Indoor Air Quality in Lecture Theatres and Large Enclosed Public Spaces

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I. Abstract

Outdoor air quality in the UK is widely governed by existing regulations. This is in contrast to the quality of air indoors which is managed by prescribing ventilation rates recommended by stakeholders from the building industry. This ventilation approach stems from the 1930s, when Yaglou first raised the importance of minimum building ventilation rates to remove body odour from rooms. The minimum ventilation rates approach may deliver acceptable indoor air quality (IAQ) for standard sized rooms, however, when considering large spaces this approach is insufficient.

To examine indoor air quality in large spaces, this research uses lecture theatres as an example of such spaces. The aim of the research is to develop a methodology for the assessment of IAQ in lecture theatres using non-homogenous conditions. The research challenges the validity of assuming that air is homogenous when assessing IAQ in lecture theatres.

The homogenous assumption was therefore investigated by collection of observational data from different lecture theatres. It was discovered that using the homogenous assumption did have limitations when applied to lecture theatres, as measuring the distribution of carbon dioxide found that spatial variation in concentrations does exist in lecture theatres. This led to the development of an IAQ assessment methodology that incorporates a predictive air quality simulation model for IAQ in lecture theatres.

The predictive IAQ model uses computational fluid dynamic software (FloVENT). A component of the modelling process subdivides the breathing zone. The lecture theatre CO_2 concentration and local mean age of air is simulated in the model and analysed using the assessment methodology. The assessment methodology focuses entirely on IAQ in the breathing zone. Locations outside this zone are not important from the point of view of the occupants' comfort and experience of IAQ. This aspect therefore improves the approach to IAQ investigations in lecture theatres. Furthermore, the predictive model was verified by comparison with observed CO_2 data from several lecture sessions and the premise of the developed assessment methodology was found to be valid.

The research findings are that air quality in lecture theatres is not prominently considered and that assessing IAQ using a homogenous assumption is inappropriate. One application of the methodology is to investigate optimum design solutions for ventilation to achieve energy efficient ventilation with high-quality IAQ, and thus enhance current knowledge of IAQ assessment in large spaces.

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VI. Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated in the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Joanne Ellis

VII. Dedication

This work is dedicated to:

My family and friends for their support over the years.

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To all of my dogs (past and present) Nipper, Luke and Jester for keeping me sane and always greeting me with a wagging tail.

CHAPTER ONE

Introduction

1.0 Rationale for this research into IAQ in lecture theatres

Approximately 90% of people spend the majority of their time indoors (Colls, 2002). As a result, individuals are subjected to air conditions indoors relatively more than outdoors. The advent of building related illnesses or sick building syndromes in the last 40 years has illustrated that there are major issues with the quality of air in the indoor environment. Its importance to individuals' health and well-being is therefore a crucial reason for research into indoor air quality (IAQ).

In educational establishments, the built environment should be conducive to learning. Students should expect a comfortable place to learn, both physiologically and psychologically. In schools, existing Building Regulations are supported by specific publications such as "Building Bulletin 101 - Ventilation of School Buildings" (Department for Education and Skills, 2005). This is not the case for universities' lecture theatres, which are not subject to such definitive ventilation guidance.

In universities, lecture theatres are occupied by a variety of class sizes and for varying durations. As such, the ventilation of the space must be sufficient to ensure comfortable learning conditions. Lecture theatres have a large room size and designs which frequently make ventilating such spaces sometimes challenging. Therefore, the IAQ in lecture theatres can be inadequate and make the environment uncomfortable for the students.

Indoor air quality is not regulated in the UK to the same extent as outdoor air. In the UK, only a list of chemicals in COSHH regulations covers IAQ in specialist industries. Apart from industrial situations, IAQ in other types of indoor environments is not specifically considered. However, there is a need to assess the air in types other than industrial buildings, to ensure that the IAQ is acceptable and to ensure that are there no contaminant issues.

Studies in large spaces have typically involved examining the effect airflow has on the space (Mora *et al.*, 2003;Lu *et al.*, 1996;Chow *et al.*, 2002). Many investigations into ventilation systems exist, of which several have findings that apply to lecture theatres. In addition, there are a selection of studies in educational establishments that are concerned with the energy performance of ventilation systems in school classrooms.

A study by Becker *et al.,* (2007) examined the differences between improving the building design of schools and improving the ventilation schemes for the delivery of acceptable IAQ in classrooms. This study can translate to lecture theatres, as both educational facilities are learning environments that should provide their students with a comfortable and favourable learning atmosphere. Therefore, from an IAQ point of view lecture theatres should be considered similar to larger classrooms.

1.1 Limited IAQ studies in lecture theatres

There are relatively few studies on IAQ in large spaces such as auditoria, lecture halls, atria, shopping malls (IEA, 1998a) and entertainment stadia (Stathopoulou *et al.*, 2008). This is mainly because these large spaces are often unconventional designs unique to the designer and client. Furthermore, the innovative designs are new territories in the expectations of how the space is going to perform regarding IAQ.

In the case of lecture theatres, recent studies have predominantly concentrated on the thermal comfort of the space (Cheong *et al*., 2003). Indoor air quality in lecture theatres is not specifically considered in established research as much as in other room types. Nevertheless, IAQ in lecture theatres is as important for occupant comfort as thermal comfort. For this reason, information on how IAQ can be assessed in lecture theatres will contribute to existing IAQ knowledge in lecture theatres and will benefit the occupants, in terms of their satisfaction of using such spaces.

Studies by the International Energy Agency (IEA, 1998b) have focused on identifying tools for the application of IAQ assessment in large spaces. Further studies have used advances in computational fluid dynamic (CFD) software, and the output parameters (such as pollutant concentrations) to demonstrate the viability of CFD as a tool for IAQ assessment (Lawrence and Braun, 2006). The outcome of such research indicated that the detailed assessment of IAQ in a large space was feasible using current software.

The advent of user-friendly computer fluid dynamics software, presents the prospect for a detailed IAQ investigation in lecture theatres. The emergence of new analytical and simulation techniques makes it possible to examine the level of IAQ under several design scenarios; for example the performance of a ventilation arrangement (Gan, 1995). Therefore, the use of such software offers the possibility of advancement in the understanding of IAQ.

The aeronautics and automotive industries commonly use CFD for design purposes. However, using CFD to predict IAQ is not a usual consideration in the built environment, except in specific designs for air quality in clean rooms (for instance, operating theatres). For this reason, the use of CFD as an analysis tool in IAQ studies is becoming more widespread, with its application in IAQ and ventilation research validated satisfactorily (Lin *et al.*, 2005b).

1.2 Energy use and the rise in concern over indoor air quality

Many IAQ problems have resulted from the economic drive to reduce building energy consumption in the 1970s. The need to conserve energy stemmed from the substantial price rises that occurred from the series of politically driven oil shocks (Boyle, 1996). The initial response to the sharp rise in energy costs was to reduce the intake into the building of outdoor air, for example by closing dampers, reducing fan speed, or shutting fans off completely.

An additional response for new buildings was the "build tight ventilate right" philosophy that led to the construction of very airtight building envelopes with reduced outdoor air infiltration. According to Hatzidimoula and Poulios (2008) the problems of ventilating indoor spaces while minimizing heat losses were *"seriously"* studied after these oil crises. This is pertinent to lecture theatres and other types of large space, which can be expensive to run due to mechanical ventilation and space heating demands (Mathews *et al.*, 2002).

The predominant method of ventilation in lecture theatres is by mechanical systems. According to Building Research Energy Conservation Support Unit, BRECSU, (2000) air-conditioned (AC) buildings have one of the largest energy demands, with ventilation being a key component of the total energy use in commercial constructions (Santamouris and Wouters, 2006). Energy consumption due to air conditioning is forecast by DEFRA to increase in the UK and that currently *"Air-conditioning electricity consumption accounts 14.8 TWh per year, which is equivalent to 2% of domestic and non-domestic energy use"* (Department of Environment Food and Rural Affairs Market Transformation Programme, 2008).

Due to the heating and ventilation requirements of large volumes of air, lecture theatres are electricity demanding and therefore significantly contribute to the energy requirement of the teaching institution. Considering lecture theatres are energy intensive facilities to run, a comfortable design that provides sufficient ventilation with acceptable IAQ would consequently reduce the energy consumption and benefit the institution's carbon footprint.

1.3 Indoor air quality regulations

Problems with indoor air quality are different from outdoor issues. Episodes of local outdoor pollution are generally produced by meteorological conditions and acute actions such as emissions from rush hour traffic (Elsom, 1996;Colls, 2002). Severe problems with IAQ are unusual but exposure to indoor pollutants often occurs over long time scales producing less dramatic, although important, effects on the quality of indoor air.

The quality of outdoor air in the UK is closely monitored and regulated. On the other hand, IAQ is only normally considered if there have been occupant complaints (Jones, 1999). Nevertheless, the importance of achieving an acceptable air in the indoor environment is reflected in several guidelines produced by prominent organisations as the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE, 2005) and the Chartered Institute of Building Service Engineers (CIBSE, 2006); with CIBSE guidance applicably to the UK. There is no specific IAQ standard established by national or European Union (EU) law. However, there are guidelines from the World Health Organisation concerning IAQ but these are not legally binding.

The CIBSE guidance is drawn from ASHRAE work on the minimum ventilation rates in buildings that should provide comfortable indoor conditions by removing odour. Consequently, the ventilation of lecture theatres is set within the recommended levels, for example with six air changes per hour the IAQ is assumed to be acceptable. This however may not be the case, as IAQ is not specifically included in the design.

As long as the ventilation rates are set according to the recommendations it is commonly assumed that if any IAQ issues arise, increasing the ventilation rate will resolve it.

1.4 Assessment of indoor air quality

The assessment of IAQ is varied and can be approached from different angles. This is reflected in the opinion that IAQ can be described as "a domain rather than a discipline" (Nazaroff *et al.*, 2003), as investigations generally begin with a concern or issue followed by research into how to address the problem. A holistic approach to IAQ assessment may be beneficial (Bluyssen, 2009) as the comfort of the occupants is the main reason for any IAQ assessment.

In the built environment, the assessment of IAQ can involve different methods. The assumption that indoor conditions are well mixed is used in several IAQ assessment methods. These approaches assume that air entering the space is instantly and completely mixed with the air already present. Consequently, any pollutant concentration, temperature or humidity are considered to be the same at all points in the space (Waters and Simons, 2002).

Indoor air quality in lecture theatres has not been studied as much as in other building types. In universities, the IAQ comfort provided in lecture theatres is frequently inadequate, as the delivery of adequate thermal comfort is a priority. For that reason, the way IAQ is assessed specifically in lecture theatres was selected as a research idea.

1.5 Research Aim and Objectives

Various existing IAQ assessment methodologies assume that air conditions and the concentration of pollutants in the space being assessed are completely well mixed. This research however incorporated an experimental design examining whether the carbon dioxide concentrations in lecture theatres were homogenous. The purpose of the CO_2 measurements was to investigate indoor conditions in lecture theatres, with the intention of proposing an assessment methodology relevant to IAQ issues. Lecture theatres are unique environments as the occupants usually spend short, but frequent times in such rooms. For that reason, assessing lecture theatres IAQ although challenging does not remove the need for such an assessment; as the indoor characteristics of lecture theatres can cause occupant discomfort.

Aim: to develop a methodology for the assessment of IAQ in lecture theatres using non-homogenous conditions.

Objectives were:

a. *To investigate relevant IAQ issues as they applied to lecture theatres.*

b. *To examine current IAQ assessment methodologies for lecture theatres.*

c. *To develop a research model in order to study the IAQ of lecture theatres using non-homogenous conditions.*

d. *To develop an IAQ assessment methodology for lecture theatres using non-homogenous conditions.*

e. *To validate the developed assessment methodology.*

1.6 Research methodology

A background review of IAQ issues relevant to lecture theatres was completed. The methods of assessing IAQ were a focus, with particular reference to lecture theatres and large spaces. The literature review concentrated on identifying the extent to which features (such as the physical characteristics) of large room volumes were incorporated in existing IAQ assessment methodologies. An outcome from the review was that the IAQ level in lecture theatres was significantly affected by the pattern of airflow. Consequently, this should be included when assessing IAQ in this room type.

Specific variables that affected the pattern of airflow were examined to shortlist the most significant that affects airflow in large spaces. Four variables were identified that notably affect IAQ in large spaces. These were the ventilation system arrangement, the ventilation rate, the pollutant source location, and the occupancy profile.

The well-mixed assumption of IAQ in lecture theatres was investigated by a pilot study that measured carbon dioxide for one working day. The results from the pilot study indicated that conditions were not well mixed. This illustrated that assuming well-mixed conditions occurred in lecture theatres limited the assessment of IAQ. It was therefore found to be more appropriate to assume that IAQ in the lecture theatres was not well mixed and varied spatially. Consequently, an IAQ assessment methodology based on a non-homogenous premise was proposed.

The IAQ variation and spatial distribution needed to be represented by suitable parameters. Existing parameters were reviewed to identify those capable of representing any spatial variation in IAQ. To portray an IAQ distribution, CO_2 concentration and local mean age of air (LMA) were chosen.

In order to use the proposed IAQ assessment methodology in lecture theatres, the selected parameters (CO_2 concentration and LMA) needed to be simulated. The pattern of airflow in a room influences the dispersion of contaminants. As fluid dynamics simulates the properties of airflow, the availability of commercial CFD software made it an appropriate tool for use in the work. FloVENT was selected in preference to several other programs, due to its user-friendly graphical interface.

The proposed IAQ assessment methodology used subdivided the breathing zone in a lecture theatre into a number of subzones to produce an air quality simulation model (AQSM) to predict IAQ. The predicted spatial variation of IAQ in a lecture theatre was portrayed using the simulated measures of CO_2 and LMA. From these outcomes, the IAQ in the lecture theatre could therefore be assessed.

The extent of non-homogeneous conditions in lecture theatres needed to be further tested to verify the methodology. Long-term CO_2 measurements were taken in a different lecture theatre. To validate the methodology the IAQ in two lecture sessions was assessed using the developed air quality simulation model (AQSM) and the results subsequently compared to actual measurements taken from the lecture sessions.

The CO_2 measurements indicated that there was a significant local variation in CO_2 concentrations in both lecture theatres. The results from the assessment methodology of the two lecture sessions were compatible with CO_2 measurements. The supplementary CO_2 measurements confirmed that non-homogenous air conditions existed in lecture theatres, and that the AQSM output gave a viable IAQ assessment. The application of the developed methodology to four design scenarios illustrated that the assessment methodology and AQSM were capable of predicting energy efficient ventilation design scenarios with acceptable IAQ.

1.7 Scope of work

In comparison with other types of indoor environments, relatively few IAQ studies have been performed in lecture theatres. Two university lecture theatres were used in this research to develop an IAQ assessment methodology. The volumes of these lecture theatres were greater than 400 m^3 with seating capacities over 100. As such, the lecture theatres can be considered as large spaces.

Mayfield House was one of the lecture theatres in this research. Carbon dioxide monitoring data was used in the pilot study (Chapter 4) and a CFD model was also made of this lecture theatre (Chapter 5). The

University of Brighton sustainability research group Durabuild, used both data sets as components of a case study report. This study was concerned with the IAQ and energy performance of the lecture theatre's air conditioning system. This report included a mass balance mathematical flow model using systems dynamics software (STELLA©) produced by the group, to describe the process in the lecture theatre. Carbon dioxide measurements and CFD output determined in this thesis subsequently contributed to the Durabuild study.

For the purpose of this research, IAQ was assessed using the CO_2 concentration in the breathing zone as an IAQ indicator. This was due to its association with the room ventilation. The study was therefore solely concerned with the influence of mechanical ventilation methods, and room characteristics on IAQ and occupant comfort in lecture theatres.

The developed IAQ assessment methodology is intended to indicate ventilation and lecture theatre design improvements that are possible for the delivery of acceptable IAQ without excessive energy demand. Thus, this research has great promise for use in the sustainable design of lecture theatres.

1.8 Thesis layout

The thesis has eight chapters. Chapter 1 describes the focus of the work regarding the assessment of IAQ in lecture theatres and chapter 2 reviews relevant IAQ themes. The current lack of IAQ legislation and universal standards is discussed, along with indoor pollutants, their sources and possible health effects. This chapter explores the available IAQ measurement methods and existing IAQ assessment applicable to lecture theatres. As a result, this chapter presents an overview of IAQ aspects relative to lecture theatres.

The various types of ventilation systems that are installed in large spaces are described in Chapter 3. The way in which air distribution influences IAQ in a large space is discussed. The main variables that affect the distribution of IAQ in large spaces are examined. These are the ventilation rate, occupancy profile in terms of the number and occupant seating position, pollutant source location, and ventilation arrangement. It is argued that these variables are needed in a methodology to assess IAQ in lecture theatres and large spaces.

A description of a pilot study in a lecture theatre is given in Chapter 4. The study was to investigate the feasibility of the non-homogenous idea. The concentrations of CO_2 were monitored for a day in the lecture theatre. The preliminary results indicated that there was a significant difference between the recorded CO_2 concentrations at separate locations in the lecture theatre.

A computational fluid dynamic (CFD) model replica of the pilot study lecture theatre was constructed to consider the comparability of the monitored and simulated results. Two lectures in the pilot study were modelled. The measured CO_2 gave good agreement with the modelled concentrations. The outcome thus supported the non-homogenous premise concluded in Chapter 3, and the choice of modelling software for the developed assessment methodology.

The development of assessment methodology and air quality simulation model (AQSM) is described in Chapter 5. The selection process for appropriate measures capable of displaying IAQ variation is detailed. The AQSM takes into account the effect airflow has on IAQ variation. The chapter concludes with an example of the expected output from applying the IAQ assessment methodology.

Chapter 6 investigates the methodology premise. A large-scale collection of CO_2 concentrations in another lecture theatre was undertaken. The results significantly indicated that non-homogenous IAQ occurred in lecture theatres. The developed methodology was further validated by its application to two different lectures. The agreement between the measured and simulated results was shown, which consequently supported the developed AQSM and IAQ assessment methodology for lecture theatres.

Chapter 7 describes the application of the methodology to assess a variety of different case scenarios. These assessments include four significant variables that influence the IAQ distribution that were identified in Chapter 3. The performance of the assessment methodology and the significant findings are discussed.

The concluding Chapter 8 finishes by discussing the work accomplished and makes recommendations for further research to enhance the field of IAQ assessment. The thesis ends with six appendices that provide additional detail related to sections of the research.

CHAPTER TWO

Indoor Air Quality

2.0 Early Studies

Acceptable IAQ does not pose a significant health risk or cause any annoyance or irritation to occupants indoors. Effects on human health and issues with IAQ are not new. Early scientific studies on indoor air included that of eighteenth century French chemist Antoine Lavoisier, who studied the composition of indoor air in occupied environments. He concluded that the discomfort experienced indoors was not only because of the room temperature, but also due to the presence of carbonic acid. His view that an excess of respiratory carbon dioxide experienced in overcrowded spaces caused discomfort still holds (Leblanc (1842) cited Hansen, (1999), p.5).

However, in 1862 Max Josef von Pettenkofer (a Munich hygiene professor) suggested a refinement to Lavoisier's carbon dioxide (CO_2) theory. Von Pettenkofer proposed that the objectionable discomfort found indoors were not solely due to temperature, humidity, excess carbon dioxide, and lack of oxygen, but also to the occurrence of minute quantities of organic material from the skin and lungs. Interestingly von Pettenkofer and some of his peers suggested a CO_2 limit for a ventilated room as 1000 ppm (Endres, 2004) and this is the same concentration as the indoor CO_2 maximum recommended by the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE).

The discomfort associated with lack of ventilation was the focus of important research undertaken by Yaglou as far back as 1936. Yaglou's research focused on describing the ventilation requirements for the reduction of body odour and prescribing a minimum ventilation rate for the inside of buildings (Yaglou (1936) cited Hansen 1999, p.5). This approach is still used as exemplified by prescribed minimum ventilation rates in many legislative building regulations. However, such ventilation rates are focused on removing metabolic odours and not necessarily on the removal of indoor air contaminants. Nevertheless, Yaglou's study does remind that much of the current IAQ understanding is based on work undertaken many years before the design of modern building ventilation systems.

2.1 Energy and Indoor Air Quality

A change in attitude to energy use has introduced new problems with IAQ. The drive to reduce energy consumption in buildings has greatly influenced IAQ. The impetus for this stemmed from the series of politically driven oil shocks or energy crises that occurred in 1973-1974 (Boyle, 1996). These events led to a dramatic increase in oil prices from roughly $3 to nearly $12 a barrel (BBC, 1974), and for this reason was a significant driver for energy conservation to save costs.

Reducing the free movement of air into a building by constructing airtight structures created a need for mechanical ventilation regimes. In many work places, a further energy conservation procedure was to introduce control measures over the indoor environment, such as re-circulating air in air-conditioned (AC) systems. An airtight design, along with an increase in the number of indoor pollutant sources consequently led to IAQ concerns such as sick building syndrome.

Ventilation systems introduce and distribute outside air around the building via fans. In AC offices air handling (including heating and cooling) has one of the largest electrical energy demands, along with the building lighting (BRESCU, 2000). A key component of the total energy cost for a building is the ventilation. This can account for a third of building services costs along with elevated energy demands (Mayer, 2007). Therefore, all spaces that use mechanical ventilation systems should be ventilated efficiently to conserve energy and reduce costs.

According to Knight and Dunn, (2002) market trend projections indicate a significant increase in the use of AC systems in the UK. This trend has an implication for energy demand in the UK. An increase in AC use will increase the energy demand of buildings, which places importance on energy conservation technologies, efficient ventilation operation strategies, and sustainable design measures.

The trend of using mechanical ventilation over natural ventilation is now common in large spaces. Modern cinemas and theatres are not normally ventilated solely by opening windows. This is also the case for large teaching spaces, such as lecture theatres, where the aim is to achieve energy conservation and provide occupant comfort by controlling the environmental parameters in the room.

Recent energy price increases in 2008 have reinforced the need to use energy effectively in buildings. Together with strategies such as the UK Climate Change Programme (Department of Environment Food and Rural Affairs, 2006), and the European Union Directive on Energy Performance of Buildings (Directive 2002/91 /EC) (European Union, 2002) the drive is to reduce the UK’s energy costs and “carbon” emissions.   This initiative includes educational sectors of the built environment.

Directive 2002/91/EC operates by providing the framework for a methodology for calculating building energy performance. The assessment and inspection of heating/cooling systems is also required. A significant part of the Directive is the energy certification of new and existing buildings (Janssen, 2004) which aims to reduce building energy demands. The Directive came into force in 2003 and it requires the building to display its energy rating and performance. However, the EU has no directive that is directly concerned with IAQ.

Building ventilation is of paramount importance to IAQ. A simple connexion between IAQ and ventilation is that increasing the flow of air into a room ensures acceptable IAQ. This may be true but there is also an associated energy penalty.

This observation is a simplification as several factors contribute to IAQ, not just the freshness of incoming air. The concentration and variation of internal pollutant sources, the room temperature, the relative humidity, and the type of air distribution system influence the quality of indoor air. The ideal scenario for optimum indoor air quality is to have a ventilation system that is able to provide thermally treated fresh air, and has a low energy demand.

Several ventilation systems have the potential to be energy efficient. Displacement ventilation with a chilled/heated ceiling uses the natural thermal movement of air as opposed to air movement by fans, and thus has an energy saving potential. This system has been considered a possible lower energy alternative to other types of AC systems such as variable air volume and fan coil (Alamdari *et al.*, 1998). According to Lin *et al.,* (2005a) displacement ventilation can provide better IAQ in the occupied zone of a room when compared to mixing ventilation. However, the comparison of air conditioning systems in relation to IAQ, and energy is not clear-cut, as additional parameters such as thermal comfort have to be considered (Behne, 1999).

The plan of lecture theatres favours a displacement ventilation (DV) system. The large floor to ceiling height and tight occupant density allows natural convection currents to move up and away from the occupants (Schild, 2004). As a result, the lecture theatre geometry coupled with the potential energy savings, makes a DV system an appropriate theoretical choice to deliver acceptable IAQ in a lecture theatre.

The relationship between IAQ and energy has many contradictions and conflicts (real and potential). The reduction of outdoor ventilation and incoming air has sometimes led to a reduction in IAQ by giving rise to an increase in the concentration of pollutants in a space. The principle of source control, where known IAQ pollutants are avoided or dealt with at the point of origin, can be used to reduce the chance of IAQ problems.

However, this approach cannot be relied on to deliver acceptable IAQ, as the amount of pollutants indoors depends on several factors.

End-users and all professions concerned with building construction crucially need to be aware of IAQ issues (Bluyssen, 2009). The occupants have a role to play in promoting and observing energy efficient measures, but they have to be educated initially. The importance of keeping an AC building airtight by not opening windows or doors needs to be clearly explained to the occupants. However, the relationship between the energy consumption of ventilation and the IAQ provided by the systems is not simple, and needs to be explored further.

According to Fanger (2001) the quality of air delivered by various ventilation methods has historically been generally poor or mediocre. Even though existing ventilation standards and guidelines are met, there are considerable numbers of dissatisfied building occupants due to the fact that the *"requirements of existing ventilation standards and guidelines are quite low"* (Fanger, 2001). The benefits of acceptable IAQ to the productivity in office workers are well documented (Fisk and Rosenfeld, 1997;Bluyssen *et al.*, 1996;Fanger, 2000b). Significantly, this is also the case for students in learning environments, as according to Mendell and Heath (2005) poor indoor environment quality affects academic performance, therefore IAQ in lecture theatres needs to be considered.

Additionally there is very little knowledge on what particular type and design of ventilation system can provide acceptable IAQ. Studies on IAQ in buildings have been conducted mainly in office buildings and to a lesser extent primary and secondary schools. The number of studies that have been performed in educational teaching rooms, such as lecture theatres is relatively few (IEA, 1998c).

Larger room volumes can be difficult to ventilate, as such spaces require an increased volume of air to be replenished by the ventilation system.

This means that there is a potential for zones in the room to have insufficient air because of the time taken for it to move around the space. Consequently, this can result in pockets of relatively stale air detrimental to IAQ.

The position of the supply and extract grilles can also influence the performance of the ventilation arrangement (Sekhar and Willem, 2004). In lecture theatres, the floor is often tiered and this can affect the type of ventilation system installed, along with the location of the supply air grilles. The ventilation arrangement or configurations that produce an airflow pattern are therefore influential in delivering acceptable IAQ.

According to Calay *et al.,* (2000) large spaces such as gymnasia or industrial buildings have different ventilation requirements as compared to small buildings. Enclosures such as lecture theatres and auditoria are expensive facilities to operate in terms of operational energy use. Ensuring that the ventilation system delivers adequate fresh air where and when it is needed, will thus save energy in terms of cost and consumption of primary fuels.

Lecture theatres are a prime example of this, as the room use fluctuates both in terms of the occupancy duration and in the number of occupants. Variation in the occupancy duration can be compensated by correctly using building management controls for ventilation and lighting. However, it should be possible to achieve further efficiency in the delivery of ventilated air to where it is needed most; to where the occupants sit.

For all room volumes, the airflow pattern delivered by the ventilation method is highly variable. The airflow is greatly dependent on the particular method of air supply. As many pollutants are volatile (gaseous) or particulate, their distribution in the space largely depends on the transport by airflow. Consequently, the airflow produced by the air supply method is an important factor influencing IAQ with the supply air (ventilation rate and configuration) affecting the contaminant distribution (Lu *et al*., 1996;Lu *et al.*, 1998).

Other than domestic residences, most buildings are not entirely naturally ventilated, as some form of assisted ventilation is usually required. In large spaces such as lecture theatres, natural ventilation can be difficult to control and can be affected by weather conditions such as wind, making it an unreliable system for this room type. Additionally, using opening windows for air intake and extract ventilation is not workable (Kavgic *et al.*, 2008). Therefore, natural ventilation is not practical in buildings that have stipulated ventilation conditions, for example minimum air supply requirements or rooms with large volumes.

2.2 Indoor pollutants and their sources

In the absence of an exact IAQ definition (Jones, 2001), this research considers acceptable IAQ as air that does not cause annoyance or irritation in odour or appearance to the occupants and does not pose a significant risk to health. Furthermore, this research defines a pollutant as a substance that has the potential to contaminate or cause adverse health effects in living systems. The distinction between real risk and perceived risk is recognized, as contrary to a general understanding, the presence of a contaminant indoors does not inevitably result in an adverse health response. Nevertheless, the exposure to minute concentrations of certain compounds found indoors does generate a health reaction in a small proportion of individuals due to individual chemical sensitivity; because only small numbers are involved this does not mean that such individuals should be overlooked in IAQ concerns.

2.2.1 Internal pollutants

Indoor pollutants and their sources are multiple and varied. There are potentially a large number of indoor pollutants. The type and level of pollution varies depending on the activities taking place in the space. Air pollutants, can be divided by their source into those commonly found indoors and outdoors (Table 2.1).

According to Hays *et al.,* (1995) over 900 known pollutants have been identified indoors. Some of these “pollutants” or indoor contaminants (including particles and pathogens) are inevitably present in the indoor environment albeit at varying concentrations. A great number of the chemicals identified indoors are, however, not covered in IAQ guidelines, as the concentrations normally found indoors pose no hazard to human health.

Of the identified pollutants, total volatile organic compounds and formaldehyde emissions are frequently reported as causes of building IAQ problems, hence their inclusion in IAQ guidelines. Sensitised individuals and certain groups of the population are susceptible to relatively low concentrations of contaminants that cause discomfort. Levels of specific contaminants, for example toluene diisocyanates or allergens are not included in existing guidelines because such chemicals only affect a small proportion of the population.

The increase in the amount and type of equipment in commercial buildings has raised the number of pollutant sources found indoors such as IT appliances. This equipment is becoming more prevalent in all buildings, therefore providing a potential increase in pollutant sources. Again, this emphasises the variation in pollutants and their sources in IAQ. As there are so many pollutants and so many pollutant source scenarios it is therefore impractical to account for all pollutants in any guidelines or standards.

Pollutant	Emission Source
Indoor pollutants:	
Carbon dioxide	Metabolic activity, combustion, tobacco smoke.
Volatile Organic Compounds	Solvents, paints, perfumes, adhesives, furnishings, building materials, tobacco smoke, dusts.
Formaldehyde	Insulation materials, furnishings, tobacco smoke.
Radon	Diffusion from soil, construction material, cigarettes.
Ozone	Photocopiers, laser printers.
Ammonia	Metabolic activity, cleaning products.
Carbon monoxide	Fuel combustion, tobacco smoke.
Asbestos	Insulation, fire retardant material.
Dusts	Household, heavy metals, skin cells.
Allergens	Animal dander (scales from skin or hair), plant pollens, insects.
Bacteria and viruses	Occupants, animals, plants, air conditioners.
Outdoor pollutants:	
Nitrogen oxides	Fuel combustion.
Sulfur oxides	Fuel combustion.
PM_{10} & $PM_{2.5}$	Smoke (tobacco, combustion)

Table 2.1 Air pollutants (Ellis *et al.*, 2003)

Developments in industrial chemistry and large-scale manufacturing in the 1950s produced an important range of synthetic products that could be used in construction, replacing natural resources such as wood. Many of the synthetic replacements and mineral composites perform better than traditional construction materials. However, some materials used in the 1960s and 1970s contained hazardous chemicals which proved to be long-term emission sources, an example being Fibreboard that is commonly used in construction and emits formaldehyde.

A review by Weschler (2009) on the general trend of indoor pollutants in the USA commented on the rise and subsequent fall of pollutants as their effects on health were recognised. This was the case for benzene. However, the level of indoor exposure to contemporary chemicals such as bisphenol-A have increased (Weschler, 2009), and so has the awareness of associated health effects. Nevertheless, volatile organic compounds remain the most significant group of IAQ pollutants.

Volatile organic compounds (VOCs) are a main category of indoor pollutants and are highly variable in their chemical composition. An extensive range of VOCs is found indoors and they are grouped by their origin, for example from construction materials, furnishings, cleaning products or microbial sources. The sensitivity of occupants to VOCs varies. Some individuals are more prone to VOCs in that they can detect an odour or experience a physiological effect, for example irritation of the eyes or nose. Consequently, the individual's sensitivity to VOCs makes them a difficult category of indoor pollutants to specify a minimum concentration indoors.

The WHO consider the radioactive gas radon as a worldwide health risk in homes (WHO, 2009). Radon (and daughter species) which may occur in building materials such as concrete, clay and granite bricks can be considered a long-term emission source. This is exacerbated by the large surface areas that are exposed to indoor air (Gustafsson, 1991;Wadden and Scheff, 1983). The walls and floors in big rooms provide a large surface area to generate emissions not only for radon but also for other volatile compounds. This applies to lecture theatres, which are also large spaces presenting large surface areas for potential pollutant emissions.

Other materials and components of the building structure can be regarded as significant influences on IAQ. Interior surface coatings, for example paints, off-gas relatively more quickly than the inner fabric of the building such as insulation materials (Salonvaara and Zhang, 2003). The rates of emission from internal decorative coatings used in buildings depend upon the type of substrate to which they are applied. For example, paints and varnishes are commonly applied to plaster coated walls or plasterboard. These types of materials have porous surfaces which paints penetrate and as a result they will dry and off-gas relatively quickly after application.

Kwok *et al.,* (2003) compared organic compound emissions from a finishing varnish applied to different substrates (aluminium, plaster, gypsum and plywood board). The study found that the greatest emissions from the painted aluminium board occurred initially via evaporation. However, the emissions from the plywood board were at a later stage via diffusion. The widespread use of plywood indoors means that it has the potential for being a common source of VOCs.

A study by Silva *et al.*, (2003) compared emissions from a latex paint applied to concrete and finished parquet flooring. The study found that emissions from concrete were lower and that concrete strongly adsorbs certain organic compounds (for example diethylphthalate) from the paint, and recommends concrete as a preferred substrate for paint. Such research suggests that material and coatings found indoors can be significant pollutant sources but on a varying time scale.

Floor coverings, such as linoleum, parquets, and particleboard are important sources of emissions of various compounds into the indoor air. Formaldehyde is a common emission from wood-based flooring materials. However, the surface coatings, varnish or lacquer that are applied to the board additionally contain other VOCs in addition to formaldehyde (Yu and Crump, 2002).

Carpets contribute to indoor VOC levels in both quantity and variety. The main VOC emissions from carpets are from the backing material, for example latex and polypropylene. After the carpet has been laid, a "new carpet smell" corresponds to compounds and solvents within the carpet off-gassing. A number of VOCs (for example formaldehyde) emitted from carpets are irritants at high concentrations and hence can cause varying health-related symptoms.

According to Guo *et al.,* (2004) the age and storage temperature of the carpet can affect emission rates, as older carpets may emit at a lower emission rate than new ones. This is possibly due to a quicker solvent emission rate in new products, which decreases with time. The environmental conditions found indoors, such as the air temperature and relative humidity, can influence emission rates from carpets. Therefore, floor coverings and furniture can be considered significant sources of indoor VOCs.

Other sources of pollutants can be introduced indoors by cleaning practices. In general, cleaning products contain many VOCs. An important compound is toluene, which is an irritant and is toxic (by inhalation, ingestion or by absorption through skin), and prolonged exposure to such compounds should be avoided. Additionally, some of the chemicals can react with other air contaminants and hence produce secondary indoor pollutants (Nazaroff and Weschler, 2004;Uhde and Salthammer, 2007).

A study by Jones-Otazo *et al.,* (2005) reported that flame retardants used in electronics and furniture were introduced into the human body mainly via inhalation of household dust. Pedersen *et al.,* (2003) suggested that dust found on hot surfaces such as computer equipment, was an additional source of volatile compounds and particulate matter. The extent to which VOC emissions from dust affected IAQ was, however, not reported.

