for various parties of IAQ engineering in setting up an efficient IAQ monitoring and assessment programme, which IAQ can be promoted.

IAQ is an environmental characteristic which varies in different regions, building types, and also changes over time. This study demonstrated a development of a monitoring and assessment protocol for typical air-conditioned offices in subtropical climates only. Because of the limited available databases, only one year profile of some selected indoor air pollutants were used for sampling schemes analysis in this study, different mode of ventilation, the seasonal concentration variations and the characteristics of individual pollutants were not accounted. Furthermore, the benchmark system was proposed in providing a relative indication of IAQ satisfaction but not an absolute one. Therefore, in future research, the proposed method can be extended to application in setting up an efficient assessment protocol that is suitable for other countries, other types of premises, and different types of ventilation system designs. The physical phenomenon of various indoor pollutants concentrations distribution can be analysed. Further works in monitoring of IAQ profile in subtropical climates are also recommended for continuous update of information and modification of the benchmarking levels for reference. Besides, the likelihood of IAQ dissatisfaction can be developed and suggested with different assessed levels from the sampling schemes to provide reference for individual performance assessment on IAQ.

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