In some air-conditioned (AC) buildings the heating, ventilation, and air conditioning (HVAC) systems can be a source of pollution (Bitter and Fitzner (2002). Bluyssen *et al.,* (2002) found that the filters and ducting in HVAC systems were the most common pollutant sources, principally for odours. These papers recommend the importance of regular maintenance of ventilation systems to avoid IAQ problems.

As a result of the increasing variety of building materials, decorative coatings and furnishings using synthetic chemicals there has been a significant rise in indoor pollutants. Lecture theatres are furnished rooms and contain a variety of electronic equipment. In lecture theatres, VOCs from the fabric and furnishings of the room and contaminants from the ventilation system are the most likely sources of IAQ problems.

In contrast to other indoor environments where the occupants spend an entire working day, the changing occupancy pattern of lecture theatres makes exposure to contaminants difficult to measure. This does not mean, however, that because occupants only spend a few hours in the room that they should be excluded from IAQ concerns. In particular, some individuals that are more sensitive to effects from VOCs. Discomfort in lecture theatres and issues with IAQ can occur for a variety of reasons. Generally, lecture theatres have a high occupant density albeit for a couple of hours, however, this does not mean that the occupants cannot experience poor IAQ.

2.2.2 External pollutants entering via ventilation

Meteorological factors such as strong winds can influence levels of indoor contaminants by changing ventilation characteristics, such as the rate of air change in the building (Yocum and McCarthy, 1991). The majority of pollutant gases in the external atmosphere are present because of combustion and industrial processes. However, background levels of nitrogen dioxide vary greatly due to seasonal variations and the traffic density of the area; nitrogen dioxide levels at a busy kerbside can range from 50 – 60 ppb (Elsom, 1996).

Air that enters a building can transport atmospheric contaminants from outdoors, particularly in buildings situated close to busy main roads in urban areas or city centres. This emphasises the importance of an effective ventilation system which should reduce the level of certain outdoor contaminants being brought into the building by filtering, such as electrostatic cleaning although this generates ozone itself a pollutant. Nevertheless, a typical ventilation system cannot remove gaseous outdoor pollutants and would therefore exchange polluted outdoor air for polluted indoor air.

The exchange of air in buildings can be achieved by infiltration, natural ventilation, and mechanical ventilation. Kukadia and Palmer (1998) showed that the IAQ of ventilated buildings followed the pollutant trend of the surrounding external air albeit at lower concentrations. This could be expected, as outdoor air is the source of ventilating air. However, the concentrations of some outdoor pollutants are normally lower indoors, due to deposition on internal surfaces, chemical reactions, or decay during the circulation time in the building.

An additional, more surprising, finding from Kukadia and Palmer (1998) showed that there was no difference between natural and mechanical ventilation in the effect on IAQ. However, whether this was due to the way the air was filtered or irregular duct maintenance was not made clear for both systems.

2.2.3 Building occupants

The occupants of the building are a contributing factor to the IAQ in a room. The number of occupants in a space will affect the concentration of pollutants, especially carbon dioxide. Occupants exhale respiratory carbon dioxide and frequently use personal hygiene products such as perfume or aftershave, which will add to the VOC content in the room and the composition of the indoor air.

There are other minor occupant sourced pollutants. These are metabolic body odours from perspiration, and compounds in exhaled breath such as VOCs (n-Butanol) (Wargocki *et al.*, 2002) ethanol, acetic acid, ethyl acetate and acetone. These result from the metabolic breakdown of foods and from other metabolic processes (Salthammer, 1999). It must be appreciated that the levels of such substances in a room with correct ventilation should not pose an IAQ issue but this illustrates the diversity of chemical compounds in indoor air. Certainly, the presence of body odour and perfumes in a room can compromise the comfort of the occupants.

An additional contribution (in certain cases) to indoor air is tobacco smoke which has been identified as containing over 4000 carcinogenic, toxic or irritating chemicals, many of which have a known health effect (Rothberg *et al.*, 1998). Even in buildings where smoking is prohibited, many compounds are exhaled from a smoker's lungs. The exhaled breath of smokers contains several chemicals and carcinogenic compounds, and, in particular benzene and nicotine may be introduced into the indoor air.

2.3 Health and IAQ

The main reasons for studies on IAQ are its potential effect on health, and the occupant's basic right to comfort, and acceptable IAQ in their residences and workplaces. The WHO definition of health is *" A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity"* (WHO, 1961).

All the pollutants discussed in the previous section 2.2 could potentially affect the health of the occupants. The effects of exposure can be acute or chronic, and the range of symptoms and diseases produced is wide ranging, such as: -

- Acute respiratory infections, which include lower and upper respiratory infections.
- Other respiratory infections, which include the throat and sinuses.
- Chronic obstructive pulmonary disease.
- Asthma.
- Allergic reactions such as hay fever or allergic rhinitis.
- Tuberculosis.
- Legionnaire's disease, associated with air conditioning systems and water handling systems.
- Lung cancer from smoking, the use of coal as a fuel for cooking and heating, asbestosis, or prolonged Radon exposure (WHO, 2001).

The ventilation of buildings plays an important role in keeping levels of contaminants to a minimum. If this is not achieved then problems can occur. Over the last two decades, there have been cases where the occupants of buildings have reported relatively minor, but discomforting illnesses such as headaches and sore throats that have been associated with poor IAQ. These types of complaints have predominantly come from offices and other buildings in which occupants repeatedly spend prolonged periods. In relation to lecture theatres however, complaints are usually linked to feelings of discomfort and stuffiness as opposed to physical illness.

Some of these cases have been described under the blanket phenomenon of Tight or Sick Building Syndrome (SBS). This syndrome can be defined as "a building with an unusual number of occupants ($\geq$20%) having a physical problem for more than 2 weeks" (Hays, 1995).

Emissions of VOCs have been considered a key factor in SBS (Guo, 2003;Chao and Chan, 2001). This is mainly due to the similarity of SBS symptoms to health effects after exposure to high VOC concentrations, namely headaches, skin, respiratory tract and eye irritation (Jones, 1999). Other links include thermal discomfort, light flicker and other psychological influences. Typically, the majority of symptoms clear up when an individual has left the building.

Wolkoff and Nielsen (2001) suggested that sections of the population are more sensitive to low concentrations of VOCs and observed that the use of low emitting products can avoid indoor air complaints. The ventilation system and the ventilation rate are also suspected to affect SBS in some office buildings (Sundell *et al.*, 1994a). Sundell *et al.,* (1994b) further suggested that "*low outdoor airflow rate and presence of certain pollution sources, such as copying machines, tended to be associated with an elevated prevalence of SBS*". It is more probable, that several causative agents, interactive processes and agents that intermingle with each other to manifest SBS. However, no study to date has been able to demonstrate that VOCs cause SBS, but many claim associations (Hodgson *et al.*, 1991).

The subjective opinion and psychology, of the occupant is additionally very important in the entire SBS issue. If a person has little job satisfaction or does not have a sense of well-being at work, it can influence their perception of their environment and possibly their state of health (Seppanen and Fisk, 2002). This SBS may not be a problem with air quality per se but associated with factors unrelated to IAQ.

Incidences of SBS may not be as prevalent in lecture theatres as in other types of indoor environment such as offices. This is possibly due to the length of time a student occupies the room. However, occupants of lecture theatres can experience SBS and become ill.

Building related illnesses (BRIs) can occur in any indoor environment. In this category of IAQ illness, the cause or aetiology is understood, for example Legionnaire's disease. This is a known illness that is caused by a bacterium *Legionella pneumophila*. Building related illnesses are distinguished from SBS in that BRIs are caused by a specific pathogen which is the agent that causes the disease.

Moulds that are commonly found in damp indoor environments are Penicillium spp., and Aspergillus spp. (associated with asthma and atopy). Moulds and their spores are sources of microbial volatile organic compounds (MVOCs) and can grow on many building materials, for example gypsum board (Wady *et al.*, 2003). The role of microorganisms, and the MVOCs emanating from them, in illnesses such as SBS at present is unclear. However proving a direct cause and effect of illness due to poor IAQ is very difficult. Demonstrating that an agent produces a disease requires considerable medical study often involving clinical trials (Whorton *et al.*, 1987).

2.4 Indoor air quality indicators

The type of building influences the indicator used to portray IAQ. The activities that occur in the building influence the type of air contaminant present. Thus, an office worker sitting in the proximity to a photocopier or printer will not experience the same IAQ as a student sitting in a lecture. How the building is used is a crucial consideration when conducting an IAQ assessment, as a knowledge of the building function will provide an idea of which IAQ indicator or indicators to use. However, the absence of a universal standard that recommends IAQ indicator types makes their selection for use in a lecture theatre problematic.

An ideal IAQ indicator should be able to identify acceptable levels of odour and relative health risk to occupants. The indicator should also be easily measured. However, many factors can affect the choice of IAQ indicators. These factors include:-

- Building type and design
- Activities of the building users
- Temperature and air movement
- Relative humidity
- Age of building
- Range and probable concentration of pollutants
- Health risk associated with each pollutant
- Suitable equipment available to measure pollutants and equipment cost.

The large number of potential IAQ pollutants means that in practice it is not feasible to measure and monitor them all. Also comfort indicators such as the indoor air temperature and relative humidity are known to influence the perception of air quality by occupants in a building (Fanger, 2000a). There are no agreed pollutants or contaminant that can be described as definitive indicators of poor IAQ. For this reason, a compromise indicator that integrates the factors mentioned above needs to be identified.

In lecture theatres, because these rooms are designed for large numbers of occupants to assess IAQ a good compromise indicator for IAQ is carbon dioxide (CO_2) as a surrogate IAQ indicator. Carbon dioxide is a respiratory by-product and its indoor concentration is often used in IAQ assessment. The ASHRAE concentration of CO_2 recommended indoors is 1000 ppm. The 1000 ppm maximum is based on the occupants ability to detect human body odour, and not on adverse health or comfort effects (ASHRAE, 1989). In lecture theatres, the transient occupancy pattern will affect the level of CO_2 in the room but the ventilation system should be capable of dealing with this.

Accordingly, the ventilation performance in lecture theatres can be evaluated using the level of CO_2 as an IAQ indicator.

2.4.1 Carbon dioxide

Carbon dioxide levels can indicate the freshness of air in a space. The concentration of CO_2 can usefully represent IAQ levels as people produce odorous bioeffluents at the same time that CO_2 is being generated. The rationale for the ASHRAE upper limit is that a CO_2 upper concentration of 1000 ppm results in less than 20% of the occupants perceiving IAQ dissatisfaction. Using occupant's perceptions is however quite subjective, as different individuals have varying degrees of sensitivities and abilities to detect odours.

Carbon dioxide is regarded as an asphyxiate as symptoms result when very high concentrations are reached due to insufficient oxygen in the air (Rom, 1992). Adverse health effects from CO_2 can occur at levels exceeding the accepted American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value of 5000 ppm (Sax, 1968), and extreme air concentrations in excess of 7.5% (75000 ppm) will have a narcotic action (Morris, 1991). Such levels however are extremely unusual.

There have been incidences where the ASHRAE 1000 ppm level has been used as a health indicator. This use is inappropriate, as CO_2 levels above 1000ppm do not pose a health risk. Significantly, this misguided interpretation of 1000ppm CO_2 level ensuring healthy IAQ led to ASHRAE clarifying its 62.2-1999 (ASHRAE, 2003). This ASHRAE Standard (62-1999) was reworded to clarify that CO_2 is not a health worry, nor is it a definitive measure of IAQ, but CO_2 above 1000ppm could indicate that the outdoor ventilation may not be meeting the minimum requirements of the standard.

There is a danger of assuming that if there is enough fresh air to remove body odour, then there is enough air to remove other (non odorous) pollutants. However, this approach will not guarantee a measure of acceptable indoor air, as many potential harmful pollutants cannot be detected by their smell.

According to Chan *et al.,* (2002) the CO_2 concentration ought be considered more appropriately as an indicator of "air comfort" this avoids it being used as a parameter for acceptable IAQ (especially in regard to health). This idea of occupant IAQ comfort is relevant to students occupying a lecture theatre. Students experiences of IAQ may be limited to the time spent in the lecture theatre, and poor IAQ, whether it be from odour or another source, will affect how comfortable the individual is in the lecture theatre. The ASHRAE standard should therefore be seen as a guideline to aid in the provision of a comfortable environment for building occupants.

The amount of fresh air supplied into a space depends on the ventilation rate. Although, CO_2 concentration indoors is not an indicator of health it is regarded as a valuable indicator of ventilation efficiency, as increased concentration can indicate reduced ventilation rates (Persily, 1994). Additional reasons for using CO_2 as an IAQ indicator is that it will definitely increase in air in an occupied room, and can be used as a tracer gas to assess the room ventilation when indoor concentrations, resulting from the presence of the occupants, are greater than outdoors (Persily, 1996).

The generation rate of CO_2 found in a room depends on the number of occupants, and the production rate of individuals. The weight of the individual, their diet, physical fitness and their level of physical activity, affect the exhalation rate of CO_2. For example, a commonly stated CO_2 generation rate is 5.6×10^{-6} m^3s^{-1}. This is calculated by taking an average adult engaged in sedentary work with body surface area $1.8m^3$ with an activity level of 1 met (metabolic rate per surface area: 1 met =

58.2 W/m^2), and a respiratory quotient (R.Q.) of 0.83 (R.Q. is the relative volumetric rates of CO_2 produced to oxygen used) (Persily, 1997). Overall, the amount of CO_2 in a room will depend on the number of occupants, the outside concentration, and the efficiency with which it is exhausted from the room.

Measurement of CO_2 can provide an indication of the amount of fresh supply air needed for each person and assist in the calculation of the required ventilating rate. In certain cases indoor CO_2 concentrations can be used to estimate supply air ventilation rates (Dols *et al.*, 1994;Persily, 1996). Carbon dioxide measurements must be recorded in the correct context for proper interpretation. According to Mash *et al.,* (2008) CO_2 should only be used as an indicator of the effectiveness of a ventilation system, and not as an indicator of acceptable or unacceptable IAQ. Nevertheless, where CO_2 concentrations are interpreted in the correct context, CO_2 levels can be used to indicate the comfort of the room's occupants, due to its connexion to the efficiency of the ventilation system.

Carbon dioxide is sometimes reported as being an unreliable ventilation rate indicator due to the uneven mixing of CO_2 levels in a room as a result of sedentary occupation or stratified airflow from the room ventilation. This can make IAQ calculations complicated because it is difficult to judge how evenly the air is mixed in a room (Woodcock, 2000). Nonetheless, a good reason for using CO_2 as an IAQ indicator is that it can be detected and measured readily.

A large range of equipment can detect and record concentrations of CO_2 but the expense of this and the type of analysis method varies greatly. Carbon dioxide however, can be detected cheaply which is an important aspect for an IAQ indicator. As a result, the expense of detection and guaranteed presence of CO_2 due to the occupants makes CO_2 an appropriate indicator choice for examining IAQ in lecture theatres.

2.4.2 Volatile organic compounds

It is inevitable that VOCs are present in increased concentrations in indoor air due to the use of building materials, carpets, furniture, and housekeeping products. In addition to indicating how well the air in the space is being ventilated, levels of VOCs are important from a health point of view. Chronic exposure to certain compounds is a hazard. When a room has been refurbished, the carpets and paint will off-gas VOCs. Therefore, in such cases, a need for measurement of VOCs exists.

Ekberg (1991) found that in a new office building the ventilation system could cope sufficiently with the CO_2 load. After one year of occupancy, however, VOCs emissions from construction materials were still present although the air-conditioning system was operating correctly. This study illustrates the long-term emission ability of this group of compounds and is important because daily exposure to VOC emissions has a potential to lead to health problems.

The importance of ventilation systems on the level of VOC emissions was supported by Dols *et al.,* (1994). This study found that in a sample of new office buildings some of the ventilation systems had operational difficulties in the initial occupancy period. Materials still off-gassing subsequent to installation can explain the higher VOC levels in newer buildings. However, in older buildings most of the VOCs will have been emitted over time and removed by the building ventilation system.

In lecture theatres, long-term occupant exposure to VOCs is likely to be less of a problem than in other indoor environments such as offices. Students in universities typically move between lecture theatres for different classes. The time spent in one lecture theatre is not more than a couple of hours, which limits the occupants' exposure to VOCs. Hence, student discomfort is less likely to result from the effects of VOC emissions and VOCs need not be considered in lecture theatres.

2.5 IAQ guidelines and standards

Existing IAQ guidelines and standards vary between different countries. The UK IAQ guidance concentrates on building ventilation and minimum ventilation rates. The World Health Organisation focuses on contaminant threshold concentrations whilst the USA has an acceptable carbon dioxide concentration.

In the UK, the key legislation that controls and regulates outdoor air quality are the Air Quality Regulations 2000. In contrast to outdoor air, there is no legislation, international or national governing IAQ. Nevertheless, several guidelines exist, as shown in Table 2.2.

The purpose for any standard or guideline for IAQ is to set an acceptable concentration for indoor pollutants. Currently in the UK, there are several standards and guidelines relating to potential human exposure to pollutants. This information is contained in the Health and Safety Executive Occupational Exposure Limits, and the Control of Substances Hazardous to Health Regulations. Both guidelines set maximum time weighted exposure concentrations within the industrial work place. Radon is an exception as it is the only indoor pollutant, which has a recognised safe indoor level of 200 Bq/m^3 (Harrison, 2002). However, at present no Government statute explicitly states acceptable levels of indoor pollutants.

Issuing body	Standard / Guideline	Comments
CIBSE	Guide A: Environmental design (1999)	Subjective acceptability in terms of percentage of occupants satisfied with IAQ
ASHRAE	ASHRAE Standard 62-1989: Ventilation for Acceptable Indoor Air Quality	Acceptability as a percentage of occupants satisfied with the IAQ and CO_2 at 1000 ppm
BSRIA	BSRIA TN 9/98: Building Controls & Indoor Environmental Quality (1998)	A Best Practice Guide covering ventilation temperature and humidity
British Standards Institution	BS 5720:1979 Code of practice for mechanical ventilation and air conditioning in buildings	States the minimum fresh air supply rates for air-conditioned spaces
British Standards Institution	BS 5925:1991 Code of practice for ventilation principles and designing for natural ventilation	States quantitative air flow rates for different naturally ventilated buildings
British Standards Institution	PD CR 1752:1999 ventilation for buildings – Design criteria for the indoor environment	Technical Report specifying requirements for design, commissioning, operation and control of ventilation and air conditioning systems
BSI (2001) Building Regulations	Approved Document Part L conservation of fuel and power	Specifies the required air tightness of buildings
World Health Organisation	Air Quality Guidelines for Europe (2000)	For 35 specific pollutants e.g. formaldehyde 0.1mg/m³ as a 30 minute average
International Standards Organisation	ISO TC 205: International Standardisation IAQ Criteria (2001)	Working Group 4 to specify ventilation and IAQ standards in terms of health
CEN TC 156 (European Committee for Standardisation – Technical Committee)	BS EN 12239:2001; BS EN 13181:2001 & BS EN 1228:2001: Ventilation for building	Specifies ventilation rates
Germany, France, Norway, Poland and Canada	Quantitative guideline values	Time average guidelines for a selection of indoor pollutants (COMEAP, 2001)
Finland	Classification of Indoor Climate, Construction, Building Materials and HVAC Components (2001)	Criteria for: construction, HVAC cleanliness, moisture control, and material emissions. States IAQ target and design values

Table 2.2 Existing indoor environment guidelines (Ellis *et al.*, 2003).

The Department of Health and DETR have previously considered a strategy to improve air quality based on building regulations, advice to the public, and research into IAQ but have avoided guidelines: As an example *“The development of guidelines for indoor air quality was considered but it was felt that producing such guidelines would not significantly assist the strategy.”* (COMEAP, 2001). In 2004, COMEAP did produce “*guidance on the health effects of indoor pollutants*”. However, this was aimed at the home environment and only set out limits (time-weighted averages) for pollutants from combustion, VOCs and compounds from tobacco smoke (COMEAP, 2004).

An established IAQ guideline in the UK is the Chartered Institute of Building Service Engineers Guide A (CIBSE, 1999) which defines acceptable IAQ as a percentage based on occupant perceptions. This is a similar approach to the American Society of Heating, Refrigeration, and Air Conditioning Engineers Standard 62 – 1989. This defines acceptable IAQ as “*no known contaminants at harmful concentration as determined by cognizant authorities and with a substantial majority (80%) of occupants that do not express dissatisfaction*” (ASHRAE, 1989). The 80% criterion is derived from a panel of 20 untrained observers who enter a space and judge whether it is acceptable or unacceptable. This approach is subjective as it is based on individual’s perception of odour, which can vary a great deal between individuals.

The USA differs from the UK in that the American Society of Heating Refrigeration and Air-conditioning Engineers prescribe an acceptable IAQ level in ASHRAE Standard 62–1989: Ventilation for Indoor Air Quality. This provides a basic IAQ guideline, and recommends a maximum indoor carbon dioxide concentration of 1000 ppm. The different USA Federal States, however, have varying environmental policies.

California has taken the lead in environmental measures with a drive to use low emission construction products in their new State buildings.

Major building products are being tested for emissions before use in construction. Eubank and Bernheim (2002) suggest that this testing of materials before use should become routine in the building process. The results of the Eubank and Bernheim investigation are intended for use in developing future IAQ chemical emission guidelines. Its purpose is to make low emissions products more readily available to the public.

The Building Services Research and Information Association (BSRIA) produce industrial guidance and technical notes for good building practice. These extend to the indoor environment. The UK design requirements for ventilation in buildings are covered by the statutory Building Regulations (which mainly apply to new buildings) that stipulate minimum airflow rates and the control of air infiltration by specifying the air tightness of buildings. The British Standards Institution (BSI) publishes this guidance. Prescribing a minimum ventilation rate does not however ensure a minimum IAQ standard.

The European Union (EU) has no Directives directly related to IAQ. In 2000, the World Health Organisation published guideline concentrations for common indoor pollutants, and were reportedly in the process of compiling a document about the building occupant's right to healthy IAQ as defined by WHO (Mølhave, 2000). In an update of the WHO Air Quality Guidelines in 2005 a working group recommended the development of specific IAQ guidelines that sub-categorised IAQ into *"(i) pollutant-specific guidelines (ii) dampness, mould and ventilation, and (iii) indoor combustion of fuels."* (WHO, 2006). In July 2009, three WHO indoor air quality guidelines for dampness mould were published. However, the guidelines for selected IAQ pollutants were further discussed by a WHO working group in November 2009 and are still under development.

In addition to the UK and USA indoor environment guidelines, Germany, Norway, Poland, and Canada have published quantitative guidelines for formaldehyde and specific indoor pollutants similar to the WHO

European guidelines. Finland has a voluntary guideline that has target and design values for IAQ. Moreover Finland has criteria for material emissions, construction cleanliness and moisture control, along with heating and air-conditioning systems component cleaning (FiSIAQ, 2000).

In the establishment of an IAQ standard, selecting criteria and defining acceptable levels of IAQ is extremely difficult. Air quality requirements for comfort are very subjective. They depend upon the occupants' perceptions and preferences. Nevertheless, acceptable levels of pollutants need to be agreed in order for meaningful criteria to be applied.

Indoor air quality criteria for educational facilities should differ from other types of built environment. Educational organizations are distinctive due to changing student numbers and the occupation pattern of individual classrooms and lecture theatres. According to ASHRAE (1999) *"All forms of educational facilities require an efficiently controlled atmosphere for a proper learning environment."*

A common problem has become apparent with IAQ in schools and colleges (Daisey *et al.*, 2003). This is that teaching rooms have high levels of carbon dioxide unsatisfactory thermal comfort and ventilation. The number of students and the length of time in which classes occupy teaching rooms are changeable. The variations in occupancy of the classrooms add to the difficulty in developing applicable IAQ criteria in order to remedy such occupant complaints.

The results of a study by Braganza *et al.,* (2000) found that in a selection of typical USA schools (elementary and secondary) the ventilation rates were inadequate in diluting occupant - produced pollutants. Some of the buildings also exceeded the acceptable thermal comfort criteria. The study found that the ventilation rates were lower than the recommended levels, which led to the problems identified.

Clements-Croome *et al.,* (2008) found support for these findings in a longitudinal study, which examined, using psychological testing, the effects of IAQ and ventilation rates on pupils' educational performance and health in UK schools. This investigation into the effect IAQ and ventilation rates have on pupils is in response to a trend in the design of UK schools to reduce ventilation rates in order to reduce energy consumption. The authors declared an intention to recommend suitable ventilation rates for classrooms, and to explore whether a relationship between learning and ventilation exists (Clements-Croome *et al.*, 2008). To date the findings of this further study are unpublished. Nevertheless, studies examining students' response to the indoor environment reinforces the importance of adequate ventilation for occupants of a educational rooms.

Statistics from the USA have estimated that 12% of students are deemed to be *"medically fragile"* as they suffer from chronic conditions. The common health conditions include asthma, rhinitis and sinusitis; with asthma being the cause of 100 million absences per annum. According to Cheong and Lau (2003) students in schools and tertiary establishments are *"prime targets for ill effects of indoor air pollution"*, with ventilation problems frequently mentioned in a lot of IAQ complaints in schools.

Lee and Chang (1999) in their study of classrooms in Hong Kong found inadequacies in ventilation. In a subsequent study Lee and Chang (2000) concluded that the two most important classroom air quality problems in Hong Kong were high carbon dioxide concentrations and particulate matter <10 μm (PM_{10}). A likely source of PM_{10} was entrainment from the outside air, but they did not explain the high CO_2 concentrations.

Several authors have found inadequate ventilation in classrooms. (Shendell *et al.*, 2004;Heudorf *et al.*, in press;Mendell and Heath, 2005;Mumovic *et al.*, 2009). Daisey *et al.,* (2003) recommended improved ventilation and pollutant source control to improve the IAQ in schools These studies illustrate that there are problems with the indoor environment in educational teaching spaces that are different from other building types.

Large lecture theatres may contain a varying number of students. The occupancy pattern is often irregular as they can be occupied intermittently throughout the day. The ventilation systems that operate in lecture theatres have to respond to this variation in load. The arrangement of many lecture theatres is that occupants at the rear of the room are seated closest to the ceiling. Therefore, ventilation systems used in lecture theatres must be quiet to avoid disturbing the students, and not create any draughts were they are sat.

The nature of the air-conditioning system and the positioning of the supply diffusers and return grilles has to be considered carefully in the design of the lecture theatre (ASHRAE, 1999). Noh *et al.,* (2007) studied the performance of a four-way cassette mixing ventilation system on the IAQ and thermal comfort in a lecture theatre. The study found that changing the opening conditions of the supply air terminal did not result in any significant differences in CO_2 concentrations. Furthermore Noh *et al.,* (2007) argued that the ventilation rates calculated by a simple mass balance equations using CO_2 concentrations are inadequate, and more advanced design methods are necessary to estimate suitable ventilation rates.

2.6 Measurement of IAQ

One objective in measuring IAQ is to assess any actual or suspected risk to occupant health. The health aspect of IAQ was discussed previously in section 2.3. Importantly however, another reason for an IAQ assessment is to ensure that the occupants of a building are as comfortable as possible in the indoor environment.

Air quality can be described in two ways. Quantitatively by measuring the concentrations of substances in the air, or qualitatively by the perceptions of individuals inhaling the air (Yocum and McCarthy, 1991). Varieties of methods of IAQ measurement are shown in Figure 2.1. Typically, however, the measurement method used in an IAQ assessment depends upon the original reason for the investigation.

Indoor air quality audits and surveys can be useful as preparatory tools in initial IAQ investigations where there has been a complaint or problem. The technique, using trained observers, has been pioneered by Fanger (Fanger, 1988). This method allows air pollution types and sources to be quantified by the olf and decipol units.

One olf is the scent emission of bioeffluent air pollutants generated from a standard, sedentary, non-smoking person, who is thermally comfortable (Jones, 2001). A decipol expresses a perception of air quality. One decipol is a unit of the *"pollution caused by one standard person (one olf), ventilated by 10 l/s of unpolluted air"* (Fanger, 1988). However, due to the subjective nature of such methods, it is often thought necessary in IAQ investigations to additionally measure physical parameters (Bluyssen *et al.*, 1996).

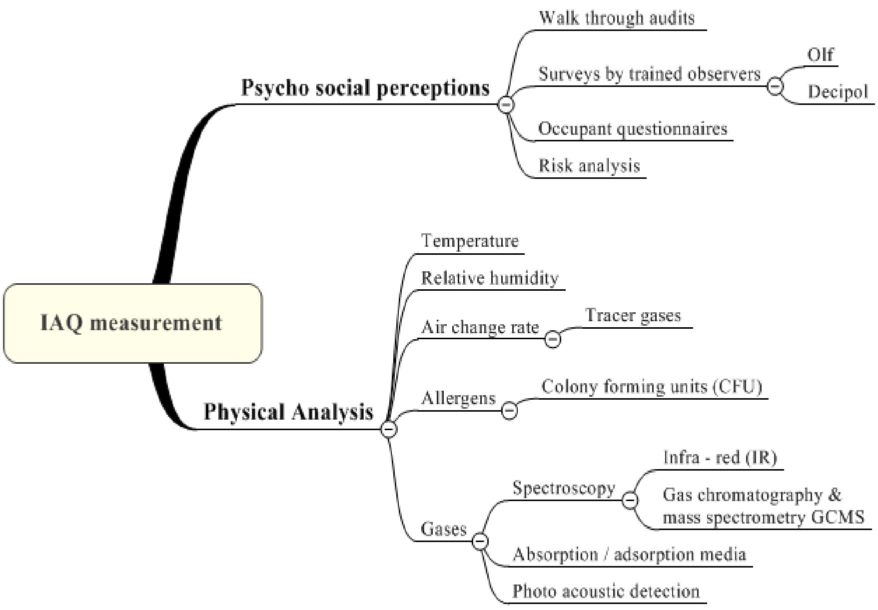


Figure 2.1 Outline of measurement methods (Ip *et al.*, 2003)

An IAQ audit methodology developed by Cheong and Chong (2001) incorporates both objective (ventilation effectiveness measures including local mean age of air, LMA) and subjective measurements (Figure 2.2). In this study, the ventilation effectiveness was measured by the tracer gas technique. The tracer gas (sulfur hexafluoride) was introduced to the office being studied, via the fan section of the ventilation system. The tracer gas was allowed to mix for 15 minutes to attain well-mixed conditions. The concentration decay of the gas was sampled at three locations. The tracer gas technique relies on perfect mixing. If however imperfect mixing exists, measurements errors can occur and inaccuracies in calculating the air exchange rate. Why the authors specifically chose 15 minutes to assume that the tracer gas was uniformly distributed was not made clear in the study.

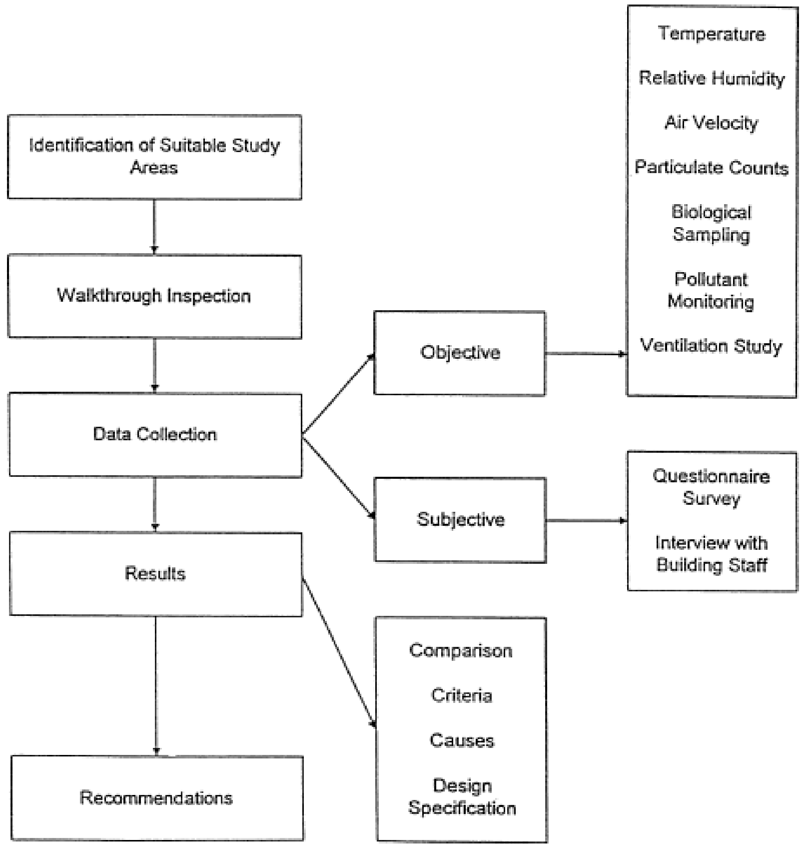


Figure 2.2 IAQ audit (Cheong and Chong, 2001)

Boestra and Leyton (2000) propose a more occupant-centred approach for the assessment of the indoor environment. Complaints from the occupants should be "taken seriously, but not always literally". They suggest that the complaint is the starting point of the assessment. The building environment should therefore be surveyed for risk factors such as damp patches and mould, or the proximity of the complainant to obvious pollutant sources like photocopiers.

An already formed "diagnosis" should be tested by performing measurements. If the measurement supports the diagnosis, corrective measures can be proposed. If not, the original diagnosis can be altered and the investigation repeated. The authors emphasise the importance of a good diagnosis, to specify the exact problem. Identifying the exact problem however can be difficult due to the differing perceptions of IAQ from individuals.

Certain organic solvents can be detected (by the olfactory senses) by some individuals at very low concentrations that pose no significant health risk. The sensitivity of individual smell and taste is itself a variable, as some individuals are more sensitive than others. The differing perception of air quality by individuals therefore adds to the difficulty in assessing IAQ.

The quantitative measurement of IAQ includes the sampling of the pollutant and the subsequent analytical or monitoring method. Some IAQ parameters such as temperature and relative humidity are recorded fairly simply. For other parameters such as the ventilation rate or air infiltration rate, measurement is less straightforward.

The ventilation of the space can be checked for adequacy by measuring the air change rate using techniques including tracer gases. The room is filled with a known amount of a suitable gas, the ventilation system turned on and the rate of concentration decay measured by sampling the gas in time. The tracer gas must be well mixed before the ventilation is turned on. However, there can be uncertainties in the determination of how well mixed the air is, especially if the room is large.

Bioaerosol contaminants include viruses, bacteria, allergens (including house dust mite allergens) and fungi (Daisey *et al.,* 2003). Assessment of bioaerosols can involve collecting air or wipe samples. Several methods of sampling exist. The biomaterial can be collected into a swirling liquid, collected onto filters or by impaction onto agar, for further laboratory analysis (SKC, 2002-2003).

Particles and aerosols are commonly analysed gravimetrically. Analysis of bioaerosols conventionally uses culture-based techniques, for example by growth on agar media. This technique is highly regarded, as it can identify the genera and evaluate the total bioaroesol concentration (Law *et al.*, 2000).

The role of bioaerosols in IAQ is unclear. Much work centres on the occurrence of asthma like symptoms in individuals. There are many agents that are classified as asthmagens, which have an association to asthma because exposure can present asthma-like symptoms (Richardson *et al.*, 2005). It must be noted that the aetiology of asthma remains unknown. However, a proportion of the population are sensitive to bioaerosols, which can occur in any type of indoor environment including lecture theatres.

The different measurement methods of IAQ reflect the variation in pollutants. The room type is independent from the measurement method, as it depends only on the pollutant being measured. There are no specific measurements according to building type or use. Accordingly, the way IAQ is measured has been a consideration for this research.

2.6.1 Monitoring equipment

Various types of monitoring equipment are used to measure indoor pollutants, the majority of which are gases. This section describes gas sampling equipment to determine which are suitable for assessing IAQ in lecture theatres. The detection of gases involves sampling the air, and can be via active or passive methods.

In active sampling, the air is drawn into the measuring device usually by a pump. Passive sampling allows the air to diffuse naturally into the measuring apparatus. After sampling, measurements can be performed either later by chemical analysis, or directly, where a sample is collected and analysed in real time.

Several IAQ pollutants can be recorded by both methods. Many types of monitoring equipment are available to detect CO_2. The equipment ranges from straightforward hand held devices that give an instant concentration reading, to more complex equipment that use spectroscopic methods to detect CO_2.

Continuous monitoring can be done by long-term installation of selected measurement devices. Real time analysis of the main IAQ indicator gases CO_2 and VOCs can be performed using photoacoustic spectroscopy (PAS) techniques (Rey and Velasco, 2000). A photoacoustic spectrometer (Figure 2.3) detects an infrared active gas by the photoacoustic effect: that is the emission of sound by an enclosed gas sample when it absorbs a particular frequency of light. When a gas is irradiated with light, it absorbs some of the light's energy. The absorbed light energy is released as heat, which causes a pressure rise.

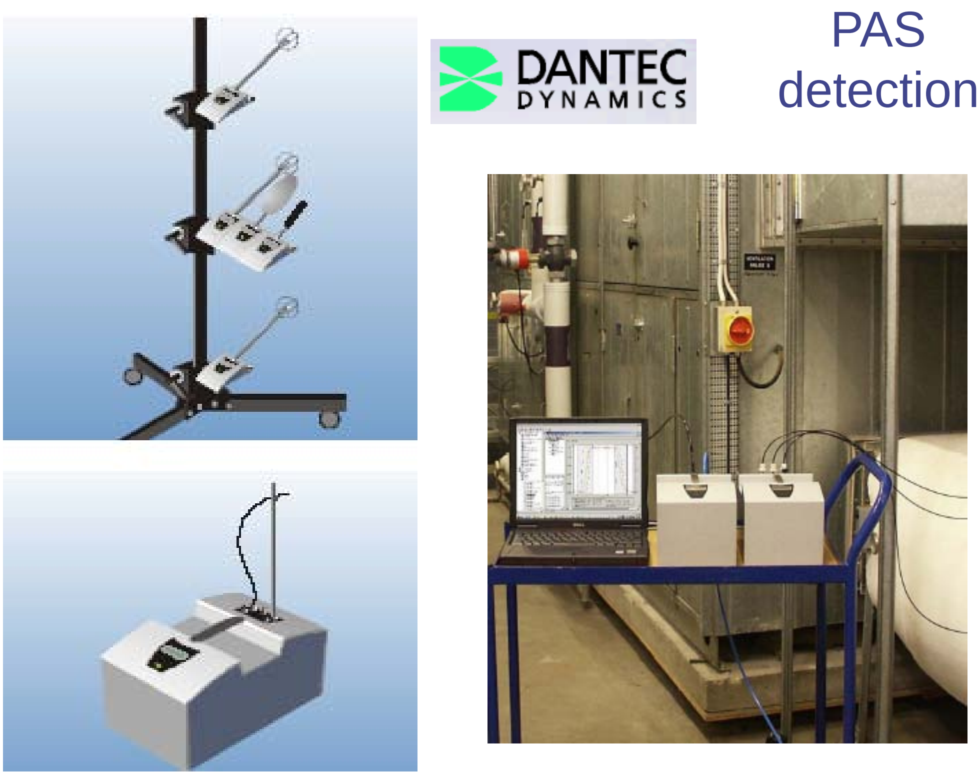


Figure 2.3 PAS monitoring equipment (Dantec Dynamics, 2001)

The main components of a photoacoustic system (Figure 2.4) consist of:

- A chamber to contain the gas sample
- A light source
- A method to modulate the light
- A microphone to measure sound
- A method of processing the signal recorded

This absorbed amount of light is proportional to its concentration. Additionally the incident light is pulsed so that the gas heats and cools accordingly. The resulting temperature fluctuations create pressure waves (sound), which is detected by a microphone. The signal is processed by the spectrometer to give a concentration reading.

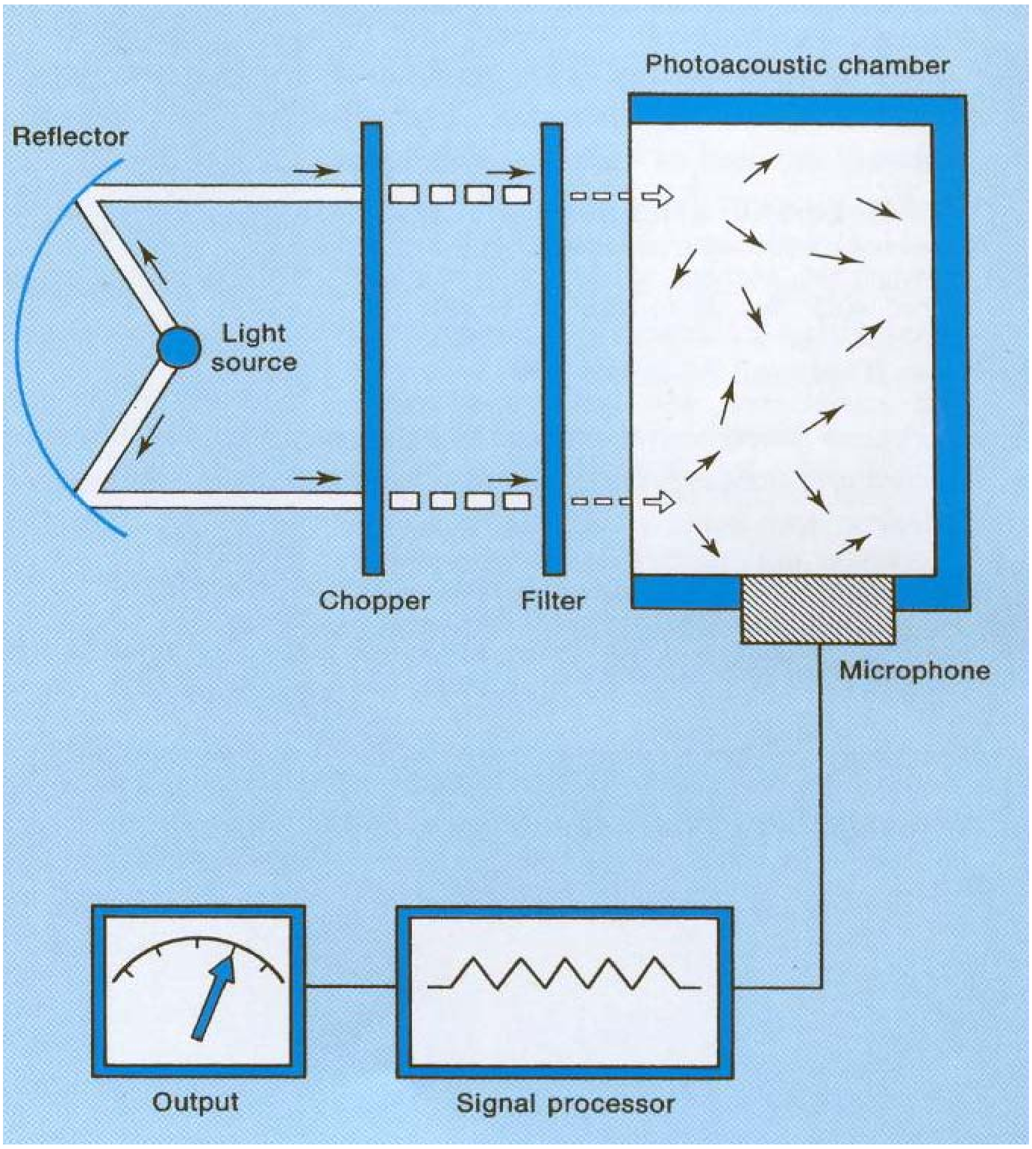


Figure 2.4 PAS schematic diagram (Dantec Dynamics, 2001)

The PAS unit can readily measure CO_2 over various lengths of time, with clear graphical and numeric results. As it can detect CO_2 instantly, no further analysis of air samples are required, which is an advantage. The relative ease of measurement of CO_2 adds to the reasons for its use as an IAQ indicator. In contrast, there is a range of VOCs that detection equipment needs to be able to distinguish. This can add to the complexity of monitoring when VOCs are used as IAQ indicators.

Carbon dioxide is widely employed as an IAQ indicator using available monitoring equipment such as PAS. This method can be used for continuous long-term monitoring of air quality, and therefore can provide important data for an IAQ assessment, or in an assessment methodology.

2.6.2 Measurement practicalities

The practicality of the measurement techniques needs to be taken into account. The costs of monitoring equipment range from hundreds to thousands of pounds. This makes cost a constraining factor. When measuring gases, the compound present must be initially known or suspected. This is particularly the case for VOCs as there are many compounds included in this classification. The search can be limited to the most common VOCs found indoors, but this may lead to some pollutants being overlooked.

Some measurement methods require further analysis away from the monitor site, which can add time and cost to the monitoring programme. The time taken to measure the pollutant concentration is also important. *In situ* measurements in real time are a more useful representation of the indoor air quality in order to detect if any immediate action is required. This differs from the taking of samples, which have to be removed from the sensor, and analysed in a laboratory. This consequently delays any remedial action.

In the determination of IAQ in a large space, the number of monitoring points needs to be considered. An investigation of the variation of IAQ in a large space will need enough monitoring points to represent the room volume. This can be impractical logistically, as the number of monitoring points may exceed the number available from the measuring equipment. The monitoring exercise could be especially difficult if the aim is to obtain measurements of the distribution of air quality because a sufficient number of locations would have to be recorded to represent the airflow in the space.

2.6.3 Computer simulation

In addition to IAQ parameter monitoring, software can be used as an IAQ analysis tool, in particular in relation to computational fluid dynamics (CFD). Computational fluid dynamics are computer simulation programs that involve the examination of systems by analysing fluid flow, and heat transfer. This type of software can model indoor environmental conditions, and can therefore be used to examine the behaviour of airflow under different scenarios.

Fluid flow and heat transfer are governed by three conservation equations of mass, momentum, and energy. These partial differential equations are the Navier-Stokes equations, which are iteratively solved to produce the output. The equations are the fundamental physical laws of fluid movement. According to Awbi (2001) CFD can be considered the “third dimension” of fluid dynamics. Furthermore, as no mathematical solution for the general Navier-Stokes equations exists due to their complexity, CFD is the favoured method that can approximate solutions.

An example is FloVENT which solves the complex equations iteratively by using a finite volume approach utilising a Cartesian grid. The number of iterations depends on the complexity of the model. Typically, tens of thousands of cells are used.

The system under investigation is modelled as a 3D grid consisting of grid cells, and for each cell, the program calculates a value for temperature, pressure and other selected parameters at its central point. Additionally on each cell face, a velocity component is calculated. When more cells are assigned, the result is a more defined solution however, this requires more simulation time.

The software is capable of investigating airflow problems encountered indoors. An important aspect in relation to IAQ assessment is that turbulence in rooms or spaces can be simulated; in particular, the solution of κ-ε turbulence models, which are currently, one of the most widely CFD models used in research. However, this requires using more memory, which adds to simulation time.

The main IAQ parameters that the software can determine are contaminant concentrations, ventilation effectiveness (Local Mean age of Air, LMA; Local Air Change Index, LACI and Contaminant Removal Effectiveness, CRE), air diffusion performance index (ADPI), and Fanger's Indices (PMV, Predicted Mean Vote and PPD, Percentage Persons Dissatisfied). The pattern of airflow and a portrayal of the pollutant pathway is an additional output. The series of output can be displayed in several formats according to what parameter is being investigated. For these reasons, the software can be useful for IAQ investigations.

The visual data ranges from audio - visual animations, jpeg pictures of planes of results or contour plots, and movement from a defined location or source. The numeric data calculated by the simulation can be exported as a CSV file. Data for all grid cells in the domain can be displayed or for defined regions, and planes. This is very useful as further analysis can be performed using the numeric data worksheet.

The capabilities of the software make it a compelling tool for modelling IAQ to provide assessment data. In the virtual domain, the number of monitoring points can be as many as required and not limited to equipment installation and room use. For that reason, there can be a greater degree of freedom in the virtual investigation than in an experimental setting (Finlayson *et al.*, 2004;Bojic *et al.*, 2002).

2.7 Assessment of IAQ

An IAQ assessment involves the measurement of parameters in order to indicate the level of IAQ. Several IAQ assessment models exist. They range from using simple mathematical formulae, to complex relationships for IAQ assessment. The assessment methods can be split into two groups: macro, and microscopic assessment.

2.7.1 Macroscopic assessment

Macroscopic models include flow element models that in general require the geometry and physical conditions of the space as input parameters for analysis using a spreadsheet or calculator. In general, IAQ is simplified by assuming well-mixed conditions. Various IAQ assessment methods exist that use this homogenous principle. Such applications include the estimation of ventilation requirements based on carbon dioxide levels and known occupancy of a space, along with pollutant transport relationships to calculate the level of contaminants.

A study by Waters and Simons (2002) aimed to produce a simple macro model by combining the mixing and displacement characteristics of airflow to indicate airflow distribution patterns without the use of CFD. This study considered the occupied zone to be one volume, and was mainly concerned with the effectiveness of the ventilation system for removing contaminants. Such simple models may be beneficial to ventilation system design and testing (Riederer and Dexter, 2003), but they do not portray the effect of ventilation on the distribution of IAQ or consider the number of monitoring points needed to portray an airflow distribution.

2.7.1.1 Mixing Models

The mixing model or homogenous model assumes that air entering the space is instantly and completely mixed with the air already present. Many IAQ investigations use this approach in evaluating and assessing IAQ for comparison to required criteria. In the use of this model any pollutant concentration, temperature or humidity is assumed to be the same at all points in the space.

The mixing approach is applied to all room sizes and is commonly used based on experimentation and good practice, which involves setting an acceptable IAQ level. For example, the ASHRAE Standard 62 defines indoor CO_2 concentrations at 700 ppm in excess of the ambient concentration as being capable of providing acceptable IAQ. The outdoor ventilation rate required to maintain a steady state CO_2 concentration below this limit is calculated from the following straightforward mass balance equation (Equation 1):

$$V_O = \frac{N}{(C_S - C_O)}$$ Equation 1 (ASHRAE, 2001a)

where

V_o= outdoor airflow rate (m^3s^{-1})

N = CO_2 generation rate of occupants (m^3s^{-1}) {typically 4.7x10-6m^3s^{-1} per person}

C_s = CO_2 concentration in the room (ppm)

C_o = CO_2 outdoor concentration (ppm)

In addition to perfect mixing, the assumptions of this approach require the supply and extract air have the same volume. In addition, other than the occupants, the model assumes that there are no additional sources of pollutant in the room, and that there are no sinks or re-emitting sources. A simple diagram of the homogenous approach in the calculation of the level of a pollutant is shown in Figure 2.5. The pollutant concentration in the space depends upon the supply ambient concentration, internal generic source generation and the concentration already present in the space. When conditions are constant, the homogenous steady state CO_2 concentration and the rise or decay from varying the ventilation rate is calculated using the previous Equation 1.

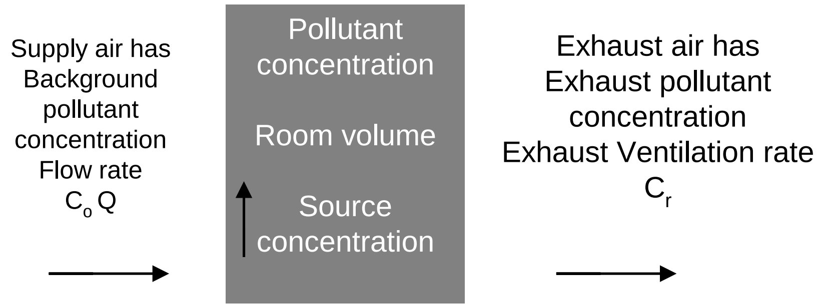


Figure 2.5 Homogenous state

2.7.1.2 An example of the well-mixed approach

The simple mass balance formula can be rewritten further as an established exponential decay equation (Appendix A). The decay equation for the pollutant concentration is for well-mixed conditions only, and does not consider imperfect mixing. Therefore, this approach is inappropriate for use in rooms that have large air volumes and turbulent airflow because perfect mixing may not be possible in such spaces.

The decay equation is described in terms of the rate at which a pollutant decays in a ventilated room due to dilution from pollutant free supply ventilation. This relates to the number of complete air changes per hour (ACH) in the room. The pollutant considered in this well-mixed model is CO_2 (a surrogate IAQ indicator), although CO_2 is more specifically an indicator of occupancy and ventilation effectiveness. The IAQ is calculated mathematically using the established decay equation.

Equation 2 is a commonly used expression for calculating the concentration of CO_2 in a space. The use of this equation involves repetitive calculations that can be done by hand or on a spreadsheet in order to obtain an output. This process is not only time consuming, but the validity of the output from the equation is limited when it is applied to large spaces, as the mathematical expression assumes the CO_2 concentration is uniform throughout the space.

$$c = \left(\frac{10^6 G}{Q} + c_a \right)\left(1 - e^{-\frac{Qt}{V}} \right) + c_0 e^{-\frac{Qt}{V}}$$

Equation 2 (Jones, 2001)

where

Q= fresh air supply rate (m^3s^{-1})

c_a = fresh air CO_2 concentration (ppm)

c_0 = room CO_2 (ppm)

$\frac{Qt}{V} = n$ the number of air changes n after time t (ACH)

G = respiration rate of CO_2 (m^3s^{-1})

2.7.2 Microscopic assessment

Microscopic assessment models consider in detail the whole space and take into account the conditions throughout. These models usually use computational fluid dynamic programs to simulate the conditions in the space being analysed. Many CFD programs are capable of simulating the airflow in a space, and are being used more commonly as an analysis tool (van Schijndel, 2003).

Zonal models take a more complex approach and range from simple calculations to detailed models for intricate problems (Yan *et al.*, 2008). There are many predictive models in existence which use zoned volumes to represent rooms in order to calculate levels of pollutants (Stewart and Ren, 2003;Stewart and Ren, 2006;Tham *et al.*, 2002). In addition, several software packages are now available for the calculation of pollutant levels indoors for use in an assessment.

Assessment that incorporates the airflow characteristics take many forms but have computer simulations in common (Zhang and Chen, 2006). Several approaches exist to represent non-homogeneous conditions either by separating the room volumes into zones (multi-zonal) or by predicting airflow using computational fluid dynamics (CFD). The increase in computer capability in recent years has enabled the further use of CFD as a tool for the detailed investigation of indoor environmental conditions.

Many effective measurement techniques are available and some have been adapted for use in assessing IAQ in large spaces (IEA, 1998b). According to Mora *et al.,* (2003) when considering large spaces, fast computers with a lot of memory are required for solving airflow, if the assumption of well mixed volumes or zones is not used. The authors go on to recommend the specifics for the CFD settings but do not stipulate a methodology for analysing the data obtained in a large space. However, there remains no common IAQ assessment method for a large space.

Cheong *et al.,* (2003) examined the thermal comfort of a lecture theatre using CFD. Thermal comfort parameters (temperature, relative humidity and air velocity), CO_2 concentrations were measured and an occupants questionnaire was also employed. A simulation model was made of the lecture theatre, which showed that the predicted results from their assessment methodology CFD gave a reasonable agreement with the measure parameters. This study importantly illustrates that CFD can be used in an IAQ assessment of a lecture theatre in the absence of a standard assessment procedure for such spaces.

2.7.3 Previous studies of IAQ assessment in large spaces

Demokritou *et al.,* (2002) measured contaminant dispersion in a large space (ice rink) using ventilation effectiveness (VE) as a IAQ parameter. A tracer gas was used to represent the contaminants present in the air.

The ice rink was empty during the experiment. The study used “many” (forty-three) sampling points that were considered “good enough” to validate the contaminant dispersal CFD model. However, the reasons for choosing the number of sampling points or the selection of representative sampling locations were not elaborated upon.

The number of experimental monitoring points is important in the estimation of the distribution of IAQ in a large space. A greater number of monitoring points will result in better coverage of the large space in which IAQ measurements are taken. The IAQ measurements can then be used to map the IAQ distribution in the large space.

Uncertainty associated with representative sampling locations has been studied by Hui *et al., (2007)*. In this study, several IAQ professionals were interviewed to determine which IAQ profession gave the most “representative” sampling locations. The difficulty in choosing the number and location of representative sampling points was measured using selected groups of individuals. It was found that the groups with the highest academic qualifications chose the least sampling points, but with a better location. Hui *et al.,* (2007) concluded that the selection of sampling locations was significantly influenced by the academic background of the assessor and not by experience in IAQ assessments.

This finding by Hui *et al.,* strengthens the rationale for using CFD in an IAQ assessment. A software-based approach eliminates bias in the selection of a monitoring location, as the IAQ parameter used in the assessment is calculated for each cell in the computer model grid. Additionally, the software is capable of reporting the calculated parameter value at any location in the space which means that at least in the theoretical science, the number of sampling point is unlimited.

Currently there are not many studies of IAQ in lecture theatres and auditoria (IEA, 1998a) or entertainment stadia (Stathopoulou *et al.,* 2008). These types of large indoor space typically have unique uses and patterns of occupancy. The occupants are still however subject to potential issues with the comfort and air quality in the room, and as such should not be excluded from IAQ assessment.

2.8 Conclusions

Scientists have studied the composition of indoor air quality since the eighteenth century. During the early decades of the twentieth century, the importance building ventilation had on the quality of indoor air was the subject of some research but issues with IAQ have gained prominence since the sharp rise in oil prices in the 1970s. This is because airtight buildings were built to reduce energy costs.

Several factors, including the “built tight ventilate right” axiom has led to increased incidences of building related diseases and syndromes that have prompted renewed concerns over IAQ. The reduction in outdoor ventilating and infiltrating air has sometimes led to a reduction in the IAQ by increasing the concentration of pollutants. There is, however a requirement for the provision of acceptable IAQ in buildings due to issues such as health awareness, litigation arising from occupant complaints, or detrimental effects on employee productivity.

The absence of an IAQ statute, adds to complexities in assessing IAQ, as it is not clear-cut what IAQ level is acceptable or unacceptable. The guidelines that exist mainly rely on adequate ventilation and source control to provide acceptable IAQ. However, studies have shown that these measures are not enough to ensure acceptable IAQ.

A majority of indoor air pollutants are gases that can be measured and monitored in several ways. The assortment of measurement techniques extend from simple hand held gas monitors to various spectroscopic devices, which additionally range in expense. The measurement technique however, depends on which IAQ indicator is selected for use in the IAQ assessment.

Several compounds are found indoors that can be used as IAQ indicators. The most frequently used IAQ indicators are VOCs and carbon dioxide. The choice of indicator greatly depends on the use of the building being assessed. In lecture theatres, the occupants are the predominant source of indoor pollutants. The ventilation system in the room should be capable of diluting the stale air from a densely occupied space. The connexion between the efficiency of the ventilation system and levels of carbon dioxide makes CO_2 a suitable indicator to assess IAQ in a lecture theatre.

Indoor air quality can be assessed by a variety of methodologies that consider the space generally as a whole or broken down into “cells”. Assessment data can be generated using models that use simple theories such as mass balance models. Models that are more elaborate include multi-zonal models, which separate the room into zones for a detailed assessment of IAQ. Even so, there is no standard IAQ assessment methodology for indoor spaces.

Several tools are capable of adaptation to analyse IAQ at a local level. Software can overcome the difficulties encountered in the direct measurement of IAQ in a large space. An important and useful software is CFD simulation. Simulation models are not constrained by a need for measuring equipment or multiple monitoring locations in the room. Indoor air quality in lecture theatres is not frequently studied, and the capabilities of CFD seem to offer considerable benefits in IAQ assessment of this type of indoor space.

CHAPTER THREE

Ventilation in large spaces

3.0 Methods of ventilation

An important aspect of any ventilation system is how the air is delivered to where it is needed, especially in relation to the occupants' position in the space. The introduction of outside air into a room should follow the fundamental provisions that the delivered air:

- is evenly diffused over all areas, especially in the breathing zone
- should not impact directly on the occupants
- should provide sufficient air movement and not allow any areas to stagnate (Awbi, 1991).

There are two main types of air distribution systems. The first is mixed flow, where air is input into the room via various air terminal devices with an aim to provide good air mixing. The other is displacement flow where fresh air is introduced in one part of the room, and allowed to flow in one direction entraining pollutants to the opposite part of the room. This uni-directional flow can be driven by the inertia of the incoming air being moved into the room, or by convection and buoyancy forces in the room (Chadderton, 1997).

Importantly the positioning of the air supply and exhaust grilles in the room has an effect on the air distribution pattern. Once the air enters the room, turbulence and various types of thermal currents govern its distribution. The movement of occupants in the room, and the heat emanated by them additionally affects the mixing of the indoor air and the airflow path. The air supply can also generate draughts if the ventilation rate is set too high. However, problems such as stagnation can occur and poor air distribution in the room can result from insufficient air circulation (Chadderton, 1997).

The main methods of air distribution (Figure 3.1) most commonly used are mixing ventilation and displacement ventilation (CIBSE, 2006). Mixing ventilation occurs when the supply air is pumped and removed at similar heights in the room or, the air is supplied at a lower level than that at which it is removed. Importantly, displacement ventilation (DV) systems are increasingly being used however as this system can deliver a large quantity of fresh air at a lower ventilation rate, in comparison with conventional mixing ventilation.

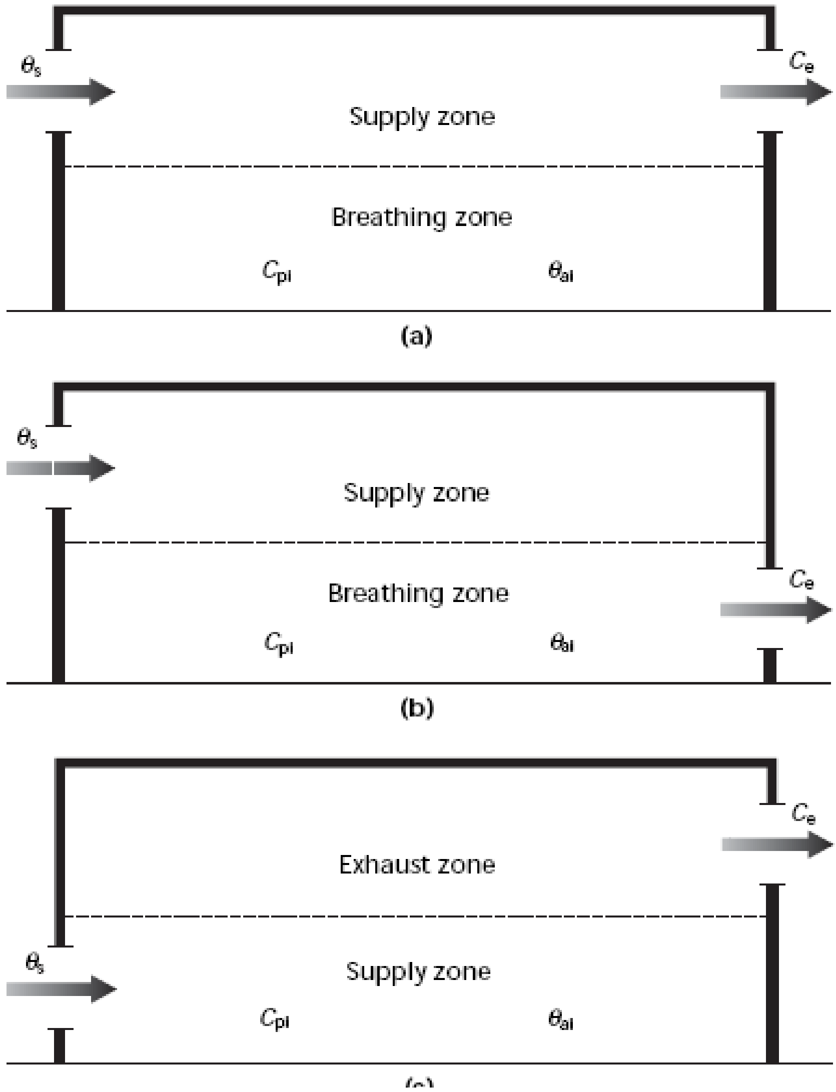


Figure 3.1 Fundamental methods of air distribution (a) high level mixing ventilation, (b) high level supply – low level exhaust mixing ventilation, (c) displacement ventilation (After CIBSE, 2006)

Displacement ventilation can have economic benefits and performance advantages over mixing ventilation, and is suited for spaces such as lecture theatres, with high ceilings (greater than 3 m) and full occupancy (Schild, 2004). However, draughts can be associated with this system and the air diffusers should not be blocked by furniture or other obstructions. This can be a problem in the design of the room as this was illustrated in the pilot study of Mayfield House, where the supply air diffusers were partly obstructed by the flooring.

Air contaminant dilution depends on the mixing of the supply and room air. Often this mixing occurs above the heads of the occupants due to buoyancy forces from heat sources. Systems that supply air at lower levels in the room are not usually designed to mix the supply and room air. This can lead to pollutants generated in the room stratifying above occupant level (Appleby, 1990). In relation to lecture theatres, occupants sitting at the highest seating level may therefore be occupying a region of stratified air.

Short-circuiting of air (where some of the supply air moves directly to the exhaust) can occur in some air grille arrangements (Figure 3.2). When air is short - circulated, the efficiency of the system is reduced, as fresh air is not being delivered to the occupants. In lecture theatres where the supply and extract air are at a high level in the room, the tiered floor and seating design can often lead to short circuiting of the ventilating air. Therefore, in order to compensate for this the ventilation rate may have to increase.

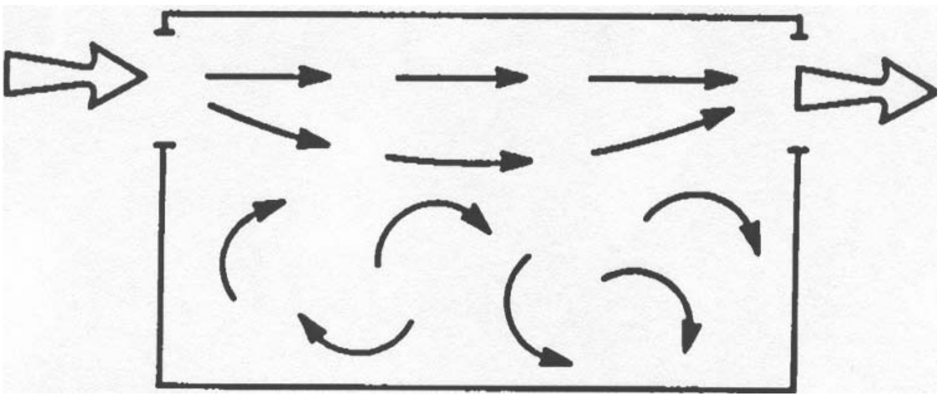


Figure 3.2 Short-circuiting of airflow (Liddament, 1993)

The pattern of airflow delivered by ventilation systems depends on the particular ventilation method. Too little air means that there is inadequate dilution of pollutants or not enough removal of stale air. Ventilation is designed to enable air to enter and exit a space entraining contaminants as it moves towards the exit. The concentration of a pollutant near an air inlet would be expected to be less than in the rest of the space due to dilution, therefore the air movement will influence the level and distribution of IAQ in a space.

The airflow produced by the ventilation system is an important factor influencing IAQ. The method of air distribution (ventilation rate and arrangement) affects the contaminant distribution (Lu *et al.,* 1996). The method of air distribution should therefore be appreciated when assessing IAQ in a space.

3.1 Air distribution in large spaces

A large space is best described by the International Energy Agency (IEA) definition, which considers an enclosure "large" if one or more of the following characteristics apply:

"The thermal buoyancy has a dominant effect on air motion;

The occupied zone is small compared to the total volume;

The Rayleigh Number, Ra, is large (namely airflow is dominated by temperature effects" (IEA, 1998a).

In this IEA definition of a large space, the word "small" however is not defined as the proportion of the total volume and thus the relationship is unclear. The Rayleigh number is linked to buoyancy driven fluid flow or natural convection. Convection happens when the Rayleigh number reaches the critical value for the fluid. Below this value, heat transfer is by conduction above this value heat transfer is by convection. Therefore, the Rayleigh number is great in large room volumes; heat transfer is predominately by convection.

The air distribution methods that are generally used in a large space are either downward or upward displacement (Awbi, 1991). These are ventilation types b) and c) in Figure 3.1. Enclosures such as lecture theatres and concert halls typically have large room volumes, and present a challenge for effective ventilation design. When investigating airflow patterns however, a full-scale model cannot be practically achieved due to model size scale issues (Awbi, 1991).

In large spaces such as lecture theatres, the room geometry has an important influence on the airflow pattern produced by the air distribution method installed in the room. The room geometry can also affect the positioning of supply and extract grilles. Conventionally lecture theatres have stepped floor levels. This means that the students sitting at the back are nearest the ceiling, so the ventilation system should be quiet and not produce any draughts or cause occupant discomfort (ASHRAE, 1999).

Typical positioning of the supply and extract grilles in lecture theatres include high-level supply from the back and extract from the front (Figure 3.3) or low-level supply underneath the seating with high-level extract (Vent-Axia, no date). The intended flow of air is from the back to the front of the room. The resultant airflow pattern however, is a vital consideration for the delivery of acceptable IAQ.

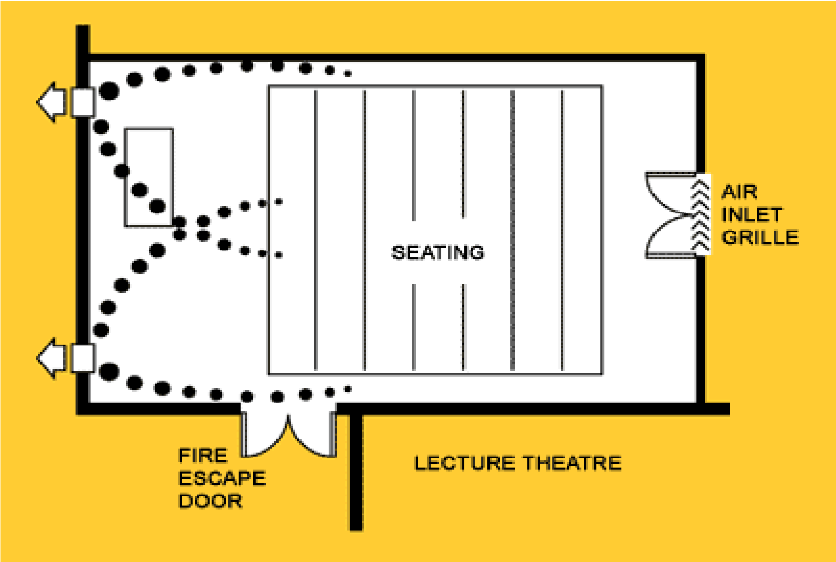


Figure 3.3 Typical Lecture Theatre Plan (Vent-Axia, no date)

Lecture theatres normally have tiered seating rows accessed by a series of steps. This stepped arrangement of the floor produces an obstruction to airflow. Conversely, the stepped geometry allows the delivery of supply air from behind the seats or in the stepped levels with the air supplied horizontally along the floor (as in Figure 3.4).

The airflow pattern in Figure 3.4 although not in a lecture theatre, illustrates the advantage of having the occupants sitting near the air supply terminal, as they receive the freshest supply air. As the air moves further away from the supply inlet, the flow becomes more diffuse. The pattern of airflow will further change due to thermal buoyancy currents when the supply air temperature changes in relation to any heating or the cooling of the room. However, the proximity of the occupants to the supply air can cause discomfort if the air is supplied at a high velocity, which will produce a draught or if the air is too cold.

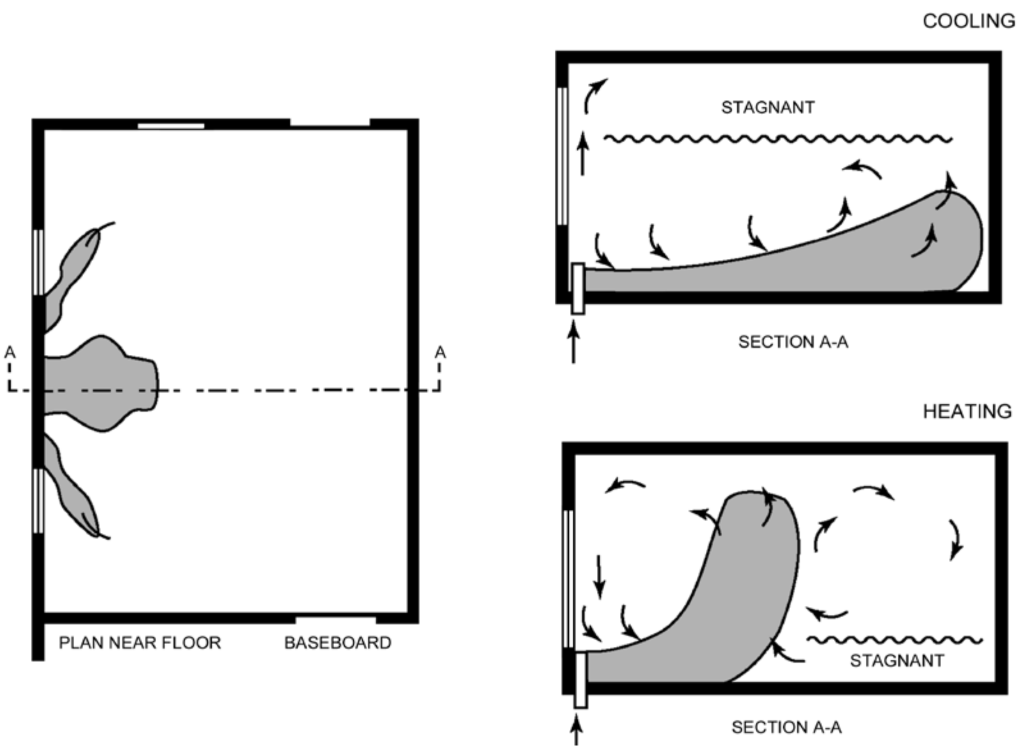


Figure 3.4 Airflow features from air supplied horizontally through grilles in or near the floor. After (ASHRAE, 2001b) chapter 32

Room ventilation characteristics alter according to the size of the space. Large room volumes provide an increased space for diffusion and the potential for zones in the room to have insufficient air delivery from the ventilation arrangement. A study by Sekhar and Willem (2004) demonstrated the significance airflow pattern has on pollutant distribution and indoor air quality. The authors used experimental measurements and CFD simulation to study the effect the airflow profile had on the distribution of pollutants. They concluded that the airflow had a critical impact on pollutant transport in the space because of the ventilation arrangement, the volume of air supply, and the design of the rooms. The resultant airflow was nevertheless a significant parameter in the IAQ assessment.

An additional factor in measuring IAQ in large spaces is the influence of obstacles on the air movement in the space. The simplest airflow pattern is laminar; however, furniture, equipment, room layout and occupants present obstructions to all types of airflow in the room. In real air conditions, time varying velocity vectors, turbulence forces such as thermal eddies and buoyancy forces influence airflow in spaces. Such forces do not readily produce airflow in straight planes but create a random chaotic flow pattern (Posner *et al.*, 2003).

Lecture theatres at the University of Brighton range in varying age and design. Only a relatively few number of new lecture theatres in the university have displacement ventilation systems installed, with the others having mixing type ventilation systems with air terminals in the ceiling. The observation that DV systems are more prevalent in newer rooms reflected the trend of using a displacement system in this type of space. Displacement ventilation systems are reported to work better in spaces with a high occupant density and a high ceiling height (Schild, 2004). Consequently, displacement ventilation systems seem appropriate for lecture theatres.

3.2 Variables that affect IAQ distribution in lecture theatres

The levels of IAQ can be variable in large room volumes such as lecture theatres, as pollutant concentration and velocity gradients are often present (IEA, 1998b). Even if the ventilation system maintains an acceptable average concentration of contaminant, there will be localised regions that have above and below the average contaminant concentration (Demokritou *et al.,* 2002).

In well-ventilated lecture theatres, the occupants will feel comfortable and any IAQ standards or guidelines are likely to be satisfied. However, variables that influence the airflow pattern will also affect the IAQ distribution. The major variables assessed in this research were:

a) The ventilation arrangement of the supply and extract air terminals;
b) Source location;
c) Ventilation rate;
d) Occupancy profile;

The following sections review these variables in further detail.

a) The ventilation arrangement of the supply and extract grilles

The ventilation of lecture theatres is not ordinarily performed by natural means. It is more common to find some form of assisted ventilation system in lecture theatres, either a mechanical ventilation (MV) system or an HVAC system (for full indoor climate control) for air delivery into the space. The airflow pattern is affected by the following parameters:

- supply air speed and volume.
- location of supply inlets.
- location of exhaust grilles.
- heat sources.
- internal obstacles – occupants, fixtures and fittings.
- room geometry.

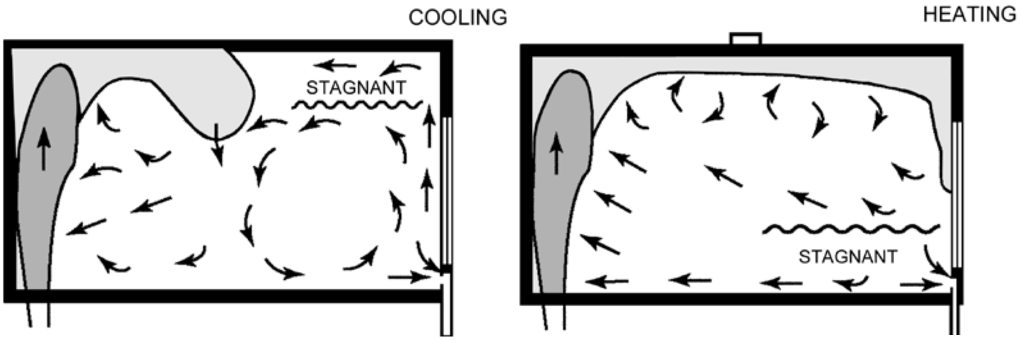
The most significant parameter that affects the airflow pattern is the configuration of the supply air inlets. This was indicated from a literature review on parameters that influence the airflow pattern. The impact the ventilation system has on airflow and pollutant movement throughout a space is supported by work by Sekha and Willem (2004), which reiterates the significance of airflow pattern on IAQ.

In addition to the above parameters, airflow is affected by variations in room temperature, buoyancy forces, thermal plumes, and turbulence. Work by Fanger (Fanger, 1972) on thermal comfort established a measure of occupant comfort by calculating the thermal balance in which air velocity plays a part. Lin *et al.,* (2005b) highlighted the importance that airflow turbulence has on the occupants' sensation of draught. Therefore airflow characteristics, as well as thermal comfort, need to be appreciated when considering the quality of indoor air for satisfactory indoor environmental conditions.

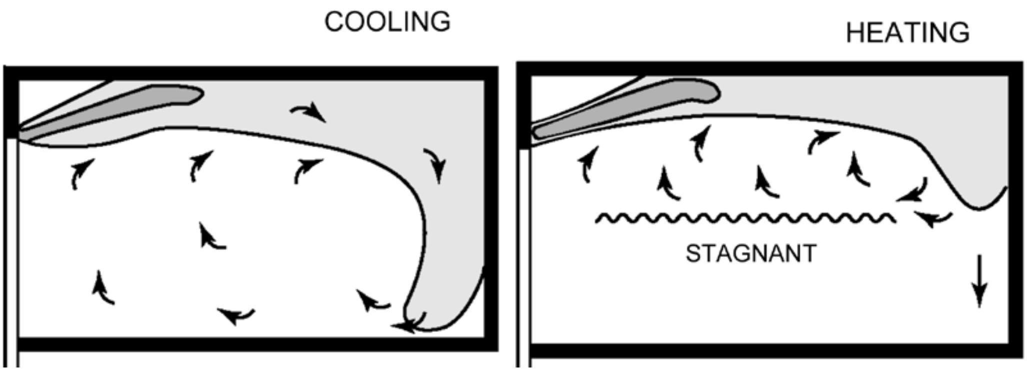
Lecture theatres have distinctive patterns of use. As with other indoor spaces the airflow conditions, contaminant dispersion, and the general movement of occupants add to the variable nature of the air. In lecture theatres however, the diverse occupancy patterns accompanied by variable numbers of students with changing occupancy durations, ensures highly variable indoor air characteristics.

The ventilation system and room characteristics directly influence the pattern of airflow. The supply air is introduced into the room at a determined velocity. Its path and movement is additionally affected by airflow from heat sources, and sinks. Additionally, the importance of physical structures cannot be ignored in an assessment of IAQ, and thus the influence obstacles have on airflow should be appreciated when assessing IAQ in lecture theatres. For that reason airflow can be considered a significant influence in IAQ (Sekhar and Willem, 2004).

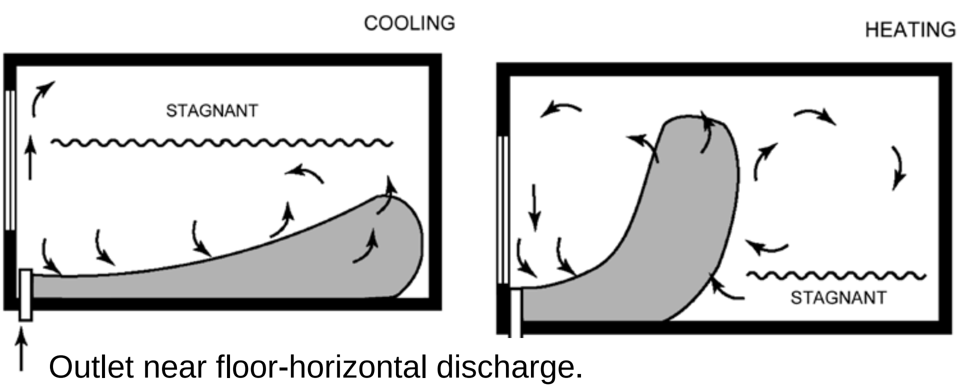
The predicted patterns of airflow from different air supply grille positions are shown in Figure 3.5. All these supply-air positions can be found in various lecture theatre designs, and are important in the delivery of ventilation air to the occupants. However, the specific design of lecture theatres such as tiered seating will obstruct airflow patterns.



Air outlet in or near the floor with a non-spreading vertical jet



High sidewall outlet



Outlet near floor-horizontal discharge.

Figure 3.5 Predicted ventilation airflow patterns (ASHRAE, 2001b)

b) Source location

The distribution of contaminant sources within a room is highly variable. The arrangement of contaminant sources and positions in the occupied zone produces a spatial IAQ distribution. The emission rates of contaminants are influenced by several factors such as temperature, and the amount of pollutant released from the source over time, which has a bearing on the overall level of contaminant. Consequently, the contaminant location will contribute to the variation of the IAQ distribution.

Typical ventilation or MV/HVAC systems are designed to provide uniform design conditions for the occupied zone in a space. According to Gao and Niu, (2004) there are two clear problems. The first is that fresh air is mixed with indoor pollutants before being inhaled by the occupants, and secondly that individual thermal comfort requirements are not accounted for. This is because the thermal comfort settings are based on comfort requirements of the majority.

Varying arrangements of supply air delivery can produce a degree of unevenness in the airflow pattern and an irregular distribution of pollutant or IAQ levels. There will be regions within the space that satisfy pollutant level IAQ requirements and regions that do not. Lecture theatres present increased air volumes for pollutants (for instance formaldehyde) to disperse. As a result, an increased dispersal of pollutants will produce a more varied IAQ distribution.

c) Ventilation rate

Recommended ventilation rates differ according to the type of room. These ventilation rates are based on calculating the minimum volume of air required to remove body odour in the room. In general, class rooms, seminar rooms or tutorial study spaces are not designed for numbers in excess of 30 pupils (Thompson and Wadsworth, 2007). Lecture theatres imply a bigger class size than secondary schools. For smaller classrooms, it may be possible for the indoor air to attain a homogenous state in a realistic occupancy period. However, for lecture theatres the larger volume of air and the ventilation rate dictates whether well-mixed conditions can be reached during the occupancy time of the lecture. There will be a re-distribution of IAQ throughout the space as the air mixes and moves around the theatre, but the speed of this air mixing depends on the ventilation rate.

An important issue with such large spaces is that the detailed assessment of airflow cannot be adequately performed using a full-scale model in a laboratory. This is due to size restrictions in the scaling factor (Awbi, 1991). Furthermore, the monitoring of airflow and contaminant distribution in a large space is technically difficult, as it requires a substantial number of monitoring points to give a reliable pollutant concentration distribution (Demokritou *et al.,* 2002).

A study by Linke (1962) on airflow movement produced by ventilation arrangements in concert halls has shown the variation in airflow that occurs due to the ventilation arrangement. The study did not indicate the effect of the room volume. The ceiling height variation in concert halls also exists in lecture theatres due to the tiered design. However, this characteristic of a lecture theatre would mean that the greatest floor to ceiling height occurs at the front of the room. Therefore, this would affect the airflow pattern in the room.

The room dimensions are an important influence on IAQ distribution. The room size will influence the time taken for the air to move from the supply to the extract, and the path of the airflow. Thus, in a larger room volume it will take longer for contaminants to build up.

The time taken for air to move from the supply to the extract points is also a consideration and depends on the ventilation rate. This is important, especially in locating IAQ sensors, as this can be problematic. For example, in a demand controlled ventilation system that works by increasing or decreasing the rate of supply air according to the ventilation required in the room, a sensor in the extract duct may not be recording the level of the room IAQ.

d) Occupancy profile

Occupants are sources of carbon dioxide and heat, which contribute to the thermal and pollutant load of the space. In addition, occupants are physical obstructions to airflow, which can influence the airflow pattern. Therefore, the particular positions where occupants sit will affect the distribution of IAQ.

In lecture theatres where the number of occupants varies throughout the day, the varying configuration of the occupancy profile will contribute to uneven levels of IAQ. These parameters fluctuate depending on the use of the room and occupant number. For this reason, the occupancy profile and the occupancy number are important parameters for IAQ variation.

3.3 A need for an IAQ assessment method in a lecture theatre

The assumption of homogenous conditions is an established approach in IAQ assessment. According to Richmond-Bryant *et al., (2006)* this approach is "standard practice" when modelling IAQ to assume that the contaminant concentration is spatially uniform. However, the authors stress that the time taken to attain such well mixed conditions is an important constraint on the modelling results.

Research, however, has demonstrated that a homogenous state in the IAQ level of large spaces is rarely attained. In a realistic time frame the homogenous assumption does not account for the initial mixing behaviour of a pollutant in the air, especially for point sources (Gadgil *et al.*, 2003). According to Gadgil *et al.,* (2003) for experimental reasons the assumption that pollutants are uniformly distributed is justified when measuring pollutant concentrations at one point in a space, but the homogenous assumption is too simplistic, as conditions in large rooms may never become well mixed.

The perfect mixing assumption is useful as it simplifies the assessment of IAQ pollutant concentrations in a space, but according to Lawrence and Braun (2006) this is at the “expense of accuracy”. In fact the ventilation of a space is a combination of both mixing and displacement of air which does not readily produce uniform conditions (Waters and Simons, 2002).

The volume of the space influences the time taken to attain a homogenous state. The greater the volume, the greater the time lag for a complete cycle of air change due to the inertia of the air. According to Statopouloo *et al.,* (2008) few studies have been made on the time lag between outdoor pollutant concentrations and the changes that they produce indoors. The authors suggest that the influence of time lag on IAQ and associated parameters should be studied further.

The occupants of a room as well as being a physical barrier to airflow are also a source of heat and gaseous emissions. Thermal heat plumes from occupants and equipment will influence the mixing of the air. In addition to being pollutant sources, the occupants influence the turbulent nature of the airflow and inhibit well-mixed conditions.

IAQ is assessed using a homogenous approach, the output is crude and lacks the sophistication to account for the complex conditions which actually occur. In addition, this is approach does not have the sensitivity to portray the spatial variation in IAQ that occurs within lecture theatres. Thus, assuming that the air in a large space is instantaneously well mixed has limitations (Richmond-Bryant *et al.,* 2006). Therefore, a requirement exists for an assessment methodology that incorporates the non-homogeneity of indoor air into an IAQ assessment procedure for lecture theatres.

A single blanket representation of IAQ in large spaces does not capture the actual IAQ experienced by the occupants. It is important that an IAQ assessment method is capable of representing this spatial variation, in order to identify, for example, any areas or regions of the room that have inadequate IAQ. Hence, an improved assessment of IAQ can provide information to aid the selection and design of ventilation systems in lecture theatres, and to assess its performance.

3.4 Conclusion

Large spaces do not ordinarily rely on natural ventilation and tend to use some form of mechanical ventilation system for control of heating and cooling of the space and air delivery (Dicks and Brown, 1997). The arrangement of the ventilation system supply air grilles greatly affects the pattern of airflow in the room (Sekhar and Willem, 2004;Lin *et al*., 2005b). This is in addition to the obstructions to airflow from furnishings. Therefore, when assessing IAQ, the effect of uneven airflow should be included in the assessment method. In reality, however, the airflow conditions, contaminant dispersion, and turbulence from heat sources including the general movement of occupants, do not necessarily give a well-mixed static environment: it is dynamic (Sekhar and Willem, 2004).

The way in which the ventilation system delivers air to a space is an important consideration from an IAQ comfort and energy point of view. However, acceptable IAQ cannot practically be provided by ventilation systems alone as, "*dilution is not the only solution for pollution*" (Rolloos, 1988). The main factors that influence air quality in lecture theatres seem to be the ventilation arrangement, source location, room volume and the number of occupants. The limits of applying a homogenous principle to IAQ assessment in lecture theatres have been discussed and it appears that the non-homogeneity of air in a large space is a significant consideration in an assessment methodology.

An assumption of instantaneous mixing can be justified in experimental studies that measure pollutants at one point in a space for short time durations, such as aerosol monitoring (Richmond-Bryant *et al.,* 2006) but the behaviour of the whole space is often included in the experiment. According to Gadgil *et al.,* (2003) for modelling studies this well-mixed assumption over-simplifies the conditions in the breathing zone of large spaces. Furthermore Mora *et al.,* (2003) reiterated this view as when modelling airflows and pollutant distribution, the mixing assumption may only be acceptable for small volumes. Therefore, this assumption is not appropriate for lecture theatres.

It is possible that an adequately ventilated space with a suitable ventilation arrangement, given enough time can have well mixed air conditions, especially during extended periods of constant occupancy or when empty such as overnight. The volume of the space however, has an important influence on the time taken for air to attain a well-mixed or homogenous state (Chow *et al.,* 2002), in that the greater the volume of air, the greater time taken for a complete cycle of air change due to the inertia of the air. Nevertheless, assuming that the air in a lecture theatre is instantaneously well mixed is too simplistic for a realistic IAQ assessment in this type of indoor environment.

Chapter 4 describes a pilot measurement of carbon dioxide concentrations in a lecture theatre to test the premise of non-homogeneity during the daytime use of the lecture theatre. Carbon dioxide concentrations were measured as a surrogate IAQ indicator. The measurements were used to examine the extent to which homogeneity of indoor air occurred in the lecture theatre.

CHAPTER FOUR

A pilot study of carbon dioxide distribution in a lecture theatre

4.0 Indoor conditions in the lecture theatre

Mayfield House is part of the University of Brighton's relatively new development on the Falmer campus. The construction has three storeys, which provides accommodation for offices and teaching, including a lecture theatre, a performance studio, and a snack shop. The architects and project managers of the building were HNW Architects, Chichester.

The design of the building incorporates several energy saving measures, which include:

- The use of overnight cooling from natural ventilation via ventilation grilles in the floor of classrooms and offices;
- An atrium which aids the natural ventilation effect as it has roof windows that open automatically when additional ventilation is required;
- Occupant sensing lighting control;
- An air conditioning system in Lecture Theatre 129, which regulates the air supply into the room using carbon dioxide sensors in the extract ducts.

The building is mainly naturally ventilated. The system is based around the central atrium, and is designed to achieve a BREEAM rating of excellence. The BRE Environmental Assessment Method sets a standard for best practice in sustainable design and is used to express the environmental performance of the building (Building Research Establishment, 2008). The indicators used in this environmental assessment methodology include health and well being, air pollution and energy use in terms of operational energy use and CO_2. The excellence rating of Mayfield House indicates that its design is state of the art, and importantly that the building incorporates innovative ventilation strategies that aim to provide acceptable air quality with efficient energy use.

4.1 Use of Mayfield House 129

The Lecture Theatre 129 is used at the weekends and throughout the teaching week by the schools based at the Falmer campus, including the Faculty of Health and the Brighton and Sussex Medical School (Table 4.1). It was not possible to obtain the number of students per lecture. In order to use the lecture theatre as a measurement site, users of the room were asked for permission. Due to refusals, it was only possible to monitor the room for one entire day (Wednesday 16th February 2005).

Wk Beg. 14th Feb
Mon 09:00 12:30 FA Mayfield House 129 14-02-2005 EE382
Mon 13:30 16:30 FA Mayfield House 129 14-02-2005 Education Studies
Tue 10:00 11:00 FA Mayfield House 129 15-02-2005-15-03-2005 SS357
Tue 11:00 13:00 FA Mayfield House 129 11-01-2005-18-01-2005 Themed Clinical Teaching
Tue 14:00 17:00 FA Mayfield House 129 11-01-2005-08-03-2005 Workshop
Wed 09:00 11:00 FA Mayfield House 129 05-01-2005-16-03-2005 LX/LN115 18673
Wed 11:00 13:30 FA Mayfield House 129 16-02-2005 English Subject Study
Thu 10:00 13:00 FA Mayfield House 129 13-01-2005-17-03-2005 Themed Clinical Teaching
Thu 13:00 16:30 FA Mayfield House 129 17-02-2005 NH330
Fri 09:00 17:00 FA Mayfield House 129 18-02-2005 BALAST Open day 19000
Sat 08:00 19:00 FA Mayfield House 129 19-02-2005 uncommon knowledge 21646
Sun 08:00 19:00 FA Mayfield House 129 20-02-2005 uncommon knowledge 21647

Table 4.1 Table of Mayfield House 129 weekly use

4.1.1 Plan of Mayfield House 129

The lecture theatre (Mayfield House 129) is a conventional design with stepped floors and three sections of benches (Figure 4.1). The room has a pentagonal shape with a maximum ceiling height of 3.64m. The middle section is parallel to the front and back walls with angled side sections (Figure 4.2). The theatre has a maximum capacity of 106-seated occupants. There is a projector room at the back of the lecture theatre.

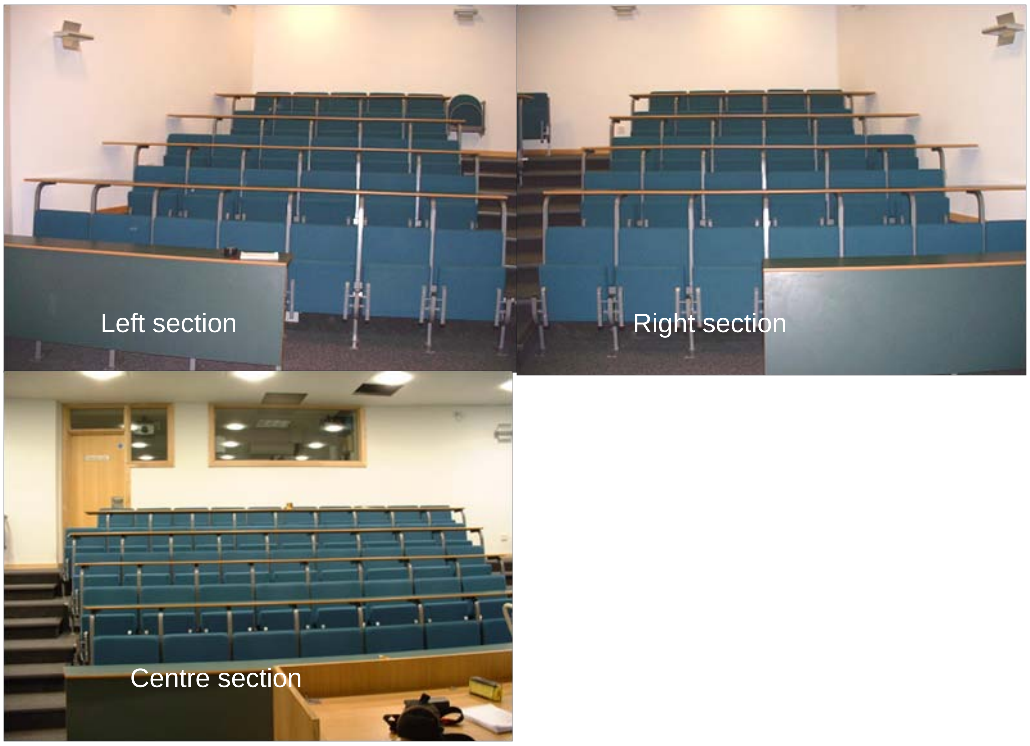


Figure 4.1 Layout of Mayfield House Lecture Theatre 129.

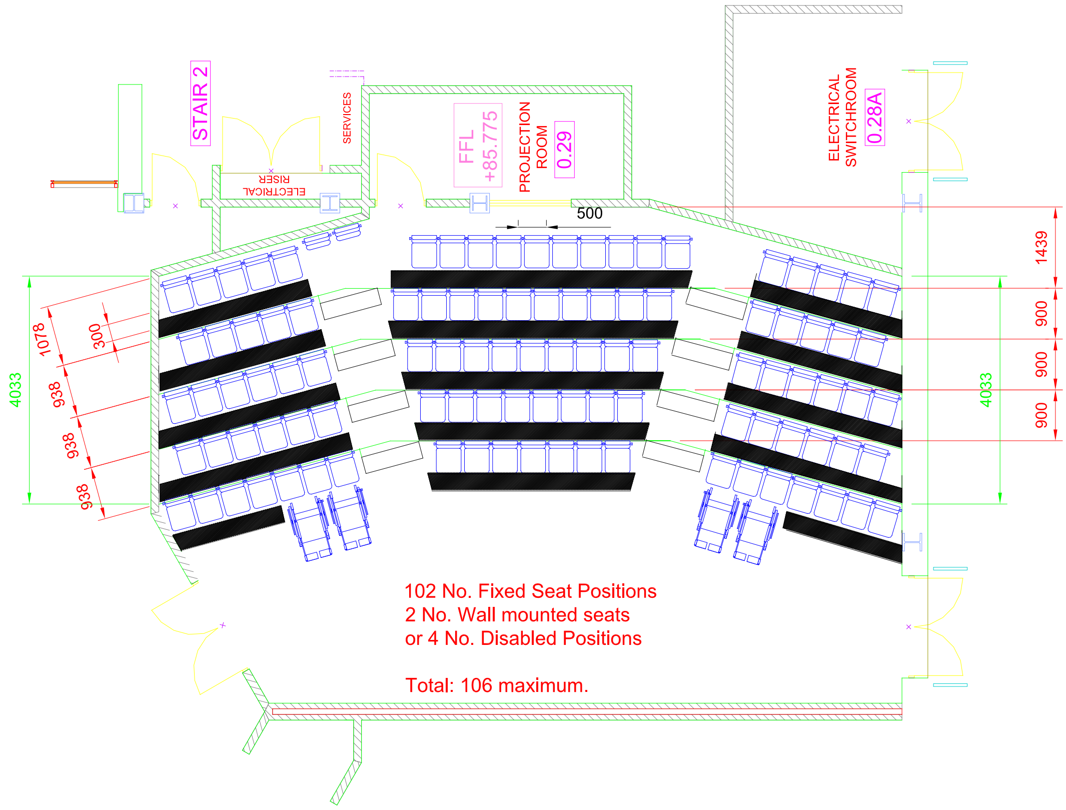


Figure 4.2 Plan of Mayfield House 129

4.1.2 Ventilation system arrangement

In the configuration of the benches and seats (Figure 4.3), air supply grilles are positioned in the vertical step of the seating, underneath the benches, in all three sections (Figure 4.4). The very back of the room does not have any supply air grilles. The extract grilles are in the ceiling at the front of the lecture theatre (Figure 4.5). Thus, the movement of air is by a displacement ventilation arrangement of supply and extract terminals.

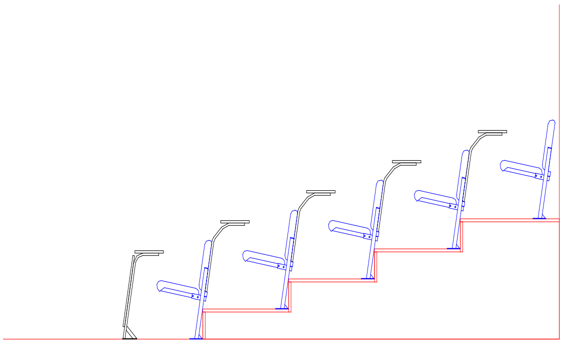


Figure 4.3 Seating configuration in Mayfield House 129

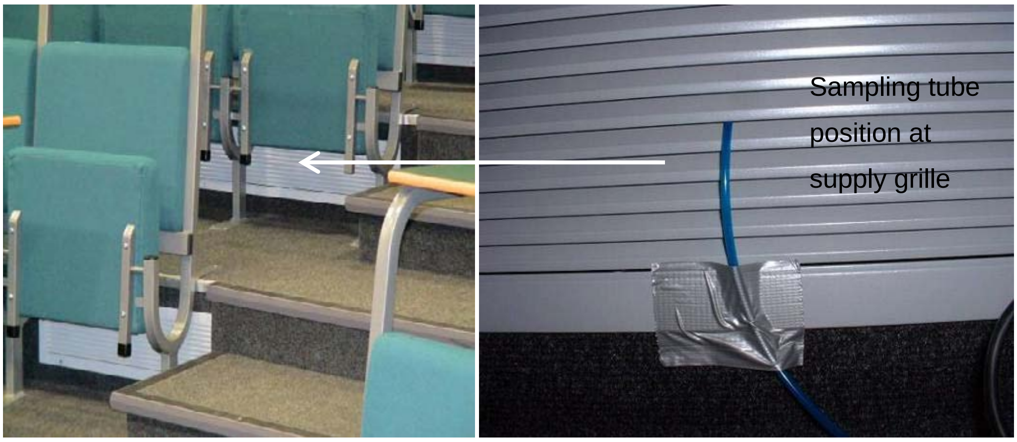


Figure 4.4 Supply air grilles in vertical step in Mayfield House 129

Figure 4.5 Extract grille positions in Mayfield House 129

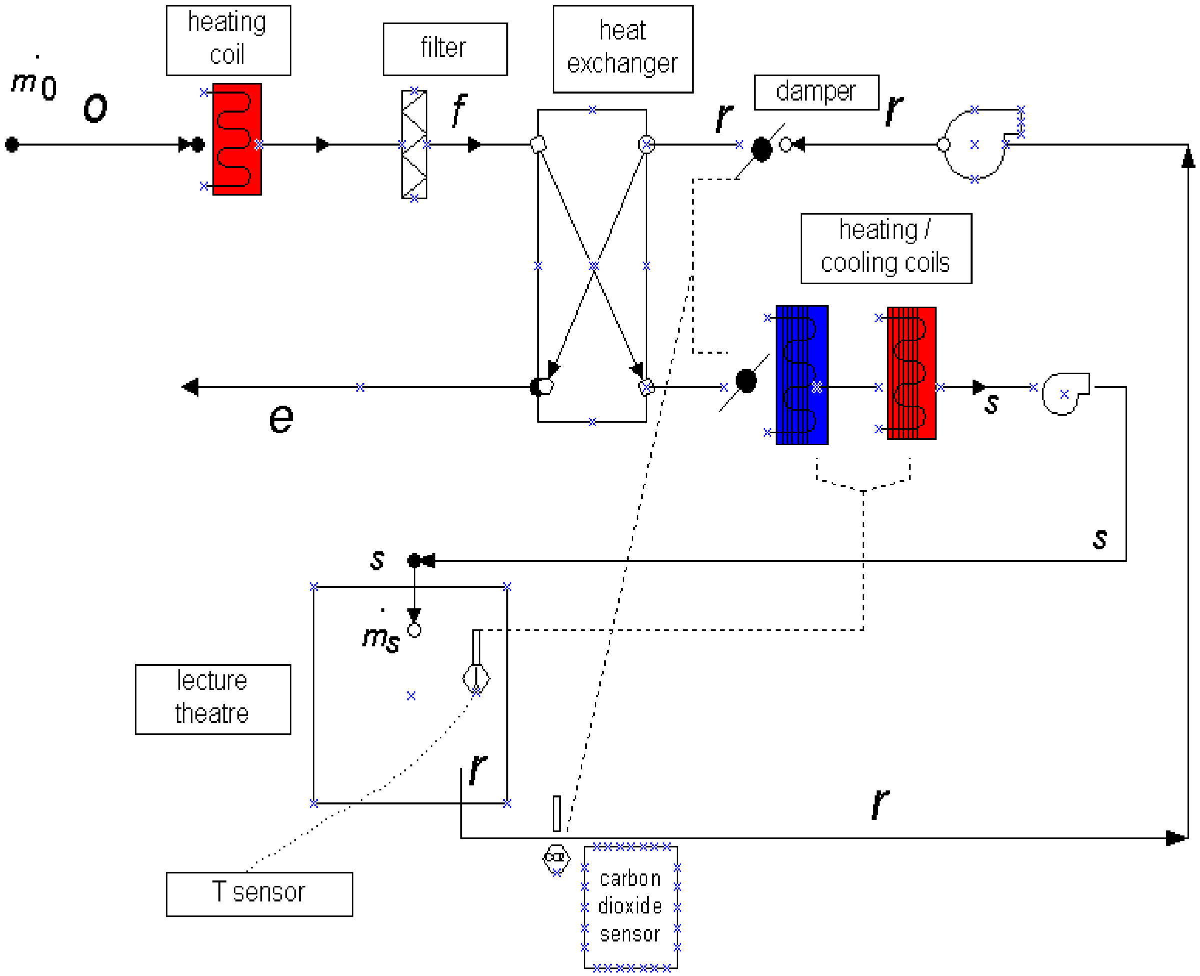
A recommended ventilation rate for a lecture theatre is six air changes per hour (ACH). A smoke test was performed to measure the rate used in the Mayfield House lecture theatre. This involved inserting a “smoke bomb” into the ventilation supply air duct, and recording the length of time that it took to remove the resultant orange smoke from the lecture theatre. The smoke device was similar to that used by domestic gas engineers. The fire alarm system was disabled before the test occurred and reactivated after the test.

The displacement ventilation arrangement installed in this room uses a variable air volume (VAV) ventilation system type, and operates by using 100% fresh air for the supply air with no re-circulation of air from the room exhaust. The exhaust air is passed through a heat recovery system, which preheats the supply air. The fans operate at two speeds (low or high). The building service engineers determine the temperature set point.

When the system is in heating mode, the fans are at low speed to control the amount of incoming air. The speed of the supply and extract fans is controlled by the concentration of CO_2 sensed in the single return air duct illustrated in the schematic of the ventilation system (Figure 4.6). If the building management system (BMS) monitor detects temperatures or CO_2 above the set point, the high-speed mode operates to introduce more fresh air into the room.

An air-handling unit serves the lecture theatre. This unit consists of a fresh air damper, a supply fan, a pre-filter, a main-filter, preheat coil, a two-stage DX (direct expansion) cooling unit, a heating coil, a return air filter, a heat recuperator, a bypass damper and extract fan. The air-handling unit is housed in the boiler plant room external to the lecture theatre.

Sensors in the return air duct control the amount of ventilating air that is introduced into the theatre. The CO_2 sensor was initially set at 600 ppm, but the energy manager found that this CO_2 concentration was too low. This judgement was based on the observation that when the occupancy number of the lecture theatre was at a minimum and well under its design capacity, the fan frequently went into high-speed mode. This resulted in over ventilation of the room and an unnecessary increase in the system's energy demand. Consequently, the set point was readjusted to between 900 - 950 ppm, which was considered to be an acceptable concentration on which to base the ventilation of the lecture theatre.



Legend

$\dot{m}_o$ outdoor air intake mass flow rate (kg/s)

f drybulb + wetbulb or (h) enthalpy

s air supply (drybulb + wetbulb or (h) enthalpy)

a drybulb + wetbulb or (h) enthalpy

r room or return air condition (drybulb + wetbulb or (h) enthalpy)

e exhaust air condition (drybulb + wetbulb or (h) enthalpy)

N.B. there was no mixing conditions as the system was 100% fresh air (FA).

Figure 4.6 Schematic showing the airflow circuit and main components of the ventilation system for Mayfield House 129.

In Mayfield House, the BMS provides computerised control of several aspects relating to the operation of the building, including the ventilation system. For instance, when the room air temperature drops below the design level, an instruction is relayed to the heating component of the ventilation system to increase the temperature of the supply air to raise the room air temperature. The regulation of the ventilation rate follows a similar process and uses the detection of 900 - 950 ppm CO_2 in the return air duct as set point measure. Therefore, the BMS is programmed to provide the energy efficient operation of the building.

4.1.3 Indoor air sampling procedure

Indoor air quality can be measured and monitored in many ways. Section 2.6 provides an overview of selected measurement methods and monitoring equipment. In the study of Mayfield House, the sampling process involved measuring CO_2 concentrations from fixed locations. The sampling method was adapted from a typical tracer gas technique used to measure air change per unit time in a mechanically ventilated room (Nabiger *et al.*, 1994).

Three air-sampling locations were used in recording the CO_2 concentrations, as that was the number of sampling points available in the monitoring equipment. The locations were placed in a vertical planar direction on one side of the lecture theatre seating. This arrangement was used in order to establish a spatial profile of CO_2 concentrations during the monitoring period. In addition, the results were required for input into a mass balance model of theoretical CO_2 concentrations in the lecture theatre (Section 4.4.1.)

Many models are available that calculate the effectiveness of a ventilation system, as a substitute to direct IAQ measurement, by varying parameters such as the ventilation rate to test how well indoor generated pollutants are exhausted from the room. Additionally to mathematical models there are other modelling techniques used for examining IAQ. These range from simple empirical models that operate on relatively low amounts of data, to deterministic computerised models that use complex mathematical codes to simulate indoor air transport and pollutant dispersion. The functionality of such models for use in this study is discussed in Chapter 5. Furthermore, a review of the models frequently used in IAQ assessment is presented in Section 2.7.

4.2 Monitoring and Data Collection

In order to measure the spatial variation in IAQ levels in the lecture theatre, a Vivo™ Trigas PAS monitoring unit was used to sample CO_2 concentrations. The unit has an internal calibration function. The manufacturer completes the calibration of this spectrometer annually, as the monitor is returned to the factory. Additionally, the unit is returned with an electronic calibration file should the spectrometer need recalibration during the year. A screen shot of the calibration file details is shown in Figure 4.7. In addition, when this equipment was used in Mayfield House it had just been returned to the University after calibration.

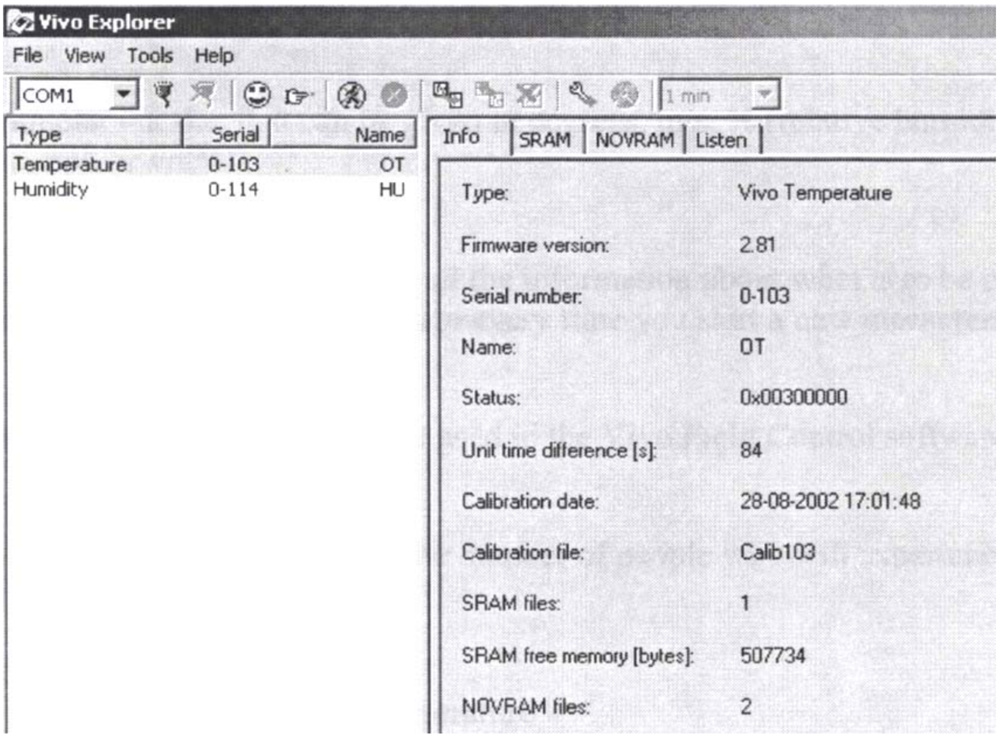


Figure 4.7 Internal calibration file for Vivo units (Dantec Dynamics, 2002)

It was not possible to inspect or check the calibration of the CO_2 monitor in the extract duct of Mayfield House due to its location within the ventilation system. This meant that cross calibration between the Vivo and the extract CO_2 readings was not feasible. The building service engineers that were responsible for the monitor and its links to the BMS computer hub in the university estates department did explain that this was a relatively new building, and the contractors had checked the ventilation system on installation. Consequently, for the purpose of this pilot study, the accuracy of the extract duct monitor was assumed to be operating correctly.

Sampling occurred on Wednesday 16th February 2005. The CO_2 concentrations were recorded in real time. The samples were taken via three intake tubes that corresponded to the three sampling channels at the same time. All the sampling locations were in the middle section of the theatre in a straight line 6.5m from the east wall in the room (Figure 4.8).

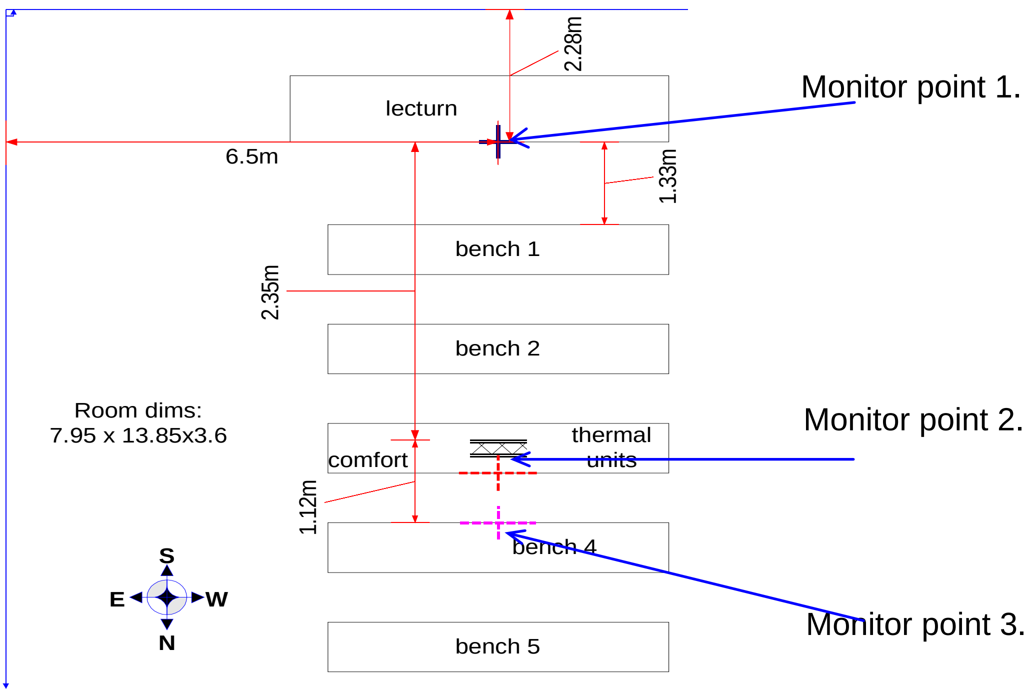


Figure 4.8 Plan of monitoring positions in Mayfield House 129.

Thermal comfort units were also placed at the centre seat of the third row of benches to measure the ambient room temperature. This was to determine any fluctuation from the design temperature range, and specifically to examine whether the ventilation system was delivering the designed thermal comfort for the lecture theatre.

The Trigas monitoring unit was placed directly beneath the thermal comfort unit. Sampling tubes were securely run from this unit to the sampling locations:

- Monitoring point 1 was positioned at the front of the lecture theatre on the vertical surface of the lectern;
- Monitoring point 2 was positioned vertically (with the open tube end pointing upwards) at the desk level as was the thermal comfort unit;
- Monitoring point 3 was placed vertically against the supply grille under the thermal comfort unit position (Figure 4.9).

Figure 4.9 Monitoring point 3 and a supply grille with sampling tube

The sampling locations in relation to the seating arrangement of the room are shown in Figure 4.10. The figure shows both plan and side views. The monitoring points one and two were chosen to enable a comparison of the IAQ at breathing levels in a seated occupied zone, and at the lectern. The front of the room has air that has passed over the occupied zone on its way towards the extract grill. Monitoring point three was selected to measure the IAQ of the air coming into the room, and to establish background CO_2 levels. The three measuring channels allowed simultaneous readings of CO_2, and enabled a comparison of the differences between measuring locations.

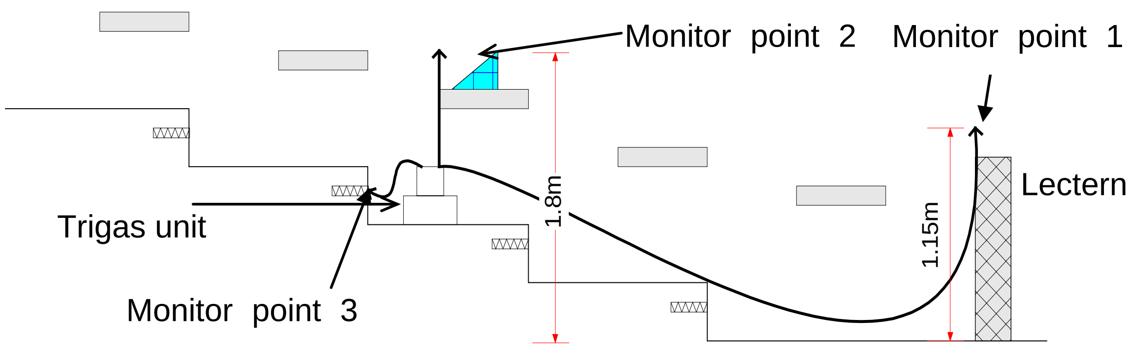


Figure 4.10 Cross section of monitoring plane in Mayfield House 129.

4.2.1 Occupancy profile during data collection

The monitoring period consisted of two lectures. A summary of the occupancy is shown in Table 4.2. The monitoring period comprised three periods; two when the lecture theatre was occupied, and one when it was empty.

Wednesday 16th February 2005	Mayfield House 129									
Time	08:00	08:30	09:00	10:00	11:00	12:00	13:00	13:30	14:00	15:00
Sampling duration										
Morning lecture: 21 occupants										
Afternoon lecture: 33 occupants										

Table 4.2 Lecture theatre occupancy schedule

The morning lecture occupancy is shown in (Figure 4.11). The lecture theatre emptied at 11:00 hrs and remained empty until 11:50 hrs, at which time, the second set of students began to fill the lecture theatre (Figure 4.12). The lecture theatre was only used twice during the day on which it was monitored, thus illustrating the intermittent occupancy of such spaces.

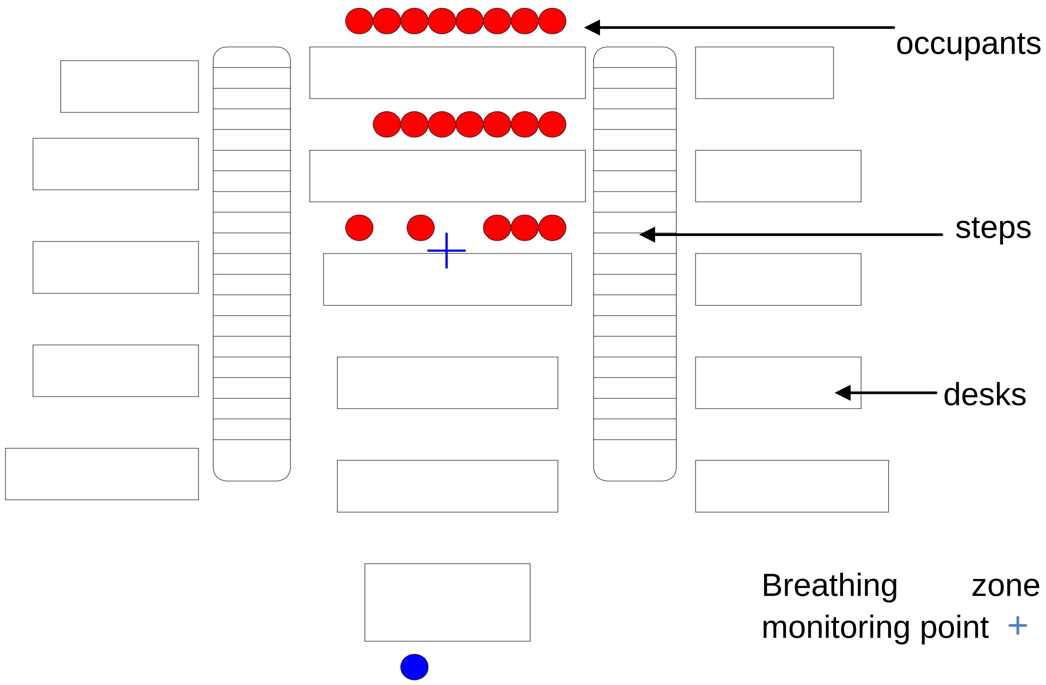


Figure 4.11 Morning lecture occupancy plan in Mayfield House 129

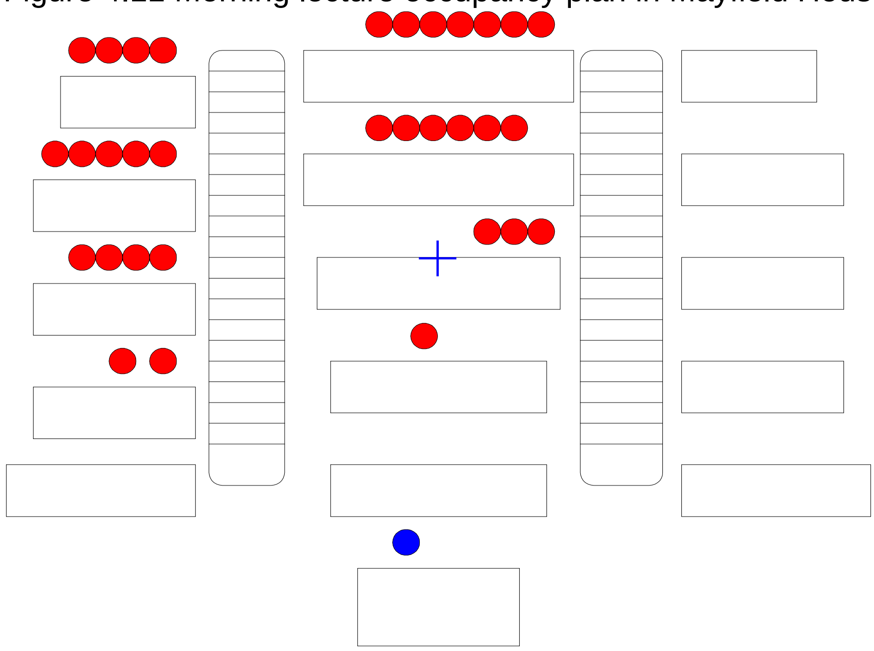


Figure 4.12 Afternoon lecture occupancy plan in Mayfield House 129.

During the morning lecture students sat in the central block of seats adjacent and behind the breathing zone sampling point. In the afternoon, however, 33 occupants sat in the left seating block, and also beside and behind the monitoring point. Therefore, the lectures had different occupancy profiles.

At approximately 12 noon, at the beginning of the second lecture, the thermal comfort-measuring unit was moved in the same plane, to the second row bench, in order to investigate any spatial variation in the temperature profile. After the second lecture finished, two people occupied the room. The remaining sampling time was spent collecting data from a handheld anemometer to measure air speed, and taking photographs.

The monitoring exercise in this lecture theatre resulted in two data sets of carbon dioxide measurements. In addition, supply air velocity measurements and thermal comfort readings at the beginning and end of the monitoring period were taken to check against the recordings made by the building management system (BMS). This check was to determine whether the lecture theatre was being ventilated according to its design specifications.

4.3 Monitoring results

The first lecture had 21 occupants who sat behind and adjacent to monitoring point two, in the middle region of the lecture theatre. The measured CO_2 concentrations (Figure 4.13) were most variable in the breathing zone, and averaged 520 ppm with a range between 426 and 671 ppm. This CO_2 concentration illustrated that the room was being ventilated correctly, as it was below the ASHRAE 1000 ppm standard. Furthermore, the CO_2 concentration was below the ventilation system set point value (950 ppm). Thus, the high fan speed would not be activated and the system would have a low energy demand.

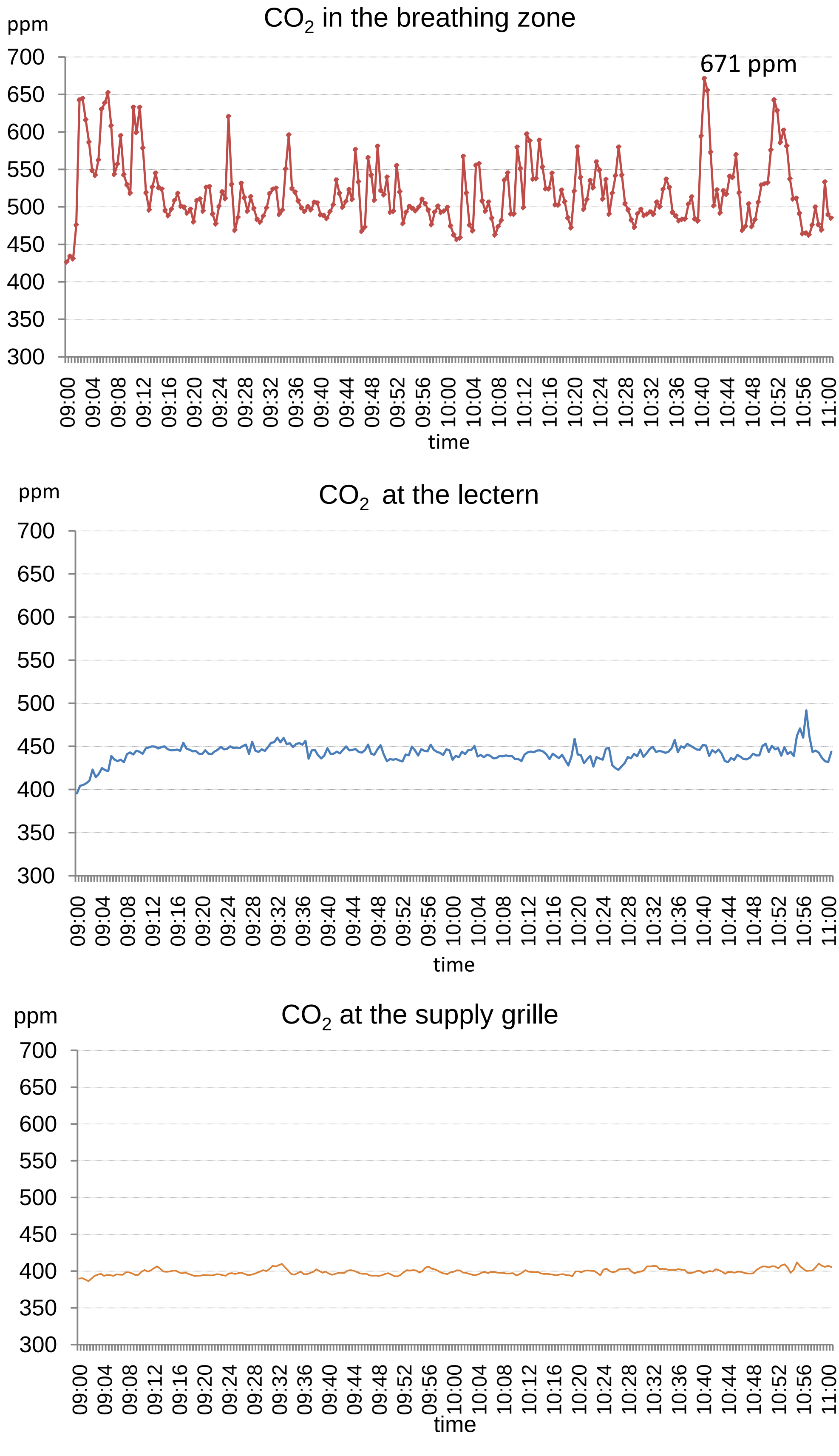


Figure 4.13 CO_2 concentrations during the morning lecture in Mayfield House 129.

The supply air CO_2 concentration showed a small range of variation (26 ppm), which fluctuated around 400 ppm reflecting the sensor variation. The concentrations at the lectern were slightly greater than the measurements at the supply grille and ranged from 395 - 492 ppm. This probably relates to the presence of the lecturer who was stood in proximity to the sampling point and produced the small rise in concentration.

The highest CO_2 concentration measured during the day (784 ppm) occurred in the afternoon lecture after 30 minutes (Figure 4.14). For this lecture, the average supply air CO_2 concentration was 397 ppm, which was similar to the measurement in the morning lecture. The measurements around the lectern averaged 444 ppm, again similar to the previous lecture. This showed that the ventilation system was working in a similar way for both lectures.

The concentration in the breathing zone ranged from 439 - 784 ppm, with an average of 521 ppm, which was a very close match to the average from the morning lecture. In the morning lecture, there were 20 students sat near the monitoring point compared with 17 students in the afternoon lecture. The number of students sitting near the monitoring point in both lectures was similar. This accounts for the similarity of the average CO_2 concentrations. Furthermore, this observation tied in with the CO_2 measurements from the other monitoring points, indicating a comparable ventilation system performance.

The two lectures monitored, showed relatively stable CO_2 concentrations at the supply grille as compared to those measured in the breathing zone. The CO_2 concentrations at the lectern were slightly higher (by approximately 50 ppm) than the supply grille but were not as even. Variations in this CO_2 concentration appeared to be related to the lecturer standing near to the lectern.

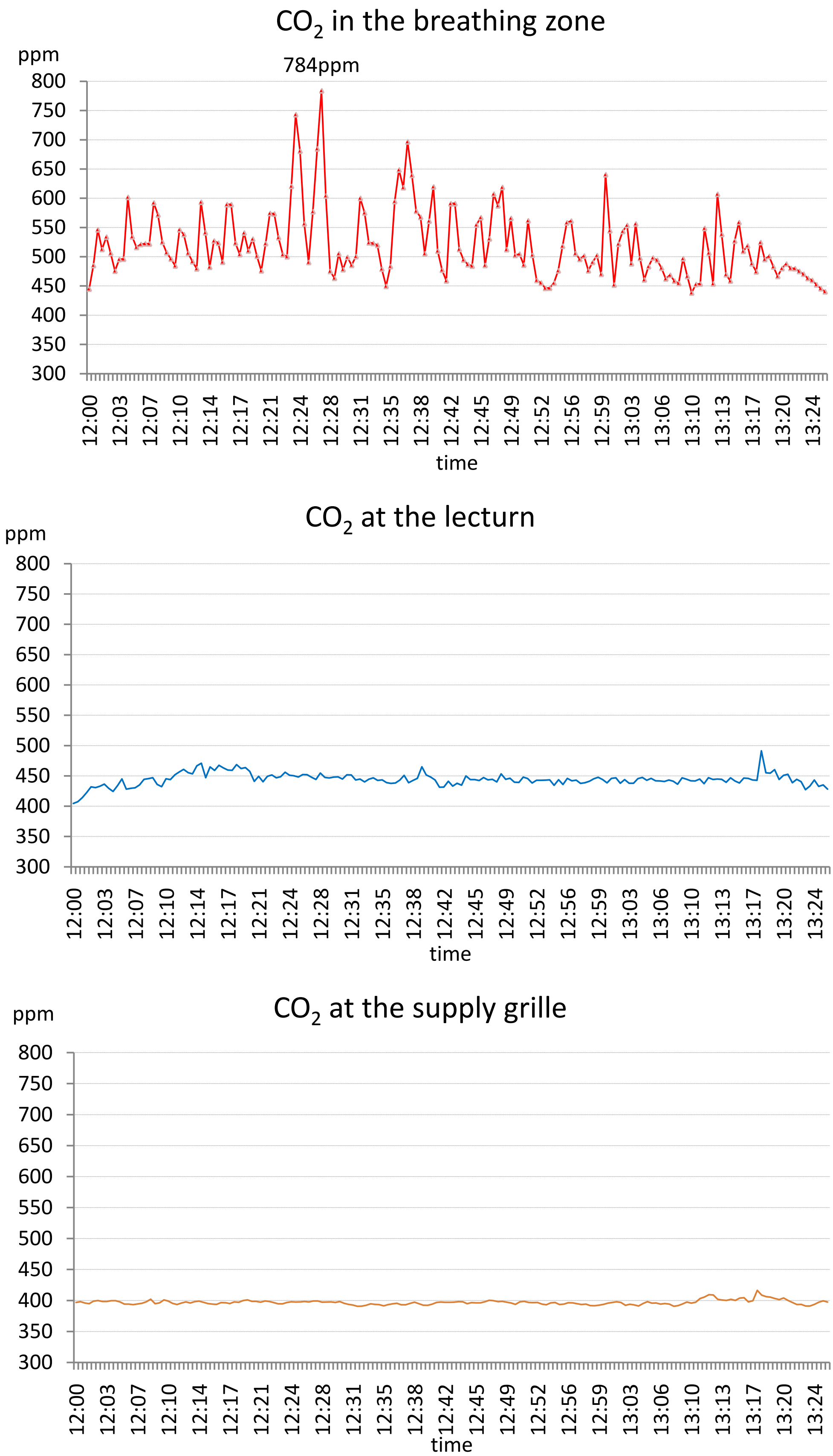


Figure 4.14 CO_2 concentrations during the afternoon lecture in Mayfield House 129.

Both lectures showed concentrations of CO_2 in the breathing zone that changed with time. The variation in the distribution of CO_2 concentrations for both lectures is illustrated in Figure 4.15. This graph shows the data measurements along a corresponding CO_2 concentration line. Even though the average concentrations in of both lectures were very similar, the distribution of the CO_2 concentrations are different.

The morning lecture had a smaller range of CO_2 concentrations that were grouped around the average concentration. The afternoon lecture showed a greater spread of CO_2 concentrations. Despite the average CO_2 concentration being very similar, the distributions are different. Given that there are a comparable number of students were sitting near the monitoring point, the difference in the distributions is difficult to account for. Nevertheless, the observations support the view that indoor concentrations are not homogenous during lecture periods.

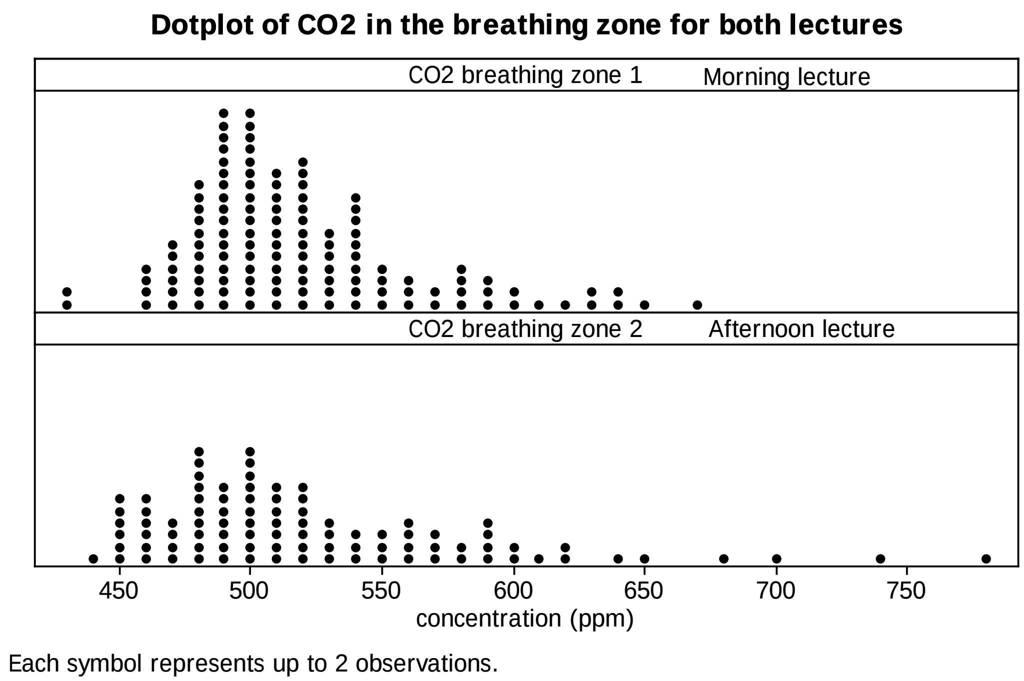


Figure 4.15 Variation in CO_2 distribution in the lectures in Mayfield House 129.

The ventilation system is designed to stream fresh air into the space and remove the stale air. An even supply of fresh air is a design ideal, but the observations suggest that the IAQ and comfort of students sitting in a lecture theatre can vary due to where they are located. For this pilot study, one monitoring point was located in the breathing zone which was not enough to provide adequate spatial coverage. A greater number of sampling points would be required to investigate whether the observed variation occurred simultaneously throughout the breathing zone.

The plot of CO_2 concentrations for the entire monitoring period (Figure 4.16) illustrates the variation in CO_2 concentrations. Examination of data recorded at the other locations in the lecture theatre showed that the CO_2 concentrations varied at the lectern, but there was less variation at the supply grille because the airflow had just entered the room and had not been affected by emission sources. However, this variation in concentrations over time suggested that the air conditions during the occupied times were not well mixed in the lecture theatre.

The fluctuation in CO_2 concentrations additionally suggests that at a local level the comfort of the occupants also changes. The detection of such changes by individuals depends on the sensitivity of the person. To account for the difference in perceptions of the population IAQ is commonly defined as acceptable if a majority of occupants are comfortable. On the other hand, even though IAQ comfort cannot be guaranteed for every individual, improved designs and IAQ assessment can minimise the chance of occupant discomfort.

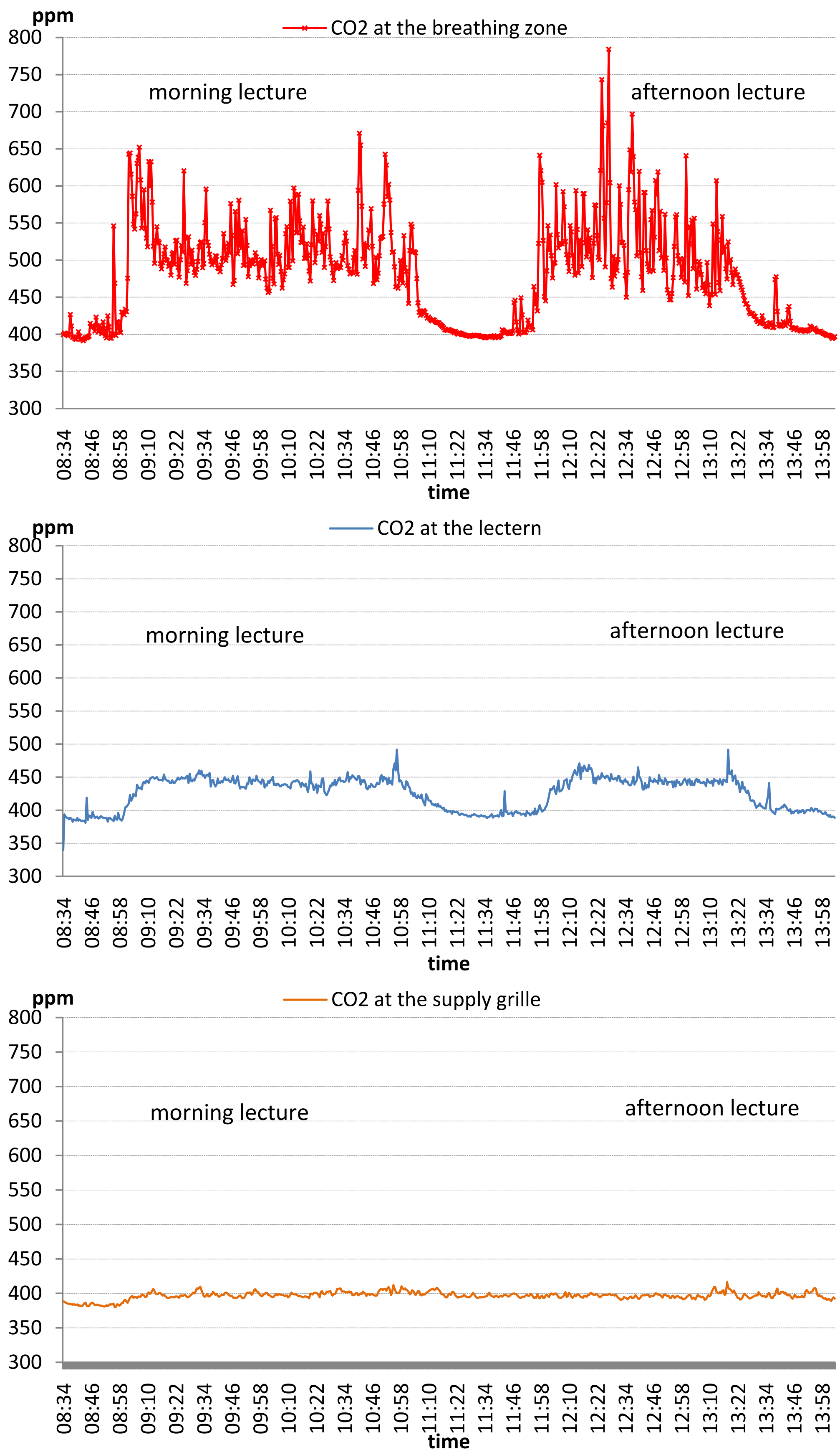


Figure 4.16 Carbon dioxide during monitoring period in Mayfield House.

The vacant episode (11.00 - 12:00 hrs) between the lectures was clearly indicated at both the lectern and in the breathing zone by the drop in CO_2 concentrations. These concentrations progressively fell towards the CO_2 level measured at the supply grille, and after 30 minutes, the room level had reached an ambient concentration. This illustrated that the ventilation system was effectively removing the CO_2 produced during the morning lecture. Moreover, this observation also suggests that homogenous conditions occur only when the lecture theatre is empty. The presumption that well mixed conditions may occur in an occupied lecture theatre may be untenable.

The concentration measured by the BMS sensor in the extract is shown in Figure 4.17, along with the breathing zone CO_2 measurements for comparison. The CO_2 concentrations recorded in the extract duct did not correspond to the concentrations measured in the lecture theatre. The unoccupied period between lectures (11 am - 12 pm) is represented by a fall in concentration. However, the concentration recorded by the BMS sensor in the extract shows a time lag. The decrease in CO_2 concentration to the ambient level was recorded later by the BMS, in the extract than in the breathing zone measurements. As a result, the BMS recorded different CO_2 concentrations from those in the lecture theatre.

The BMS extract data did not show the peak concentrations that were measured in the lecture theatre. This was possibly due to dilution of the CO_2 concentration in the higher regions of the room which led to a lower reading by the sensor in the extract duct. The measurements from the BMS sensor however, followed the same trend as the measurements in the breathing zone. The BMS data curve was however comparatively smoother than the breathing zone concentration measurements. The increases and decreases of the measured CO_2 concentrations were more pronounced in the breathing zone, and the data suggests that this region had a greater degree of variation in CO_2 concentration.

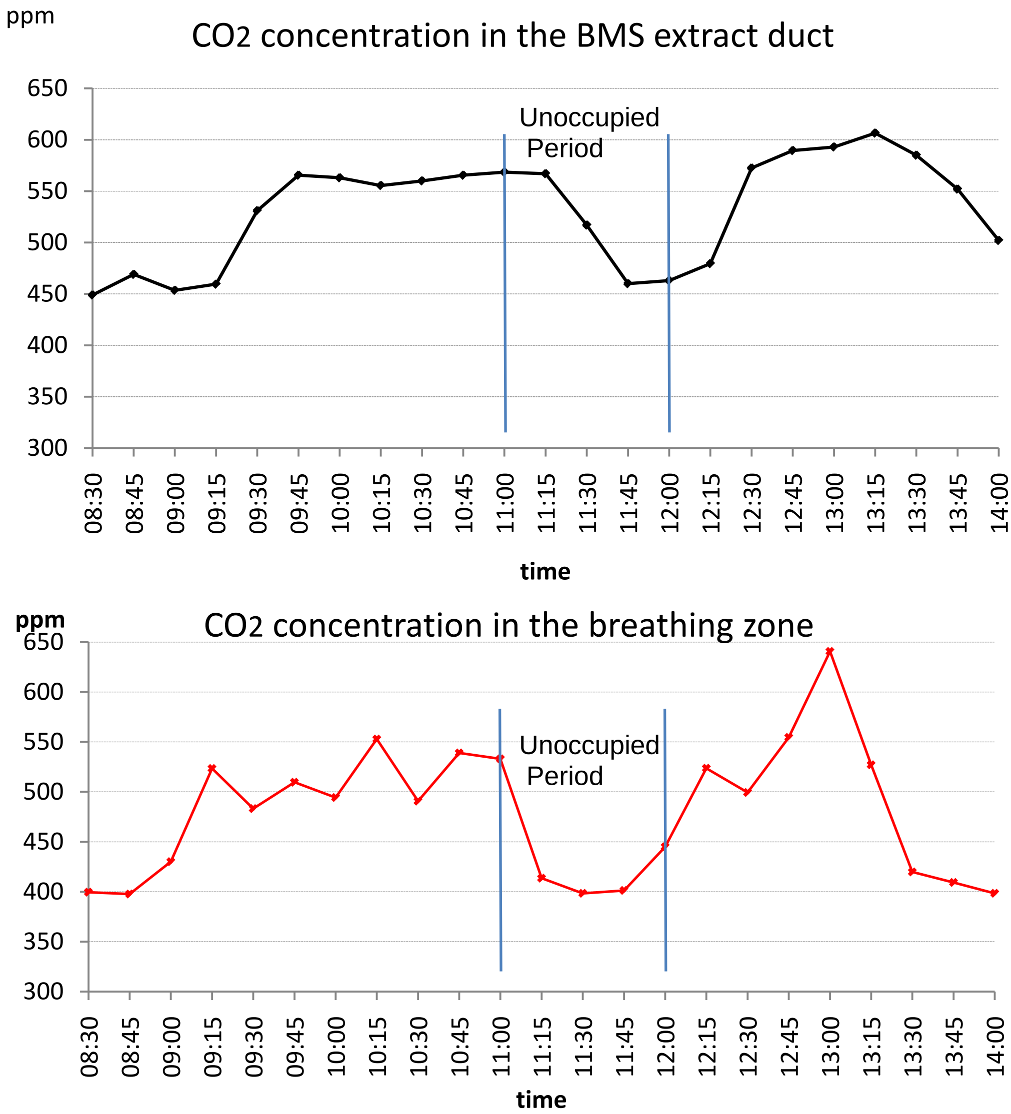


Figure 4.17 Comparison of CO_2 concentrations monitored in Mayfield House 129.

The location of sensors in large rooms, including heating controls, is not normally a high design priority as it is assumed that large spaces "are easy to control and therefore control provisions need relatively little thought" (Dicks and Brown, 1997). Hence, locating the sensor in the extract duct is a general practice and the assumption is that the concentration of CO_2 extracted represents the concentration in the lecture theatre. This assumption is reliant on the air in the lecture theatre being well mixed to give a representative measure of the CO_2 (and IAQ) in the room. This does not however seem a sensible assumption, and this view is reinforced by the observation that the monitoring data showed a greater variation of CO_2 readings in the breathing zone than in the extract duct.

The differences between the monitoring point readings and the BMS readings are clear from the graphs. The data sets were significantly different at a 95% confidence interval ($p<0.05$). The BMS concentration followed a similar pattern to the concentrations measured in the room, but at higher values. However, the sensors in the extract duct did not pick up the highest concentration peaks measured in the breathing zone, and could be considered to be misrepresenting the comfort levels in the lecture theatre.

The CO_2 concentrations recorded in the extract duct did not correspond to the concentrations measured in the lecture theatre. The difference was pronounced during the period between lectures, when the room was empty between 11:00 and 12:00 hrs. During this time, the BMS was recording different CO_2 concentrations from those in the lecture theatre.

The differences in concentrations recorded in the room, and in the extract duct, illustrate the importance of correctly positioning CO_2 sensors in order to represent CO_2 level in the room. In order to record the CO_2 levels experienced by the occupants, the sensors would be better placed nearer the breathing zone. A sensor in this location would provide a closer portrayal of CO_2 in the occupied zone.

During the monitoring period the CO_2 concentration did not exceed the set point of 950 ppm, which is the signal for the ventilation system to use a higher fan setting. The lower fan setting was operating for the duration of the monitoring period. The lower CO_2 concentrations that were measured in the room (compared to that in the extract duct) were due to the number of occupants in the lectures and not because more fresh air was being introduced into the lecture theatre by the ventilation system using the higher fan speed.

4.3.1 Supplementary thermal comfort measurements

In addition to measuring the carbon dioxide concentration during the lectures, thermal comfort was recorded as further evidence relating to the operation of the ventilation system. Data consisted of recordings from hand held equipment, the BMS, and the Vivo™ Thermal Comfort unit. The thermal readings from each measurement method are described in the following subsections.

Hand held measurements

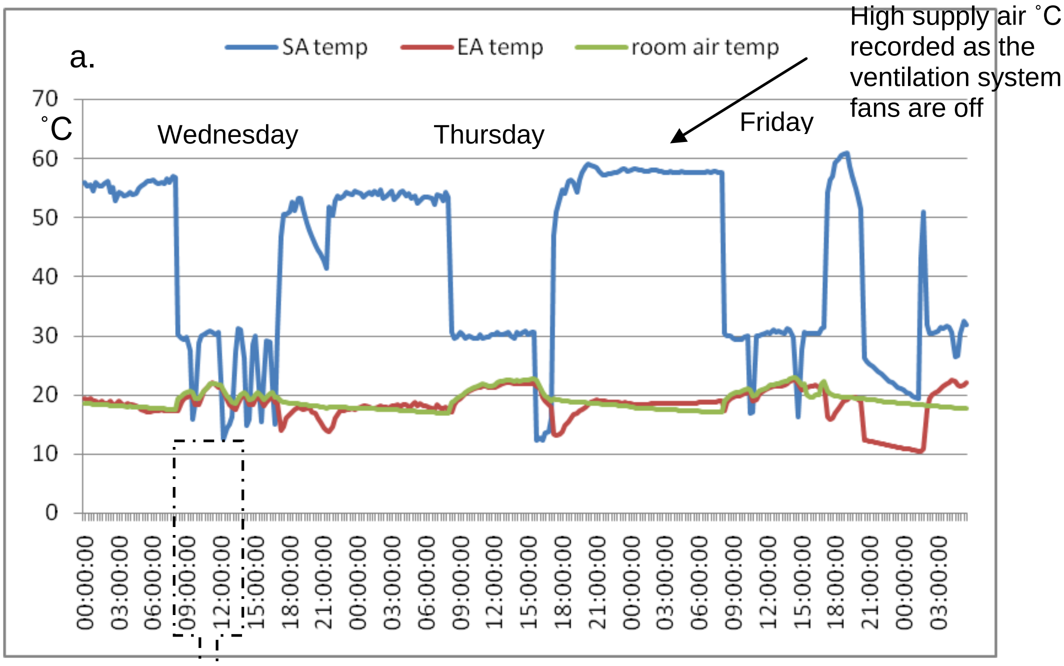
To complement Vivo thermal comfort data, air temperature and velocity measurements were taken from different supply ducts using a hand held anemometer (testo 435 hot wire anemometer, accuracy ±0.05 m/s) and a thermometer (4 in 1 environmental meter which uses a thermocouple device, accuracy ±3.0%±2d). The readings are summarised in Table 4.3. The supply air velocities were greater than the recommended 0.15 m/s and were above 22 °C near the floor. The ventilating air therefore met the thermal comfort requirements (CIBSE, 2003).

Measurement location	Air Temperature ˚C range	Air velocity m/s range
Lectern (at 07:30hrs)	20.9	0
Supply duct: front row	22.0 – 24.6	0.13 – 0.29
Supply duct: step level 2	24.4 – 25.2	0.45 - 0.48
Supply duct: step level 3	22.7 – 23.1	0.35 – 0.40
Supply duct: step level 1 mid section (at 14:00hrs)	25.1 - 25.8	0.29 – 0.45

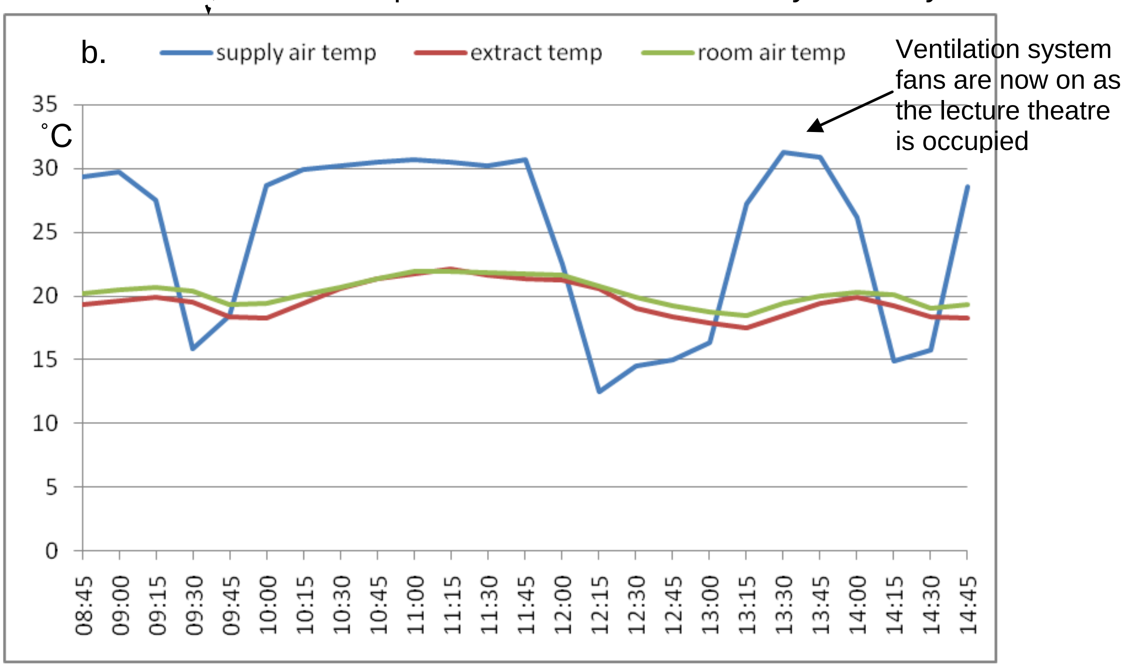
Table 4.3 Hand held measurements of air temperature and velocity readings in Mayfield House 129.

Building Management System

The occupancy sensor in the room relays information to the BMS. This controls the ventilation air temperatures and lighting. The BMS data for the week when monitoring occurred (Figure 4.18) shows the ventilation air temperatures.



BMS temperature data for Wednesday to Friday



“Snap-shot” of temperatures during monitoring period 09:00 to 14:30 on the Wednesday monitored lectures

Figure 4.18 Ventilation temperatures recorded by the BMS in Mayfield House 129.

The supply air temperature at the main air-handling unit is kept heated at approximately 60˚C graph a. in Figure 4.18. When the fans are in operational mode, this heated air is delivered along the ducting to several supply grilles at which the temperature has fallen towards the design supply air temperature.

Hence the supply air temperatures of 60˚C do not represent the air temperature in the lecture theatre, as both supply and extract fans were off because the room was unoccupied. The reduction to the design supply air temperature is shown in graph b. Figure 4.18. The BMS room air temperature sensor positioned on a wall in the lecture theatre recorded values around 20˚C. This was within the recommended design temperature range (19-21˚C). Therefore, the delivered air was thermally acceptable.

<u>Vivo™ Thermal Comfort Monitor</u>

The Vivo™ Thermal Comfort unit measures three components of the indoor air that influence the thermal comfort of the room. The equipment measures the following thermal comfort parameters: operative temperature (which measures the air's cooling effect on a human body), relative humidity (the amount of water vapour in air), and air velocity. The unit was placed on the bench at monitor point two in the occupied region in order to represent one seated student.

The air velocity in a room should not exceed 0.15 m/s (Jones, 2001). The air velocity recorded by the Vivo unit was 0.13 m/s and this was within the recommended limits for the displacement ventilation arrangement in the lecture theatre. Thermal comfort readings (a) Figure 4.19) gave an average operative temperature of 24°C above the CIBSE design values 19 - 21°C (2006). The operative temperature was 4°C higher than the BMS room temperature of ~ 20°C. Considering that the measurements were made in February, and people were dressed in winter clothes, the room was therefore above the recommended comfort temperature.

The lecture theatre also had a low relative humidity of 19% (Figure 4.19), which was below the CIBSE recommended range 40 - 60%. This low relative humidity may have been due to the dry air of a prevailing cold weather period at the same time the sampling was carried out. As it was winter, the room ventilation system was in heating mode and this couple with low outside humidity would lead to a relative humidity reading lower than the CIBSE recommended range.

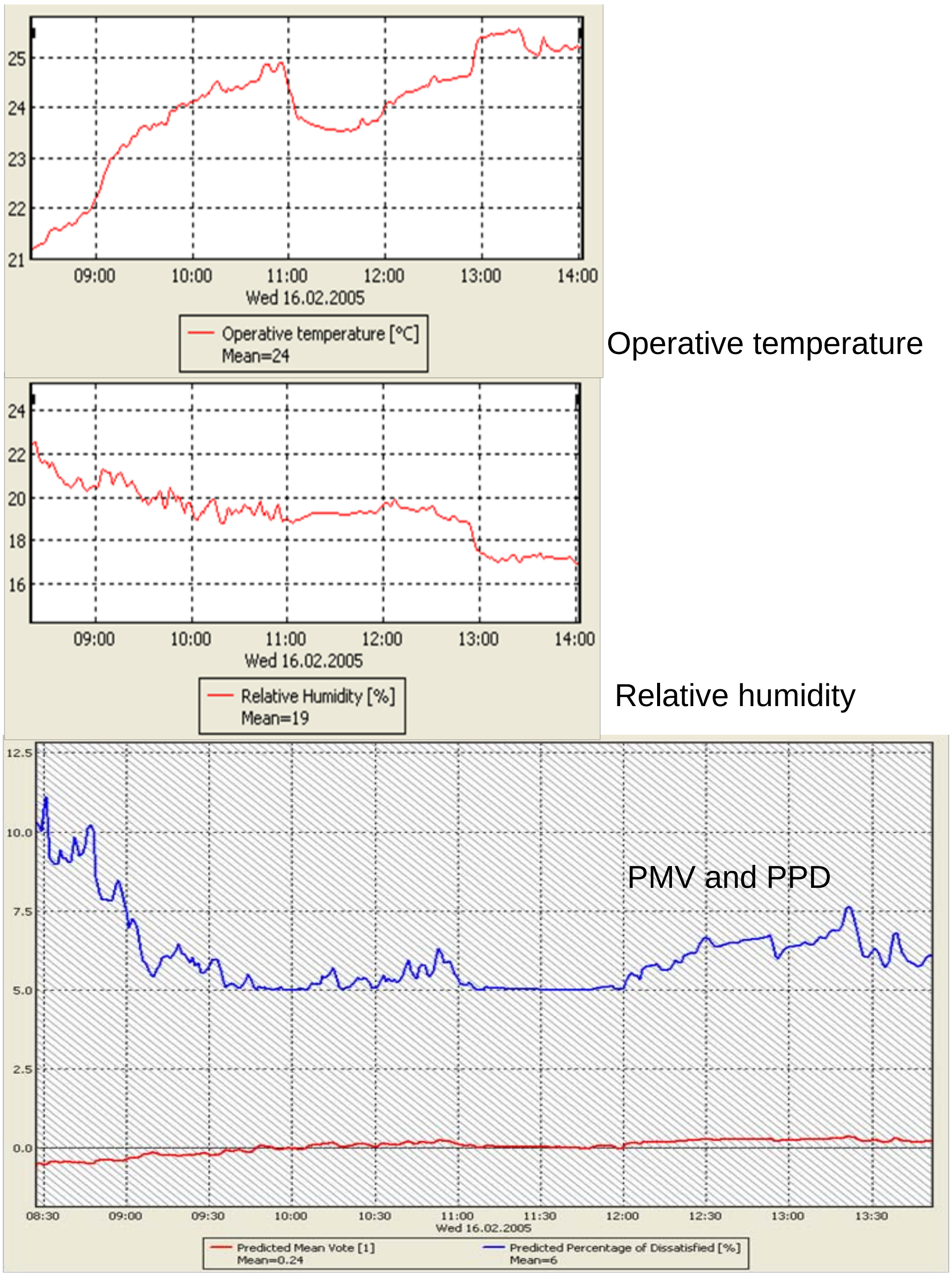


Figure 4.19 Vivo™ Thermal Comfort monitoring in Mayfield House 129.

The thermal comfort was described using the PMV and PPD methodology as developed by Fanger. The Predicted Mean Vote (PMV) was 0.24 (Figure 4.19). This was close to neutral on the thermal comfort scale, and was confirmed by the reading of 6% predicted percentage of dissatisfied (PPD). At the time of monitoring in this lecture theatre, several of the occupants complained that the room was too warm in winter and too cold in summer.

The measured data suggested that the ventilation system was performing according to the recommended design values. Even though the lecture theatre was partially occupied, the operative temperature was above the recommended thermal comfort level. Therefore, the heating in the lecture theatre was above the level that was required.

4.4 Discussion of the pilot study

The CO_2 set point for the BMS system was 900 ppm, and the CO_2 detected in the extract duct did not record values higher than ~ 600 ppm during the pilot study. The lecture theatre was not full for either of the two lectures. The morning lecture had 20% of the seats occupied with the afternoon lecture having 31% occupied. The maximum measured CO_2 peak for the morning lecture was 671 ppm and for the second lecture 784 ppm. However, these peaks and variations in CO_2 concentration within the breathing zone were not detected by the BMS.

One reason for the difference between the CO_2 measured in the breathing zone and the measurement from the extract duct may have been due to the sensor in the extract recording the air with a lower CO_2 concentration from the regions outside the breathing zone. This suggested that CO_2 levels within the occupied space were underrepresented by having control sensors only in the extract duct. Consequently, any dead zones indicated by high levels of CO_2 within the breathing space could not be detected.

From a consideration of the BMS data on its own, the ventilation system would appear to be delivering acceptable IAQ as the levels did not go over the set point, and that the ventilation system was performing well. The occupancy for both lectures was significantly below the design of the room. Accordingly, a lower ventilation rate could have been used to save energy.

Using CO_2 sensors in the extract duct to adjust the ventilation level of the lecture theatre may lead to over or under ventilation. As the CO_2 distribution varies in the room according to the number of occupants and the ventilation characteristics, the CO_2 level at the breathing zone will be different due to this inhomogeneity. If the likely distribution of the air quality in the lecture theatre could be accommodated into the design of the ventilation system, an energy efficient ventilation regime could be achieved. Therefore, this reflects a need to account for the non-homogeneity of IAQ conditions at the design stage of the building.

4.4.1 Theoretical CO_2 concentration

Using Equation (2) in a homogenous approach, lecture one had a calculated steady state CO_2 concentration of 525 ppm and lecture two a concentration of 605 ppm. Where c is the pollutant concentration in the room at any instant, c_o is the initial pollutant concentration, G the pollutant generation rate, Q the fresh air supply rate, t time after the beginning of occupancy and ventilation, and V is the volume of the room.

$$c = \left[\frac{10^6 V_c}{Q'} + c_a\right]\left(1 - e^{-n}\right) + c_0 e^{-n}$$ Equation (2)

The measurements on the other hand indicated that the CO_2 levels were variable, and fluctuated from the ambient to peaks in concentration after periods of occupancy. The variation in the levels was not forecast by assessing IAQ using equation 2, as it only provides a blanket figure and did not reflect the variation of IAQ in the breathing zone because of non-homogenous conditions.

The measured CO_2 data however did not reflect the variation in the CO_2 levels throughout the entire occupied zone. This was because the measurements were constrained to three sampling points. Nevertheless, it did show that there was an important variation in IAQ. This highlighted the fact that conditions inside the lecture theatre were therefore not homogenous under the conditions measured at that point in time.

4.5 Conclusions

Information and carbon dioxide and thermal comfort monitoring data from this pilot study was used in reports (Appendix E) by the Durabuild project at Brighton University Centre for Sustainability of the Built Environment (Durabuild, 2005). Mayfield House is a relatively new lecture theatre and as such was designed according to state of the art energy efficient strategies. The pilot study indicated that the displacement ventilation system in the lecture theatre was correctly ventilating the room during the times that the two lectures that were monitored. However, the field measurements representing the occupants' experience of thermal comfort showed that the room temperature was slightly above the design requirement.

The carbon dioxide concentration monitoring of the three locations within the lecture theatre implied that there were spatial variations in IAQ during both of the lectures that were studied. The CO_2 concentration recorded by the lecture theatre BMS sensor was different from the concentrations monitored in the lecture theatre breathing zone for the two lectures. This finding illustrated that CO_2 concentrations at the same point in time, were different at several locations in the lecture theatre. Thus, indoor air conditions were not well mixed during the lectures monitored. Furthermore, this important finding suggested that basing an IAQ assessment of a lecture theatre using a well-mixed assumption of indoor air conditions is inappropriate.

The CO_2 concentrations recorded in the breathing zone and the extract duct varied with time. The monitoring points that were located by the lectern and at the supply air grille were relatively stable. This was particularly the case for the supply grille measurements. Thus, the temporal variation at these two locations was not as marked as that observed in the other locations monitored in the lecture theatre.

The peak CO_2 concentrations that were measured during the morning and afternoon lectures were below the 900 ppm set point control of the ventilation system. The system was supplying fresh air the highest airflow rate recommended for a displacement system. Considering that the lecture theatre was occupied below its design capacity (20% to 30% of the design occupancy), a lower ventilation rate could have been used to supply air to both lectures. This would have saved energy.

Chapter 4 has shown that the assumption of homogeneity used in simple models of IAQ in lecture theatres is not supported by measurements of ambient air in the lecture theatre at Mayfield House. Chapter 5 describes the development of a methodology relating to the assessment of IAQ in lecture theatres under non-homogenous conditions.

CHAPTER FIVE

Development of an IAQ assessment methodology for lecture theatres

5.0 Selection of appropriate software

Several IAQ assessment methods use modelling and computer simulation tools. The difficulties in experimentally measuring an IAQ distribution in a lecture theatre were demonstrated in the pilot study of Mayfield House. In order to determine a representative IAQ distribution in a lecture theatre several monitoring points throughout the room were required. This was impractical in the experimental location, as there were limits to the number of monitoring points available to obtain sufficient data for portraying a spatial IAQ distribution. However, the use of computer simulation can overcome such constraints, and has the advantage of not requiring a physical experimental set up.

One solution to overcome the measurement practicalities mentioned in Chapters 2 and 3 is to use computational fluid dynamics (CFD). Computational fluid dynamics packages are now commercially available and can run on a personal computer. Therefore, the simulation output can give a fundamental insight into the processes occurring in a system.

An advantage in using computer simulations is that many scenarios can be studied in detail that would be otherwise difficult, if not impossible, to evaluate in a laboratory or test chamber. A range of computer packages were reviewed (Table 5.1) in a preliminary exercise to identify which software was applicable for the research. The main software requirements were to be able to:

- replicate airflow;
- represent actual measurements and variation from multiple monitoring points;
- measure CO_2 and LMA;
- generate output that can be manipulated for further data analysis;
- be user friendly for individuals other than software engineers.

An additional desirable quality of the software was the way in which the raw data output could be used for further interpretation. To enable an IAQ assessment a software package was required that could satisfy all the above criteria.

5.1 Outcome

All the software reviewed (Table 5.1) satisfied at least one of the requirements. The software that fully satisfied the selection criteria however was FloVENT. This program stood out from the others because it was able to:

- carry out detailed airflow simulation;
- describe the effectiveness of the air distribution method (including local mean age of air LMA values) used in a model;
- calculate concentrations of the contaminants present including CO_2;
- define zone and subzone volumes;
- present output in various formats for further data analysis.

FloVENT is a CFD package supplied by Mentor Graphics Corporation© (formerly Flomerics Group Plc UK), and is state of the art engineering design class software currently used within industry. Details of the software and its capabilities are contained in Appendix B. The required zoning of the ventilated space was achieved in FloVENT by defining the different zones as volumetric regions, which is a built-in function of the software. Consequently, this software was chosen with the sole purpose of being a tool for the proposed IAQ assessment methodology.

Software	Ideal features	Restrictive features
Airpak	Airflow simulation. Contaminant transport. Temperature and relative humidity distribution. User-friendly GUI (graphical user interface).	Cost. Support service was not free. Extensive training required.
COMIS	Simulation of multi-zone airflow and pollutant transport. HVAC systems accounted for in simulation.	Not very user-friendly GUI. Nodal model. No 3D description of geometries in the model.
CONTAMW2	Gratis down load available from the host internet site. Calculation of airflow rates and contaminant levels. Performs steady sate or transient analysis.	Does not simulate the airflow pattern. No 3D display of model or results. Need to input data of contaminant's physical properties into a database.
COwZ	Prediction of airflow rates, temperature, transport and dispersion of indoor contaminants.	Does not predict airflow pattern. Need to be familiar with COMIS.
FloVENT	Numerical, graphical, and animated output of airflow, temperature, and contaminant distribution. User-friendly GUI. Extensive library of fluids, model structures and surfaces. Steady state and transient analysis. IAQ calculation of ventilation effectiveness, ADPI, LMA, contaminant dispersion. Thermal comfort PMV, PPD. Tutored instruction course held within travelling distance of the University.	Some training initially required. Cost. Very large and complicated models can take more than a few hours to solve. Hardware must be must have a minimum of 1 Gb RAM.
IAQ Tools	Output of IAQ parameters, tracer gas calculations and ventilation system design.	No 3D airflow simulation. Predominantly design software.
Microflo	Simulation of airflow pattern. Output results for air quality and thermal performance.	No calculation of ventilation effectiveness.

Table 5.1 Software review summary

5.2 Lecture theatre computer models

Computer models were made of two lecture theatres at the University of Brighton. Lecture theatre 1 (LT1) was as used a template to investigate the effect on IAQ from different parameters. The series of test scenarios using LT1 are detailed in Chapter 7. A computer model of the other lecture theatre, Mayfield House 129, was produced for two reasons. The first was to test whether CFD was capable of representing the observed variation in IAQ. Secondly, to establish if the modelling software was viable as a tool in an IAQ assessment.

Both lecture theatres were different sizes but were regarded as large, according the IEA definition mentioned in Section 3.1. The selected software FloVENT was used to examine IAQ by modelling the airflow pattern and CO_2 distribution in both lecture theatres. The following sections describe the simulation output from both lecture theatre computer models.

5.2.1 Lecture Theatre 1

The lecture theatres' characteristics were included in the model. The walls, floor and ceiling of the rooms had their construction properties allocated to them. For example, the brickwork was defined as an outer leaf used for the external walls with the associate parameters such as wall material and thickness additionally defined. This was in order to set the construction properties as near to reality as possible for the simulations. The procedure was additionally followed for the desks and other furnishings in the rooms. The building materials in the model lecture theatre thus were as close to reality as possible.

The occupants of the lecture theatres were constructed from different sized cuboids. Each cube represented the head, limbs and torso (Figure 5.1). The people were simulated in all cases as having a total heat output of 70 W. This corresponds to the body heat radiating from an individual with moderate physical activity, such as taking notes whilst seated.

The cuboids represent solid objects (in the software) that are sources of heat output and impervious to airflow. Collections of cuboids are already available in the software's extensive library of objects and can be loaded into the model where required. Hence, the seated position of the occupants was transferred relatively easily into the modelled lecture theatre.

The outdoor and indoor air conditions were additionally set before simulations began. This included the supply air velocity, temperature and CO_2 concentration. The supply air conditions were determined by the ventilation system installed in the particular lecture theatre modelled. As a result, the air properties in the model were defined according to the design parameters (supply air temperature and velocity) of the ventilation system. A summary of a simulation report for a scenario is shown in Table 5.2.

Model Summary Report

Generated By FLOVENT 6.1 (Build 5.41.5/flo61) Copyright (c) 1989-2005 Flomerics Ltd. All Rights Reserved
Created: 12:52:37 PM Friday January 05 2007 **Project Name** MODEL 2 DV 3 ACH 82 OP
Modelling Settings
Flow and Heat Transfer
3-Dimensional, Radiation Off, Concentrations Active
Turbulence Settings
Turbulent, LVEL K-Epsilon
Gravity Settings
Normal, Negative Y-Direction
Project Fluid Carbon dioxide (CO_2)
Global System Settings
Datum Pressure: 1 Atm, External Radiant Temperature: 20 degC, External Ambient Temperature: 20 degC
External Ambient Concentration(0): 350 ppm
Solver Control Overall Control Settings
Segregated Conjugate Residual, Outer Iteration: 11000, Fan Relaxation: 1
Estimated Free Convection Velocity: 0.2 m/s
Solver Variable Information

Variable	False Time Step (s)	Term Residual	Inner Iterations	Initial Values	Linear Relaxation	Error Compute Frequency	Successive Over Relaxation
Pressure	Not Used	0.0124199 kg/s	50	1e-010 Pa	1	0	1
XVelocity	0.0894673	0.00526807 N	1	1e-010 m/s	1	0	1
YVelocity	0.105734	0.00526807 N	1	1e-010 m/s	1	0	1
ZVelocity	0.105734	0.00526807 N	1	1e-010 m/s	1	0	1
Temperature	116.307	32.9349 W	100	20 deg C	1	0	1
Concentration1	116.307	4.34697e-006 kg/s	100	350 ppm	1	0	1
Density	Not Used	Not Used	Not Used	1.82915 kg/m^3	1	Not Used	Not Used
KETurb	11.6307	0.00223452 W	1	0.000179914 J/kg	1	0	1
DissTurb	11.6307	0.000275215 W/s	1	2.21591e-006 W/kg	1	0	1
TurbVis	Not Used	Not Used	Not Used	1e-010 N s/m^2	1	Not Used	Not Used

Table 5.2 Example simulation summary report of modelled conditions in LT1

Figure 5.1 shows the simulated CO_2 concentrations in LT1 as a colour coded contour plot. The value and the simulated measurement point (at the X, Y, Z directions) in the lecture theatre are labelled on some of the contour lines. The “point-and-click” feature of the software reports the measurement points. A cross section at the Z plane position at 4 m along the width of the room can be displayed which therefore illustrates a vertical CO_2 profile of the conditions in the lecture theatre.

To simulate the exhalation of CO_2 by the occupants the mouth region was defined in the software as a pollutant source. The fluid properties of CO_2 were already in the software’s library so an exhalation rate of 4.7×10^{-6} m^3/s was the only variable that required entering. The water vapour of exhaled breath was not considered in this instance but again to define this, a new source would have to be created.

The front seating row in Figure 5.1 has a group of high value concentration contour lines (shown in red). This region corresponds to the heads of the occupants. This illustrates the higher CO_2 concentrations that occur in the immediate breathing space of an individual. Thus, the concentration of CO_2 extending outwards from the mouth can be displayed in the breathing zone.

The ventilation system simulated in LT1 (Figure 5.2) is a low level supply and air extract at the front of the lecture theatre. This figure illustrates the speed of airflow in the Z plane at 4 m from the side of the lecture theatre. The air is seen circulating clockwise from the front of the room, passing over the occupants to the back of lecture theatre and returned to the front extract grille. The simulated local mean age of air (LMA) in the seated region does not have the lowest values and is hence less fresh. This indicates that the ventilation design is failing to supply the best possible air to the occupants at the back of the lecture theatre.

In addition, there is a band of air with the oldest LMA value positioned above head height on the first four rows of seating. This simulation indicates that although the air was not the slowest moving, shown by the speed arrows in Figure 5.2, air at this level was possibly stratifying. Such information from simulations is useful to ventilation system designers as modifications can be made before the system is installed in a lecture theatre.

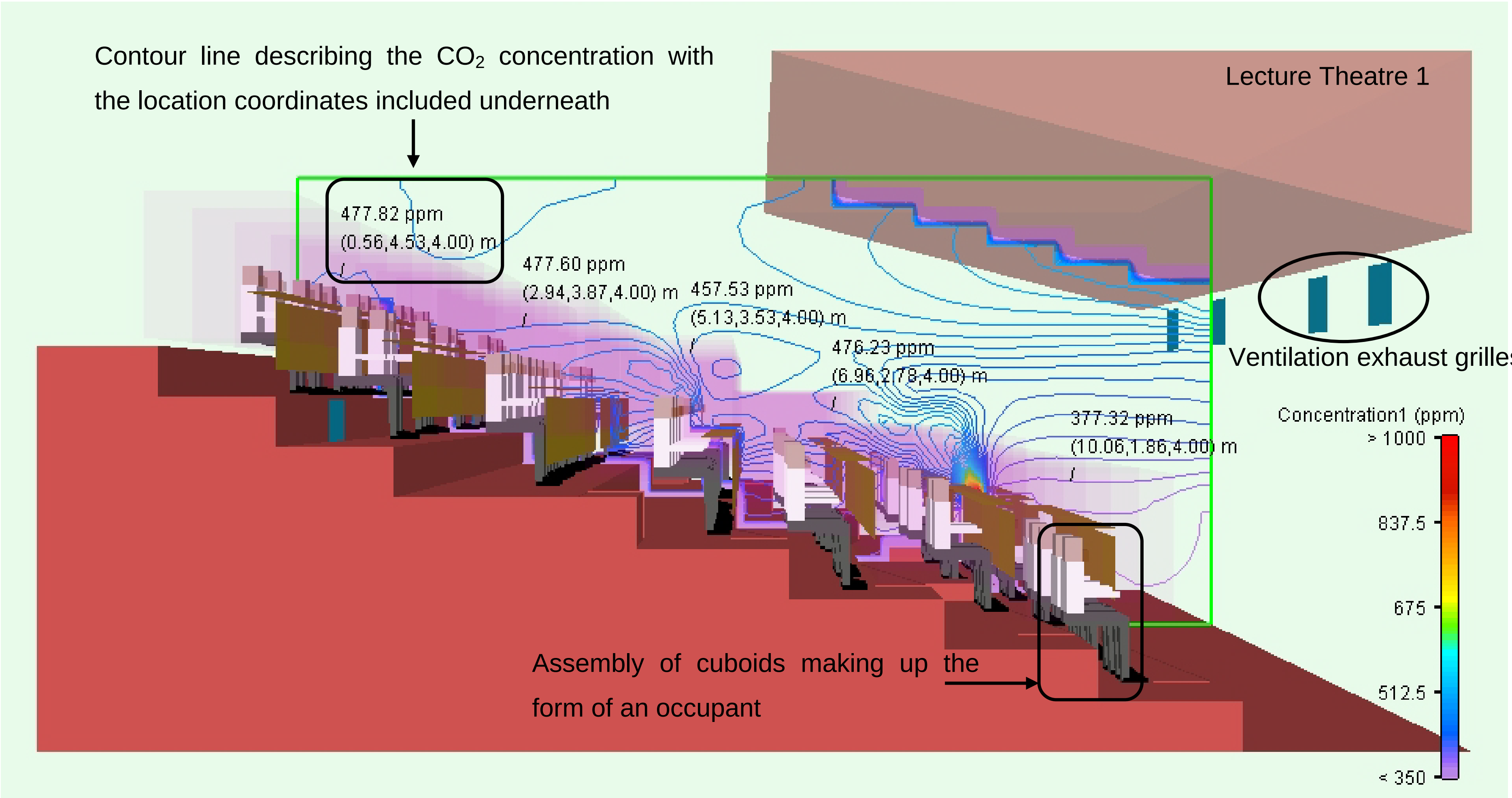


Figure 5.1 CO_2 concentration contours in the Z planar direction of 4 m

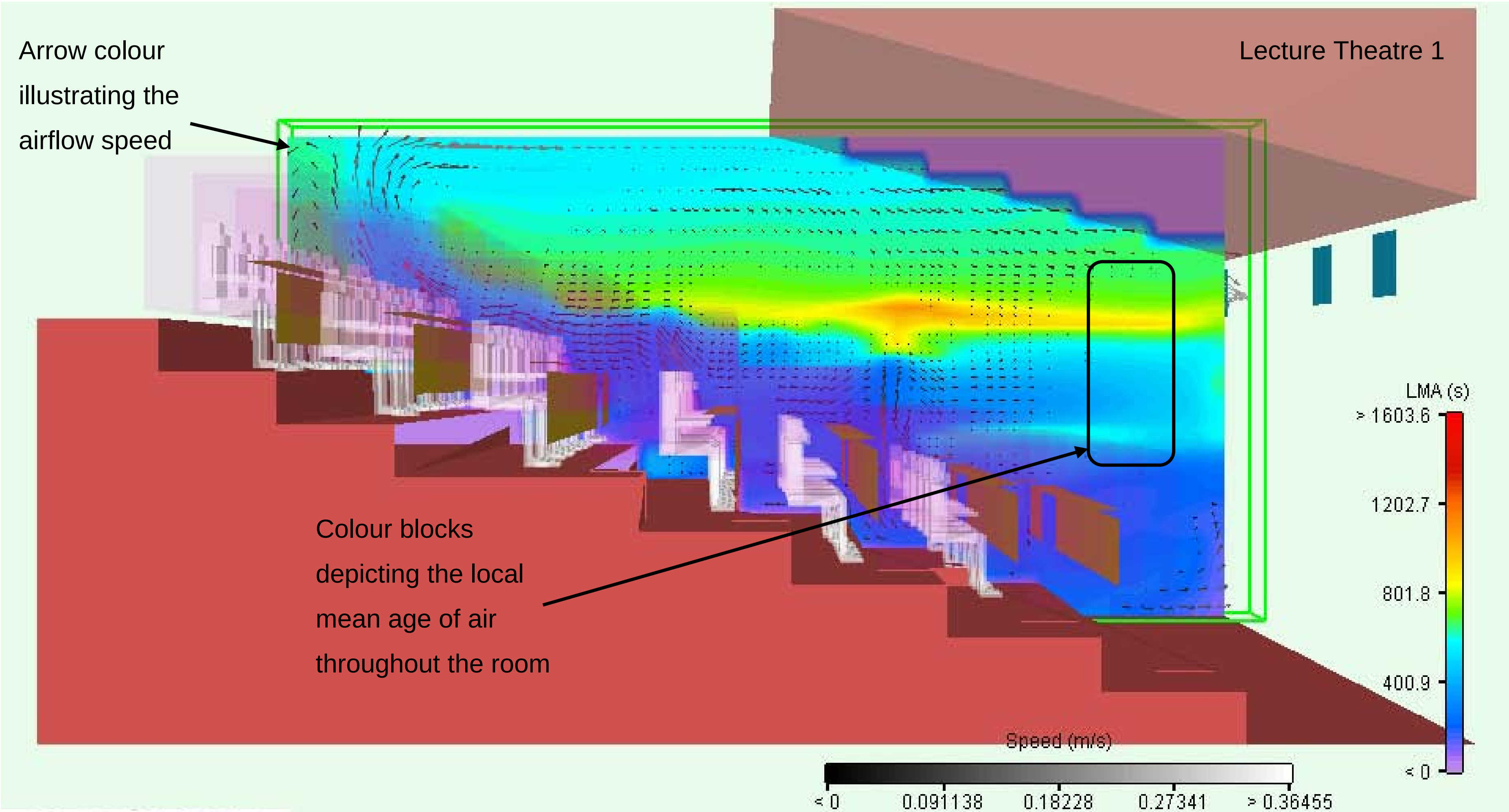


Figure 5.2 Simulation plot illustrating the airflow speed and LMA values in LT1

5.2.2 Mayfield House 129

A CFD model of Mayfield House 129 was made to simulate the CO_2 distribution observed in the pilot study. The model was constructed using dimensional data from a measured survey of the lecture theatre. The data included the size and position of the air-conditioning grilles and the location of the furnishings in the room.

The airflow pattern produced by the displacement ventilation system installed in Mayfield House 129 aims to move stale air away from the occupants. To investigate this, the different seating positions of the students from the two lectures documented in Chapter 4 were recorded for inclusion into CFD models. The corresponding CFD models were then run to investigate the effect of the airflow pattern on the CO_2 distribution. Figures 5.3 and 5.4 show the CFD output from the simulations of the two lectures. The figures show a cross section vertical plane, which corresponds to the three monitoring points in Mayfield House.

The LMA plot (Figure 5.3) illustrates the “fresh” air supply coming out of the grilles as white contours with the lowest LMA values. This air rises as shown by the darkening contour lines representing increasing LMA values. The LMA values increase as the air is further away from the supply grille at the floor level. The flow of air with a low LMA value, to higher values is seen by the stratified coloured contours labelled in Figure 5.3. The ventilation arrangement in Mayfield House was a displacement ventilation (DV) system and is intended to produce this airflow pattern. Hence, the simulation output indicates that the lecture theatre should be correctly ventilated with few IAQ issues.

The airflow velocity pattern from the supply grilles (Figure 5.4) reiterates the LMA plot in Figure 5.3 as the ideal behaviour for a DV system is shown by the air speed arrows. The air moves out of the grilles towards the back of the room in a circular motion in the direction of the ceiling extracts at the front of the room. The supply air with a greater velocity moves upwards and over the occupants removing the stale air. Thus, the simulation of the system suggested that it was adequately ventilating the lecture theatre.

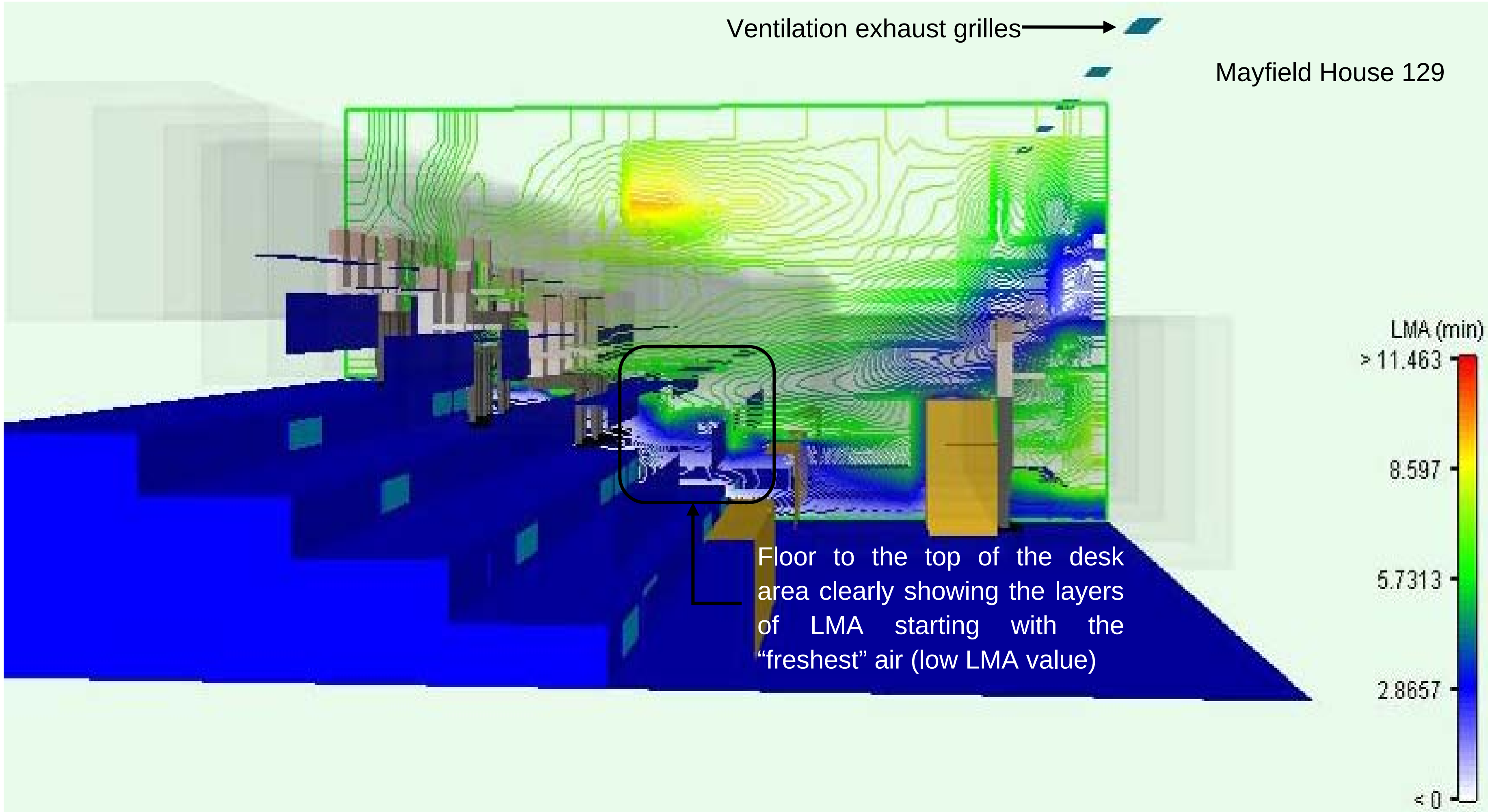


Figure 5.3 LMA contours (morning lecture) Mayfield House 129

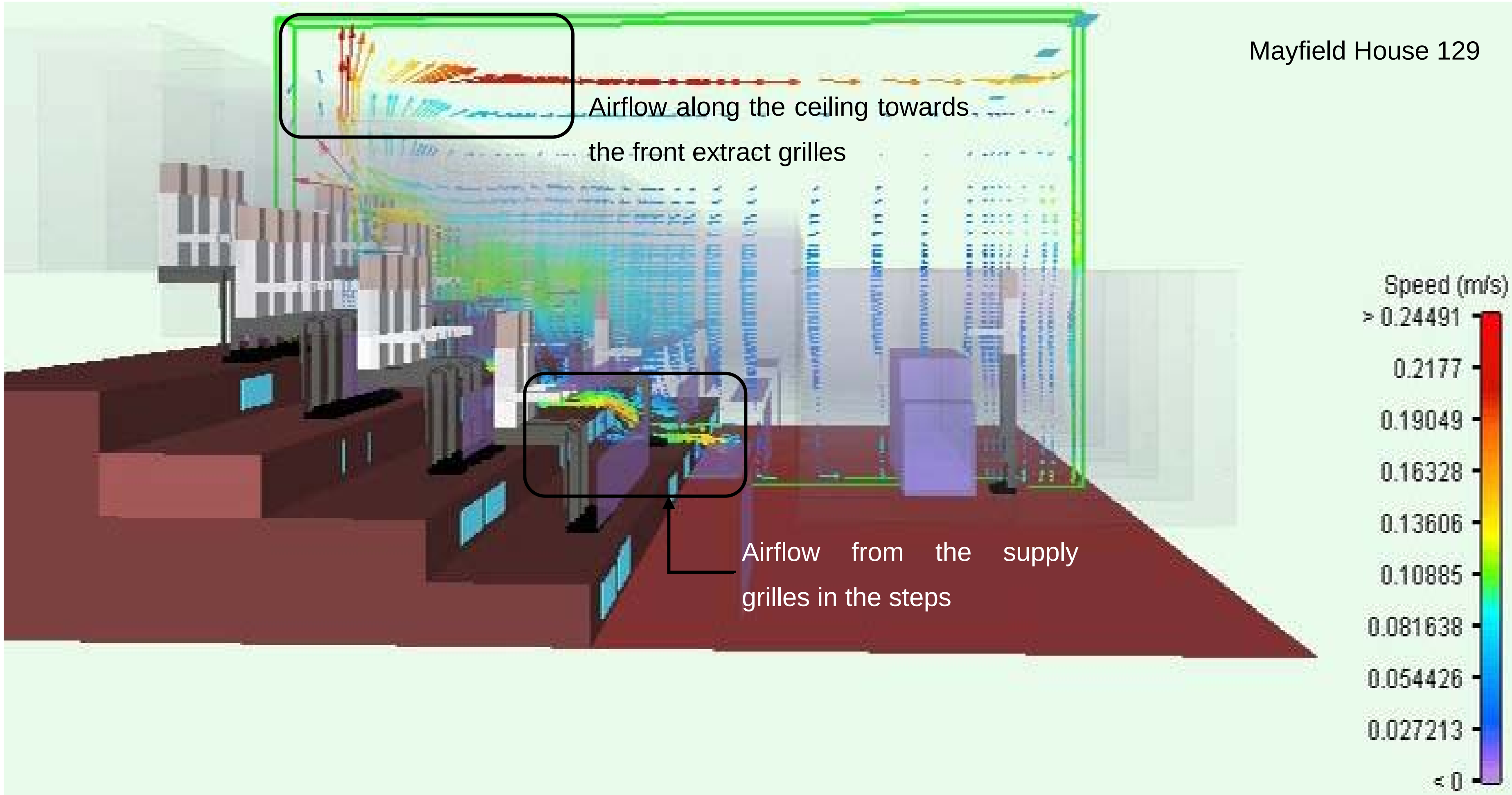


Figure 5.4 Velocity plot in monitoring plane to illustrate airflow movement (afternoon lecture) Mayfield House 129

The CO_2 distribution simulations follow the intended design airflow pattern from a displacement ventilation system. This DV airflow pattern is shown in Figure 5.5 where the CO_2 distribution patterns in the monitoring plane illustrate the vertical CO_2 concentration gradient (low at floor level to high towards the ceiling). In the simulation output, the floor regions have the lowest concentration due to the location of the fresh air supply grilles in the steps. The higher concentrations around the occupants are illustrated by the contour lines, which increase in concentration with height. These high concentrations at head height are due to the simulated CO_2 exhaled by the modelled occupants. Therefore, the CFD model is capable of simulating the CO_2 distribution resulting from occupants seated in the breathing zone of the lecture theatre.

The regions of high CO_2 concentrations in the lecture theatre can be identified from the simulation model. In Figure 5.5 the back region of the space shows higher CO_2 levels indicating poorer IAQ in this region. This is an important design consideration. However, the use of CFD illustrated the variation in CO_2 and LMA values in the lecture theatre, and enabled the behaviour of IAQ to be visualised and theoretically calculated over the entire room volume; and not just in three monitoring points. Therefore, it was shown that CFD software is a valuable and viable tool when assessing IAQ.

Further to the CO_2 results the local mean age of air simulations suggested that air movement was relatively still at back of the room as it had high LMA values. This corresponds to the CO_2 results and suggests students sitting there may experience some discomfort. Simulating the length of time air occupied regions in the lecture theatre reiterated that the simulation was capable of identifying regions of poor IAQ for use in an assessment.

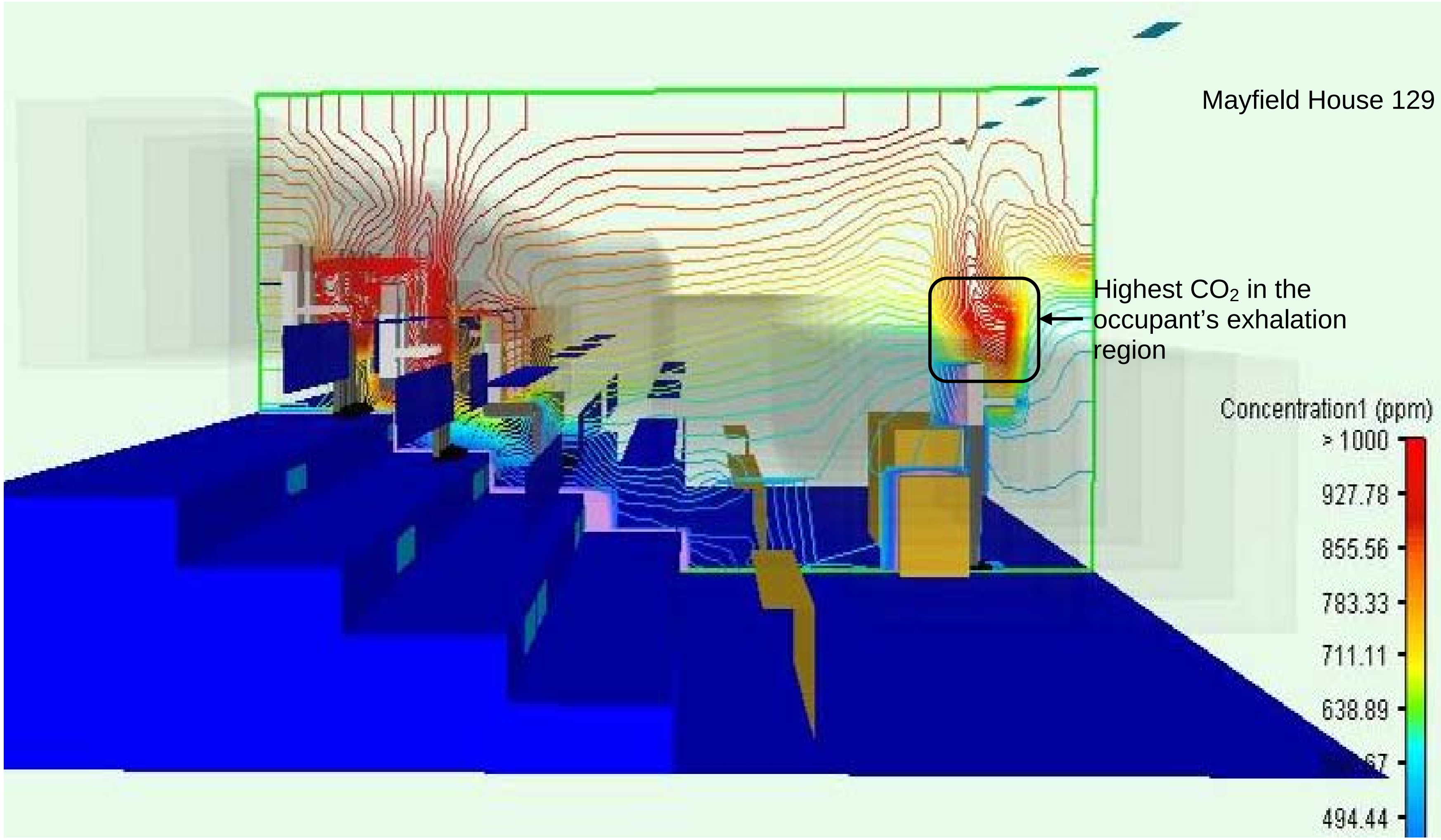


Figure 5.5 Contour plot of the CO_2 concentration in monitoring plane (morning lecture).

Crucially, a homogenous assessment of the monitored lectures would not have indicated regions of high CO_2 concentrations. Assuming that these conditions exist oversimplifies the actual behaviour of the IAQ in the lecture theatre. However, as conditions are not homogenous, using CFD in IAQ assessment is therefore a functional tool.

5.3 Pilot Study implications

The aim of monitoring indoor conditions in Mayfield house was to investigate whether homogeneous conditions occurred in a lecture theatre. In order to do this, several assumptions and generalisations were made. The ventilation rate was assumed as six air changes per hour (ACH). This was suggested by the results of a smoke test in the room (as it took 10 minutes to clear all the smoke in the space).

Table 5.3 reports the measured CO_2 concentrations and the CFD output. Direct comparison of data was not viable, due to the relatively small number of monitoring points and the measurements are recorded per unit time. The CFD results are a solution from established fluid dynamics equations. The measured and simulated concentrations are of the same order of magnitude, and therefore showed a good agreement.

Lecture 1 Monitoring point	Measured CO_2	CFD CO_2
1	442 ± 10	401± 4
2	520 ± 44	432 ± 29
3	399 ± 4	403 ± 4

Lecture 2 Monitoring point	Measured CO_2	CFD CO_2
1	444± 10	400 ± 3
2	521 ± 59	417 ±11
3	397± 4	408 ± 8

Table 5.3 Monitoring point measurements of CO_2

The CFD results when compared to the measured data support the view that conditions were not homogeneous, and gave confidence that the data from the CFD model was comparable to the empirical data. The evidence of non-homogeneity suggested that using a homogeneous approach was insufficient to assess IAQ in lecture theatres. Thus, alternative IAQ assessment using a non-homogenous approach could improve the IAQ assessment of lecture theatres.

Multiple monitoring points would be needed to sample a greater area of the breathing zone in the lecture theatre to establish an IAQ distribution. Practical limitations restricted the monitoring of CO_2 to three sampling points. As a result, it was practically impossible to sample enough locations in the lecture theatre to determine a detailed spatial IAQ distribution for each lecture monitored.

Nevertheless, the simulation results obtained support the result from the CFD model. The measured concentrations and CFD data were comparable under the set of conditions described. This improves confidence that it is possible to use CFD simulation to model a greater number of monitoring points to provide an indication of IAQ levels in lecture theatres.

The carbon dioxide concentration data as measured correspond well to the virtual model results. However, validating a CFD model of the lecture theatre was not the aim of the research as the intention was not to reinforce the reliability of software but to investigate its IAQ application to a lecture theatre. Other users have already verified this software as a tool including the manufacturers (Flomerics Group plc, no-date), and authors such as Alamdari (1994) and Bojic *et al.,* (2002). In addition, computational dynamics is routinely used to predict and simulate air movement (Abanto *et al.*, 2004;Karimipanah *et al.*, 2007). For this reason the software was regarded an appropriate tool for implementation in an IAQ assessment methodology.

5.4 Principle of the proposed assessment methodology

The idea of developing an assessment method arose from the finding in the pilot study that indoor air conditions were not readily homogenous. The non-homogenous conditions observed suggested that different areas of the lecture theatre were subjected to different levels of ventilation. For that reason, the comfort of the various occupants of the lecture theatre would be different, as the room was not uniformly ventilated. Thus, it was apparent that areas in the lecture theatre would exist where students would feel discomfort and experience a poor learning environment.

The proposed methodology arose from questioning how an existing assessment approach could be enhanced to include the non-homogenous conditions of airflow. The existing concept of zoning was considered logical as a means of portraying the IAQ variation in a lecture theatre. Therefore, the assessment methodology had to recognize the existence of non-homogenous indoor conditions and be able to portray a spatial variation in IAQ.

The starting point in the development of the methodology was the consideration of the assessment procedure in the homogenous approach. The use of the homogenous method is shown in the flowchart (Figure 5.6). The assessment starts by considering a room volume and the numbers of occupants at a particular ventilation rate. These parameters are used in Equation 2 (mentioned in Section 2.7.1.2) to calculate a concentration of CO_2. The stages of the methodology have associated constraints, which are numbered and labelled after the flowchart.

The IAQ assessment approach in Figure 5.6 has a number of limitations. The main limitation in using this homogenous assessment procedure is that the entire room volume is considered. Furthermore, the number of occupants is a variable in the equation, but their seating location is not considered in the assessment.

The homogenous IAQ assessment procedure produces one result, the pollutant concentration. This approach assumes that the level of IAQ is uniform at all points in the room. The outcome of using this homogenous approach to assess the IAQ in a lecture theatre is that the variation of IAQ in the room cannot be determined or appreciated. Additionally, the occupants' feelings of comfort with the level of IAQ cannot be assessed. Thus, areas with unacceptable concentrations of IAQ contaminants will not be identified using this approach.

Using the homogenous methodology the calculation procedure can be tedious and repetitive if the aim is to optimise an acceptable IAQ level. This methodology is restricted by only considering the ventilation rate and the number of occupants exhaling CO_2. In a design strategy, this approach cannot be used to select the most effective type of ventilation system or plan the positioning of the ventilation arrangement of grilles and therefore can only provide an elementary IAQ assessment.

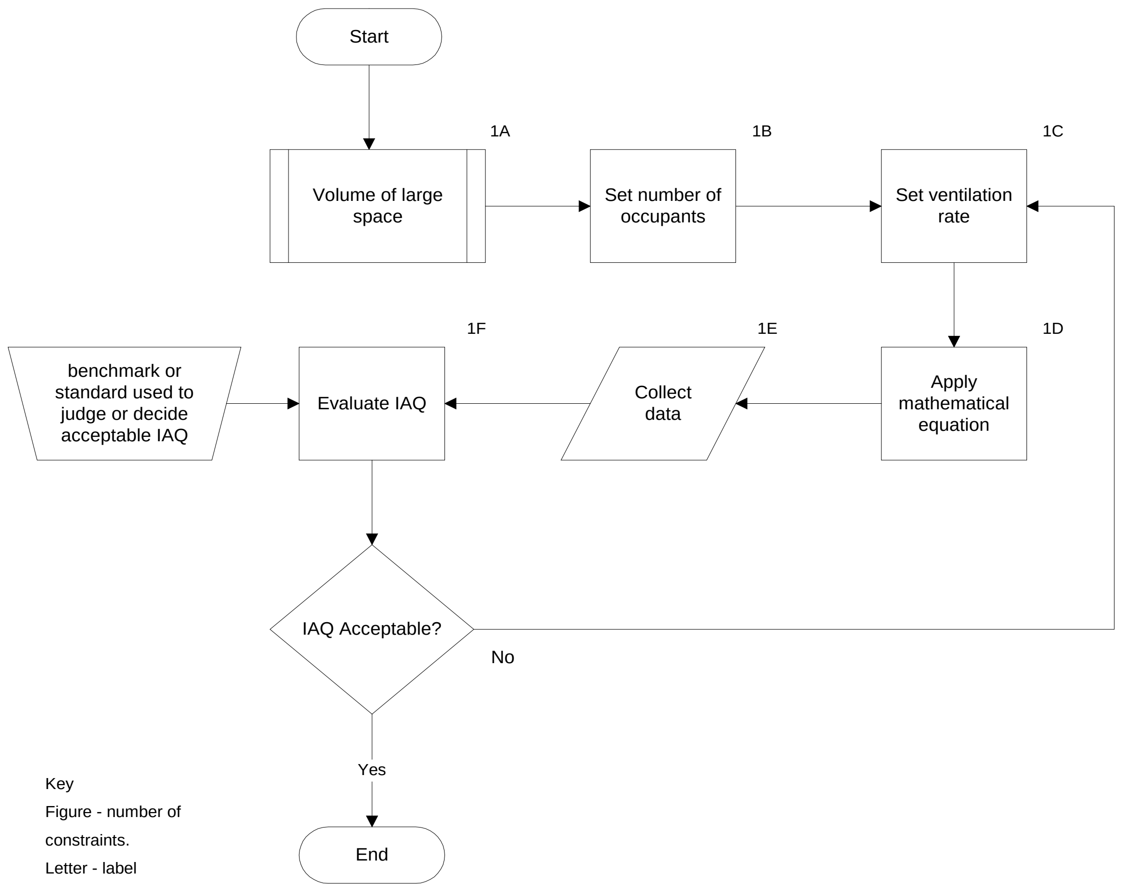


Figure 5.6 Homogenous methodology

<u>Process Constraints</u>

1A Performed on the entire room volume or the recommended volume per person

1B Only considers the number of occupants as a generation source of pollutant and not where the source position is.

1C The ventilation rate is the main equation variable i.e. number of air changes per hour or volume flow rate of air

1D Restricted to pollutant concentration decay or rise with respect to time under equilibrium conditions.

1E Only one solution to the equation

1F What benchmark or standard to use to evaluate IAQ?

5.5 The proposed assessment methodology

In order to assess the IAQ in a lecture theatre, the proposed methodology will use descriptor parameters discussed in the next section as a component of the assessment procedure. Additionally, CFD will be used to generate data for assessment. The framework of the proposed assessment methodology is shown in the flowchart (Figure 5.7).

As in the homogenous approach, some of the processes have constraining factors. For a case or scenario that requires an IAQ assessment, the first stage of the methodology is the construction of a computer scale model. The assessment requires a process to calculate the descriptor parameters in order to analyse the IAQ level in the space. This process is detailed in Section 5.8. However, a crucial feature of the proposed methodology is the construction of a detailed computer model of the large space that is to be assessed.

The use of computer modelling in an IAQ assessment has the capability to simulate the expected IAQ in a detailed manner. However, there are constraints associated with using modelling which are highlighted in the process constraints list.

Both methodologies (homogenous and the proposed) share the same problem in that a CO_2 concentration needs to be set for the accepted maximum IAQ level, but this is not established by regulation. This is a generic constraint and therefore not a unique limitation to the proposed assessment methodology.

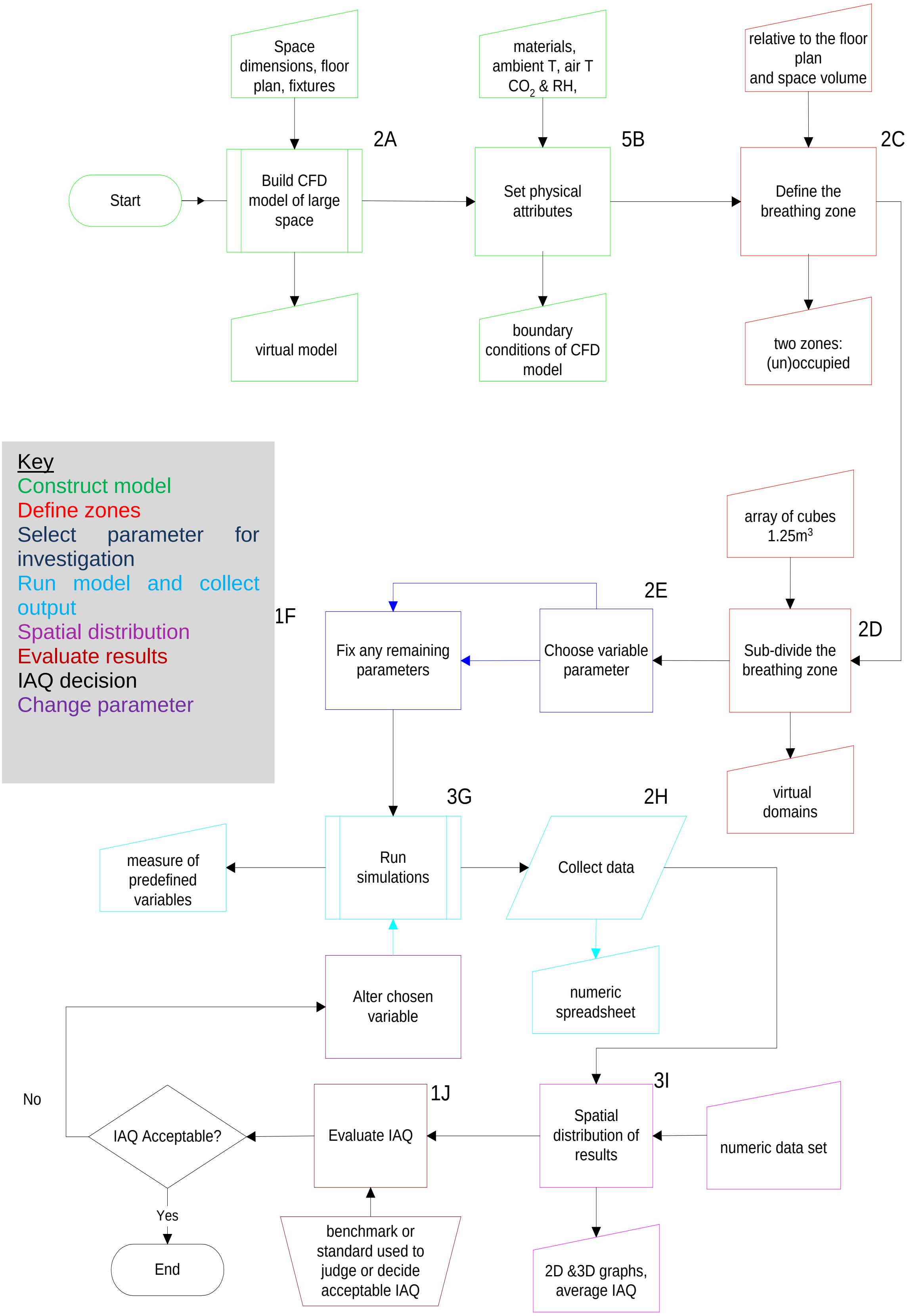


Figure 5.7 Proposed methodology

Process Constraints related to steps in figure 5.7

2A Software has difficulty in drawing non-angular geometry.

Time taken to draw the model, more complex room plan, and fixtures longer to draw.

5B Need an idea or an assumption of the construction materials of the room.
Assumption of the surfaces temperature.
Assumption of internal air temperature.
Assumption of internal air relative humidity.
Assumption of ambient carbon dioxide concentration.

2C Relative to the room floor plan and shape.

Restrained by the room topography.

2D Restricted by topography and fixtures.

Will include some solid fixtures of the room that will interfere as not included in the solution.

2E Must start the choice with a ventilation system type.

Three of the physical variables are concerned with the ventilation type.

1F Confined to the original variable under investigation.

3G Time taken to converge i.e. for the partial differential equations to be solved.
Complex geometry, very large room volumes, and low velocity supply airflows influence the computer processing time.
Occasionally there is an incomplete convergence of solutions.

2H The amount of data produced by the converged solution as data for all grid cells is typically greater than tens of thousands.

Need to define domains and planes or points of reference in order to produce a realistically manageable data set.

3I Limited to the model boundaries.
Case specific for the large space drawn.
Case specific for the effect investigated.

1J What benchmark or standard to use to evaluate IAQ?

5.6 Measurement of IAQ in the assessment methodology

The proposed methodology was developed to assess the IAQ in a lecture theatre. The assessment methodology required variables that were capable of calculating a level of IAQ for assessment. A tool was also needed that could describing the variation of IAQ in a lecture theatre. As a result, a number of variables were reviewed in order to select appropriate measures for use in the methodology.

5.6.1 Selection of appropriate IAQ measures

Several measures can quantify the characteristics of indoor air. To narrow down the choice of IAQ measures, selection criteria were applied. The IAQ measure needed to indicate a pollutant concentration and be capable of being experimentally measured. Additionally the IAQ measures should be able to describe the IAQ variation in a lecture theatre, and be a measure that could be simulated by the software.

The output from the assessment methodology needed to describe the IAQ in the space being assessed, as a combination of the overall spatial IAQ level, the maximum IAQ level, and the spatial IAQ distribution. In addition, the IAQ measures selected should satisfy two selection criteria; namely an ability to illustrate the effectiveness of the room ventilation system and report a contaminant concentration. Several existing variables were shortlisted as suitable measures of IAQ (Table 5.4). A detailed description of the measures included in Table 5.4 is found in Appendix C.

Measure	Units	Advantages	Disadvantages
Local Air Change Index	Unit less LACI = 1 indicates perfect mixing conditions	Calculates the age of the air at a point in the space relative to the supply air. Used to indicate the ventilation effectiveness of a particular ventilation method.	Cannot give information on the concentration of contaminants in the space.
Local Mean age of Air	Time	Calculates the average time taken for air to move from the supply inlet to any point in the space, and can indicate the ventilation effectiveness.	Indicates the fresh air location, but not the concentration of pollutants
Air Diffusion Performance Index	Percentage	Provides a measure of uniformity of the indoor environment	Primarily concerned with thermal comfort, and does not give information about contaminant levels.
Contaminant Removal Effectiveness	Unit less CRE=1 perfect mixing conditions. CRE >1 contaminant being removed CRE < 1 suggests some short-circuiting in ventilation	Provides a measure of how efficiently the ventilation system exhausts contaminants.	Does not directly indicate the airflow pattern.
CO_2 concentration	ppm	A measure of pollutant concentration Simply measured	Distribution is partly a result of airflow

Table 5.4 Summary of possible measures of IAQ.

5.6.2 Selection outcome

All of the reviewed measures have advantages and disadvantages. The LACI and LMA give an indication of how the supply air spreads into the room, but cannot directly provide information about the contaminant levels in the room. The ADPI is a measure of the air uniformity but is primarily concerned with the thermal comfort of the occupants, and cannot indicate a contaminant level or the variation in IAQ.

The CRE is useful for indicating the ventilation system's efficiency in removing contaminants. This measure does not give an indication of the contaminant distribution within the room, or represent the degree of IAQ unevenness. Even though the CRE can indicate the ventilation system efficiency, it was not considered to be suitable for use in the proposed IAQ assessment methodology, as it does not give an indication of the local airflow pattern.

Two measures were selected to indicate the IAQ distribution; the LMA and CO_2. Local mean age of air was chosen, as this can give an indication of the airflow pattern in the space. For the overall and maximum IAQ level, carbon dioxide was chosen as an indicator, as the amount of exhaled CO_2 is directly related to the number and metabolic rate of the occupants (one met activity level can generate 0.004 L/s). Furthermore, the "met" rate can be assumed as it is related to the activity that is taking place. Thus, in the lecture theatre a met rate can be taken as one (a sedentary activity) as the students are seated.

5.7 Establishment of an IAQ distribution in a lecture theatre

The proposed IAQ assessment methodology was based on the assumption that non-homogenous conditions occurred in lecture theatres. The uneven indoor conditions would lead to variations in IAQ and occupant comfort sensitivity. As a result, an investigation of the way in which IAQ was distributed in a lecture theatre was an important aspect of the assessment methodology.

In order to determine a spatial IAQ distribution in a model lecture theatre, the space was initially divided into two volumes: an occupied zone, which encompassed the seating area of the room, and an unoccupied zone made up of the remaining area. The occupied zone was further divided into sub units of equal volume (determined by simulations using the software).

This division procedure, made up an array of simulated LMA and CO_2 values, to portray an IAQ distribution. The rationale for zoning, was that by sub dividing the breathing zone, the spatial distribution of IAQ in a lecture theatre could be assessed. The reason for determining an optimum subzone volume, was to obtain a unit of the occupied space that could be used to describe an IAQ distribution. The process of dividing the breathing zone in a lecture theatre into zones and subzones is described in the following sections.

5.7.1 Zoning of a lecture theatre volume

An occupant in the sitting position requires a certain amount of personal space for physiological and psychological reasons. This immediate space within the occupied zone is the personal breathing space. As this region contains air breathed in by the occupants, it is essential that this space be considered in an IAQ assessment and in the mbz of the proposed IAQ assessment methodology

The occupants of a room do not occupy the entire space, and there are regions free of occupants (such as the ceiling) where fresh air is not a priority. The level of air quality needs to be the best in the breathing zone as this is where it matters most. Thus, the occupied zone of the lecture theatre needs to be defined in terms of its spatial position and volume. According to Schild (2004) the occupied zone is that spatial volume which is regularly occupied by people in the height range 1.3 ~ 1.8 m when sitting or standing. In the lecture theatres, this zone follows the tiered room geometry.

In the proposed IAQ assessment method, the occupied zone includes the seating areas, and regions in between. The tiered floor of a typical lecture theatre however, restricts the height of the occupied zone at the back of the room. The breathing zone at the back of the lecture theatre is considered to have the same height as the occupied zone. The occupied zone is offset from the walls by at least half a meter (as this space is clear of occupants).

In addition to zoning, the activity level in the lecture theatre has to be set to reflect the room use. The outcome of this exercise is a value for each subzone that will be used to represent the IAQ in the lecture theatre in a number of ways. Hence, the lattice of mini-zones enables the IAQ distribution to be effectively visualised and analysed in further detail.

There are existing models that use the concept of zoning to determine an IAQ level, but this approach has not been much used for lecture theatres. Work by IEA ten years ago described case studies using different analysis, prediction, and measurement techniques for evaluating efficient ventilation of large spaces (IEA, 1998a). However, not a great deal has been published since, specifically regarding IAQ in lecture theatres.

5.7.2 Simulation of IAQ in the lecture theatre subzones

The significant influence that airflow has on the distribution of IAQ needs to be appreciated in order to measure the IAQ in lecture theatres. In order to simulate the IAQ distribution, the lecture theatre was divided into sub-zones. Using the subzones, primary data was obtained to assess the IAQ in the modelled space.

The level of IAQ was simulated for each of the defined sub-zones; the number of which depended on the specific room volume, shape and layout. The output from the simulation was then compared against a desired criterion to assess the IAQ. As an example, the ASHRAE standard, which quantifies a maximum concentration of CO_2 not to be exceeded indoors, could be used to determine if the IAQ was acceptable in the lecture theatre.

The spatial distribution of the IAQ values from the subzones (mini breathing zones mbz) can be portrayed in several ways. A frequency distribution plot, a measure of the IAQ central tendency and the range of IAQ levels is capable of reporting the IAQ in a lecture theatre. The spatial distribution can also be plotted as 2D and 3D maps of IAQ levels throughout the lecture theatre. The distribution of IAQ can then be further assessed (using standard statistical tests), leading to an assessment of the IAQ in the lecture theatre.

5.8 Determination of the subzone size

In existing IAQ assessments, the whole room volume is usually considered in the evaluation. The issue is that using this whole room volume includes regions that could never be occupied by students, for example near the ceiling, and consequently should not be considered in an IAQ assessment. As a result, an alternative IAQ assessment methodology was proposed. In this IAQ assessment methodology, the purpose of the subdivision of the entire lecture theatre volume was to establish the lengths of an optimum sized mbz that gave a reasonable level of detail which illustrated the CO_2 in the personal space of the individual.

This section describes the derivation of an optimum volume for the subzones. A volumetric sub-unit of the lecture theatre breathing zone was required to portray the simulation results as an IAQ distribution. Therefore, the dimensions of the mini breathing zones (mbz) needed to be determined.

A model of a generic lecture theatre (volume 644 m^3) complete with a detailed room geometry and occupants was drawn using the CFD software (Figure 5.8). The lecture theatre was ventilated by a mechanical mixing supply system that consisted of a low-level supply with a high-level extract. The supply air conditions were set at the same design temperature and flow rate for all simulations, to ensure consistency for each modelling exercise. In addition, the lecture theatre was modelled fully occupied.

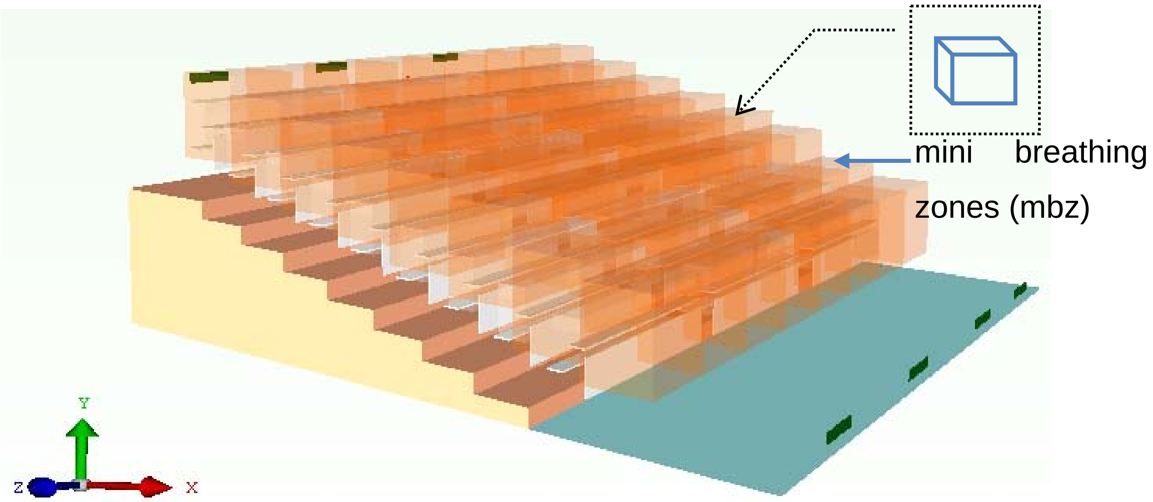


Figure 5.8 Model lecture theatre.

The model dimensions are a boundary for the IAQ assessment. Within this boundary, the software can calculate the effect of several parameters on airflow. The factors that can be varied in the air quality simulation model (AQSM) are summarised in Table 5.5. The influence on IAQ of any of the factors mentioned in Table 5.5 can be then investigated using the model.

Model parameters	
Constant factors	**Variable factors**
Room geometry	Occupancy number
Corresponding mini breathing zones position	Occupancy seating position
	Method of air distribution
	Ventilation rate
	Supply air temperature
	Ambient CO_2 concentration
	Exhaled CO_2 concentration

Table 5.5 AQSM parameters

5.8.1 Determination of the mini breathing zone X and Z length

The occupied zone was initially defined as an area of the lecture theatre 10 m x 10 m in the planar directions of X and Z. This area was divided in sequence to obtain CO_2 concentration data for the smaller areas (known as mini breathing zones) resulting from the division process. As a result, the breathing zone was subdivided into smaller regions in order to inspect the IAQ around the occupants of the room.

Subsequent divisions consisted of bisecting each original zone; two zones became four zones labelled as mbzs 1 to 4 in Figure 5.9. The next division became eight zones and so on until the lengths of the sides of the zones were less than 1 m. The height dimension was also varied in the simulations as 4 m, 2 m, 1.5 m, 1 m, and 0.5 m (detailed in Section 5.8.3). A point was reached in the division process where decreasing the lengths of X and Z made no noticeable difference in the CO_2 concentration. Hence, the CO_2 concentration determined the sizes of the mini breathing zones.

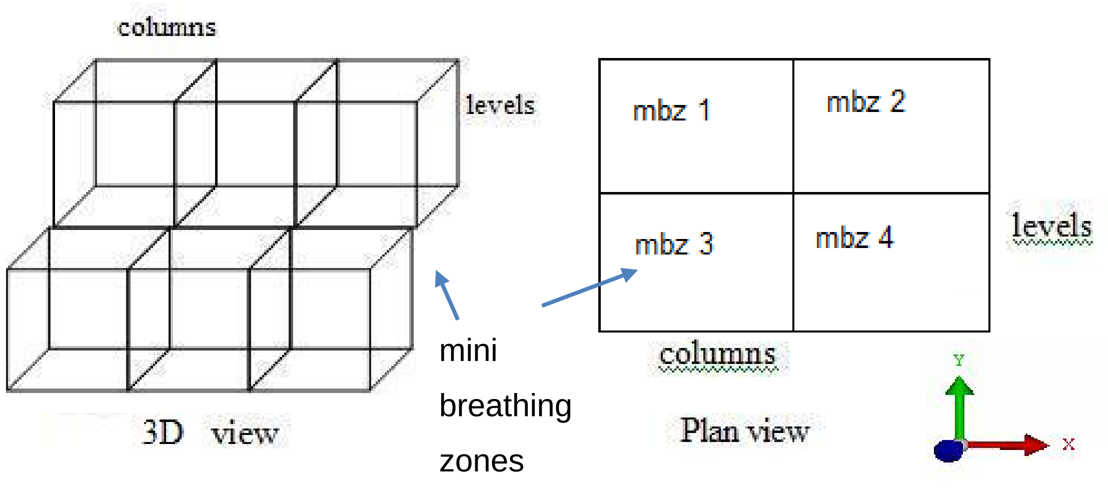


Figure 5.9 Typical arrangement of mini-breathing zones (mbzs) in a lecture theatre

The total number of zones produced after the division process are shown in Table 5.6. The first zone measured 10 m x 10 m and corresponded to the occupied zone of the lecture theatre. This division process was repeated until both X and Z measured 0.625 m x 0.625 m. This dimension of X and Z produced 256 mbzs, each of which had simulated CO_2 concentrations.

Number of mini breathing zones	Length of X (m)	Length of Z (m)
1	10	10
2	5	10
4	5	5
8	5	2.5
16	2.5	2.5
32	1.25	2.5
64	1.25	1.25
128	0.625	1.25
256	0.625	0.625

Table 5.6 Number of mbzs and length of zone after each division

5.8.2 Simulation procedure

CFD software was used to determine the sub zone dimensions by performing several computer simulations using a lecture theatre as a model large space. The determination of the mbz size started with a breathing zone volume that was the size of the lecture theatre. This starting volume was reduced repeatedly until a volume was reached where no discernable difference in the simulated IAQ values was observed. When this point was reached, the dimensions of the subzone were considered the optimum mbz volume to use as a simulation unit in the assessment methodology.

The software uses the Cartesian coordinates to describe the three dimensions. The Y direction represents up, the X direction is across and the Z direction is transverse (Figure 5.10). These direction labels were therefore used to describe the lengths of the sides of the mini breathing zones.

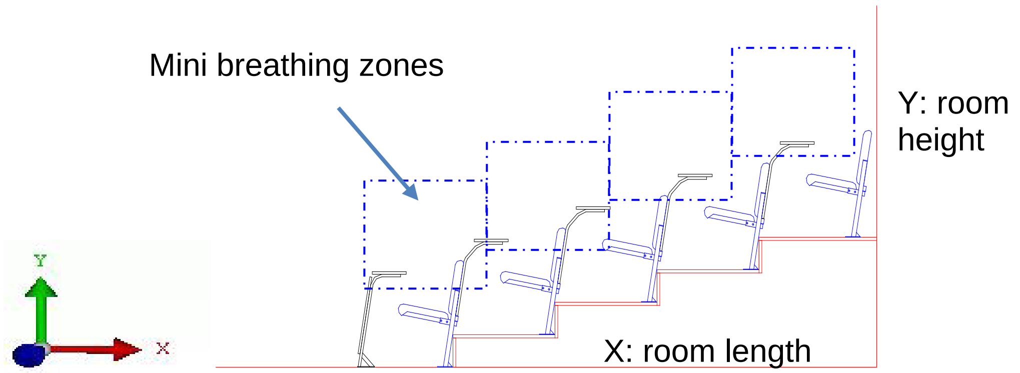
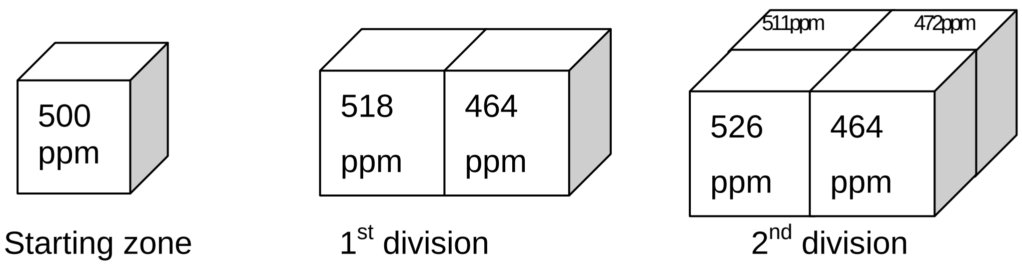


Figure 5.10 Side view in Y and X plane of seating and mini breathing zones

The simulation procedure entailed defining each mbz as a domain in the software that contained a number of grid cells. For each cell, the program calculates a value for temperature, pressure and CO_2 concentration at its central point and gives an mean value for the cells within the domain (in this case mbz). Hence, the simulation calculated (after each division) the mean CO_2 concentration for each mini breathing zone (Figure 5.11 a). A diagram of an example of the data output from the simulation is shown in Figure 5.11 b. The increase in the number of mbzs after each division resulted in zones that had a CO_2 concentration that approached the minimum concentration of the room air.

a.



b.

	Region Name	Minimum(ppm)	Maximum(ppm)	Mean(ppm)	Std.Dev.(ppm)
Starting zone	1	435.17	784.40	499.99	55.11
1st division	Region Name	Minimum(ppm)	Maximum(ppm)	Mean(ppm)	Std.Dev.(ppm)
	1	423.15	781.87	518.03	51.86
	2	400.67	757.51	464.18	44.35
2nd division	Region Name	Minimum(ppm)	Maximum(ppm)	Mean(ppm)	Std.Dev.(ppm)
	1	430.27	812.24	525.29	55.81
	2	425.21	728.45	510.73	49.04
	3	401.99	696.27	464.32	39.82
	4	400.77	766.50	471.51	50.55

Figure 5.11 Simulation output

As the mini breathing zones size decreased, it was possible to stagger the mbzs to reflect the stepped levels in the room. This meant that the mbzs could be tiered to resemble the seating in the lecture theatre. To establish the height of the mbz off the floor, it was assumed that the minimum mbz position height was ~ 0.5 m (that is at a bended knee level). Hence, the mbzs in the model were positioned at 0.5 m from the step/floor level, and staggered in line with the geometry of the room (Figure 5.12: pink boxes). The mbz zone height at 4 m was outside the modelled room when offset from the floor, so divisions started at 3 m and subsequently decreased (after the divisions) to 2 m, then 1.5 m, then 1 m, and 0.5 m. As a result, the simulations at various heights above floor level illustrated that a sensible offset height of the mini breathing zones was 0.5 m off floor level.

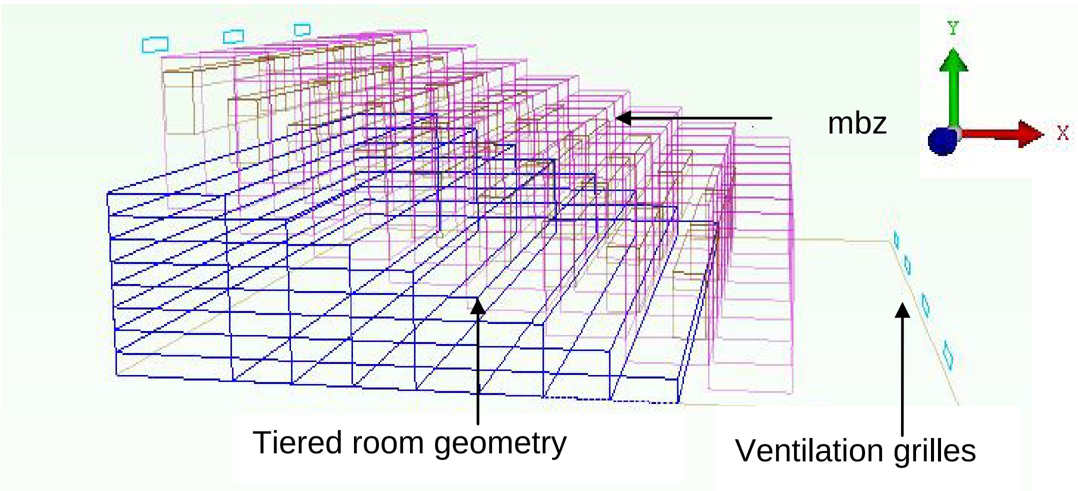


Figure 5.12 Mini breathing zone (mbz) arrangements according to room layout (wireframe diagram)

To examine the mini breathing zone number where an optimum sized mbz was first observed, a plot was made of all the mbz lengths (Figure 5.13). When the concentration is plotted against the number of mbzs, the approach to the breathing zone CO_2 concentration is shown as a close band. As the number of mbz increased, the simulated CO_2 concentrations reduced to approximate a minimum concentration of 430 ppm for the entire occupied zone of the room.

Graph a. in Figure 5.13 shows the CO_2 concentrations resulting from the 3rd division process. The sixth division gave a total of 64 mbzs (Figure 5.13 graph b.) that represented a mid way point in the size of the X and Z lengths. A stage was reached where subdividing the room volume further produced a large number of mini breathing zones that were close to the ambient air CO_2 concentration (shown as levelling off on the graph Figure 5.13c). Therefore, it was not necessary to carry on with the subdivision process, as it would produce very small mbzs with ambient CO_2 concentrations.

The levelling off (approaching an ambient CO_2 concentration) in the simulated CO_2 concentrations was greatest when the number of mbz were 128 and 256 (Figure 5.13 graph c.). At 128 and 256 mbz, the CO_2 concentration levelled at a small concentration range of approximately 40 ppm. An X and Z length that produced the number of mbz of 125 (0.625 x 1.25 m long) and 256 mbz (0.625 m) would portray a CO_2 distribution too close to the person's exhalation zone. Furthermore, this size is too small to portray the breathing zone surrounding the individual.

It was deduced that the number of mbzs that were practicable to display an IAQ distribution in the lecture theatre breathing zone did not need to be as great as 128 or 256 mbz. Furthermore, the series of simulations indicated that the mbz did not need to be as small as 0.625 m x 0.625 m. Decreasing the size of the mbz to less than 1.25 m did not make a practicable difference to the levels of CO_2 experienced by the occupant. In addition, mbzs of this size would just simulate the level of exhaled CO_2. Therefore, this work has shown that a dimension of 1.25 m for X and Z in the horizontal plane was appropriate.

The division procedure and the modelling method effectively simulate the carbon dioxide distribution in the regions of the room where students sit. The subdivision resulted in data that was banded around a small concentration range. Hence, the simulations implied that the optimum lengths of the mini breathing zones occurred when X and Z were 1.25 m.

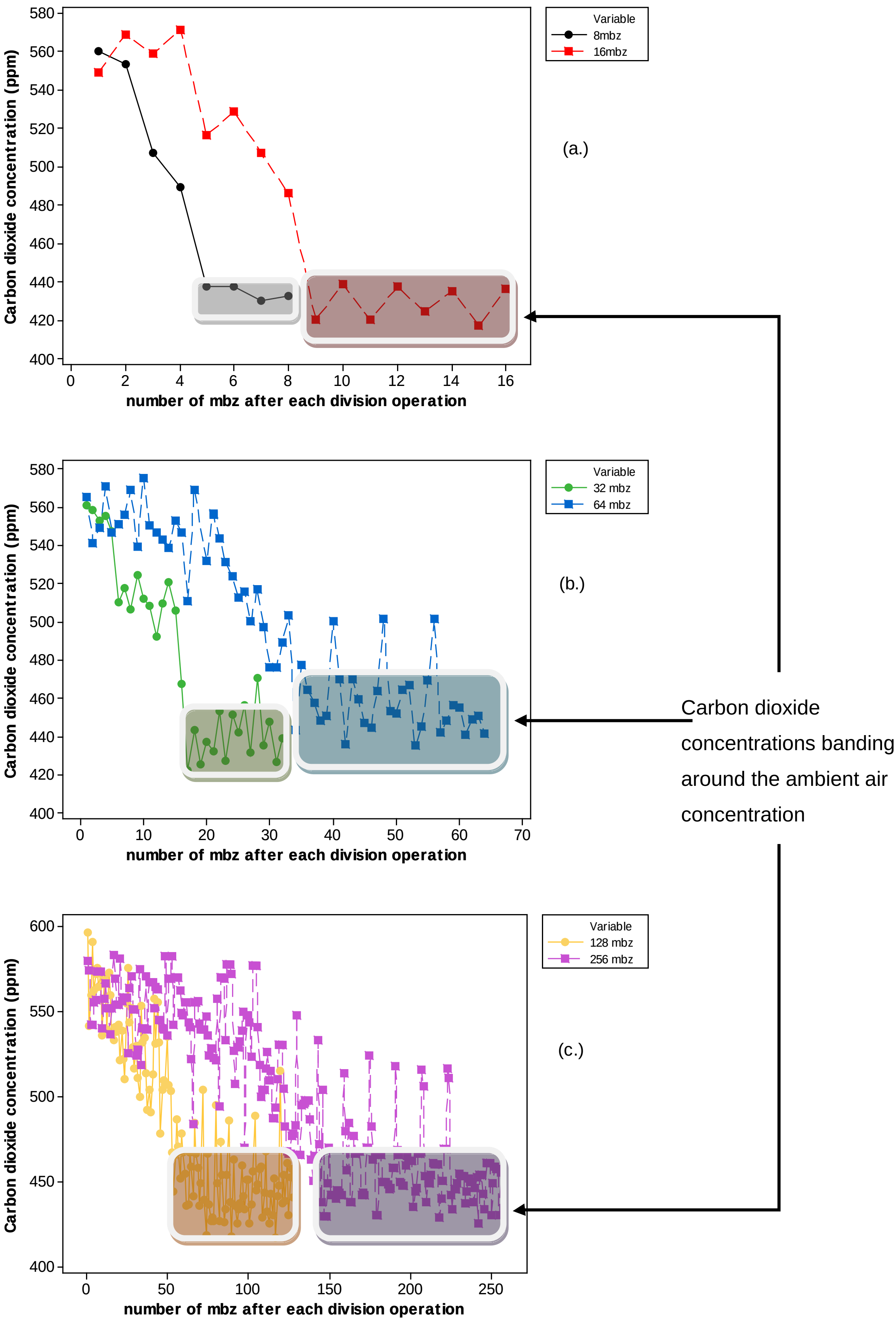


Figure 5.13 Carbon dioxide concentrations with increasing number of mbzs

5.8.3 The height of the mini breathing zone

To determine of the height Y of the mbz, the simulation process undertaken for X and Z, was repeated. The starting height for the Y size was 4 m which decreased under the divisions to 2 m, then 1.5 m, then 1 m, and 0.5 m. The X and Z dimensions used in the simulation were 1.25 m (from the earlier exercise) which totalled 64 mbz that comprised the lecture theatre breathing zone. The simulation results for the different heights are shown in Figure 5.14.

The greatest heights investigated for the Y dimension were 4 m and 2 m (Figure 5.14 graph a). The levels observed at 4m were similar to those at 2 m. Because of the stepped geometry of the room, this height included spaces that were outside the boundary of the model. The 4 m size included spaces where there was furniture and the stepped floor. Therefore, a height of 4m proved too large as it included regions that did not exist in the real lecture theatre.

For 1 m and 2 m heights (Figure 5.14 graph b), the decrease in CO_2 concentrations towards the minimum concentration followed a similar pattern. However, a breathing zone height of 2 m may be too big to represent a mini breathing zone of an occupant. Considering the zone height is offset from the floor level, a height of 2 m at the back of the lecture theatre will be also outside the model boundary.

The smallest height simulated for the Y dimension of the mbz (X and Z set at 1.25 m) was 0.5 m (Figure 5.14 graph c). The simulation results produced higher CO_2 concentrations in general. This was because the simulation captured the high levels of CO_2 localised around the head region from the occupant exhaling. Consequently, an mbz height of 0.5 m was deduced to be too small to measure the IAQ in a lecture theatre.

The simulation results suggested that the optimum length of Y lay between 1 – 2 m and the CO_2 levels for Y = 1 m and Y = 1.5 m followed a similar pattern where the concentration decreased to the similar small values. Therefore, it was deduced that a sensible estimate of height Y was between 1 and 1.5 m, and considering that X and Z were found to be 1.25 m, it seemed reasonable that Y should be the same.

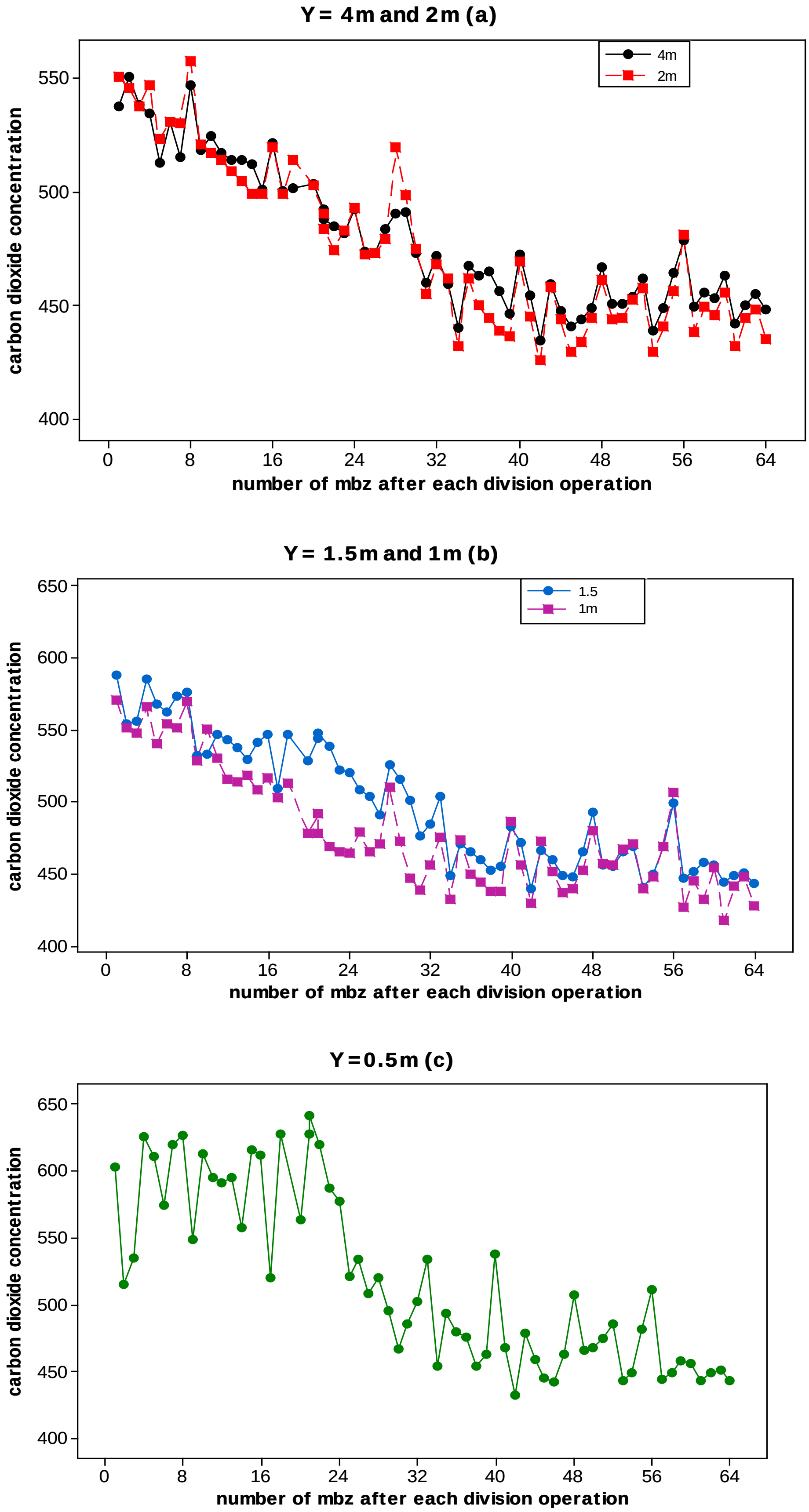


Figure 5.14 Dimensions of mbz length Y

5.8.4 Discussion

The outcome clearly demonstrated that the optimum dimensions of X and Z were 1.25 m. A height of Y=1.25 m meant that the mini breathing zones started at a height of 0.5 m off (approximately at knee level) the floor and extend to a height of 1.75 m. The mbz was a cube with X,Y,Z dimensions of 1.25 m and was the optimum space that would reflect an occupant's comfort experience of the IAQ (in terms of CO_2 levels) within the lecture theatre.

The optimum volume for the mbz was determined using a room with tiered geometry, occupants, seating and desks, all of which were physical obstructions to airflow. If the room were an auditorium or cinema, the same obstructions to airflow would exist, such as the rows of seating and the occupants. Therefore, the volume determined here in theory can be applied to all such spaces and hence the determined mbz can be used in the proposed assessment method.

The dimension of the mbz was determined as 1.25 m. This volume of mbz was established by starting with a lecture theatre that had a volume of 864 m^3. The conclusion that this subzone size was appropriate for use in the IAQ assessment methodology was because a cubic array of mbz would accommodate the tiered geometry of a lecture theatre and allow the portrayal of a spatial IAQ distribution.

The volume of the lecture theatre that was used in this particular determination of mbz size was approximately 650 m^3. If a larger lecture theatre was being modelled the process of establishing an mbz size would be the same. Whatever the lecture theatre volume, a point will be reached in simulation where going from a larger to a smaller scale will not result in other benefits. This is because the simulation will calculate parameter values, which are too detailed to be practicably useful in an IAQ assessment of a real lecture theatre. Therefore, the procedure of obtaining the mbz volume is an important component of the assessment methodology, rather than the resultant volumetric size of mbz.

Using a greater number of mini breathing zones that cover the entire lecture theatre will give a more detailed portrayal of the IAQ in the room. However, the main focus of interest from an IAQ assessment is the volume of the room occupied by people. Consequently, the IAQ distribution in breathing zone was the main priority of the study and areas outside this zone were not considered in the assessment methodology. Nevertheless, examining the whole room volume could provide information on regions where problems exist in relation to, for example, the ventilation method or the design of the space.

5.9 Assessment Methodology Details

The software selected for use in the proposed assessment methodology was FloVENT. The suitability of this software for assessing IAQ was checked by comparing the observed carbon dioxide measurements taken in Mayfield House with the simulation results from a corresponding model constructed using this software. It was found that, the simulation results were comparable with the carbon dioxide concentration measures made in Mayfield House. Furthermore, the user friendly aspects of the software reiterated its choice as a tool in assessing the IAQ in a lecture theatre.

The pilot study indicated that conditions in the lecture theatre studied were non-homogenous. This observation became the premise of the proposed assessment methodology. Appropriate measures of IAQ were selected for use in a non-homogenous assessment methodology. The selected measures were the CO_2 concentration, to simulate the IAQ level, and simulated values of LMA to describe the ventilation effectiveness in a lecture theatre. Thus, an IAQ assessment methodology was developed that appreciated the non-homogenous nature of airflow in a lecture theatre.

Following from the non-homogenous premise of the assessment methodology, the CO_2 concentration and LMA needed to be modelled in three dimensions to map the IAQ distribution. Thus, the breathing zone in the lecture theatre was subdivided into mbzs with a determined volume (1.95 m^3). Using the software to simulate values of CO_2 concentration and LMA in the mbzs provided a spatial portrayal of IAQ from which the IAQ assessment could be made.

5.9.1 Procedure for establishing the IAQ distribution

The IAQ assessment methodology that has been developed consists of six procedures. A summary of the key stages of the assessment methodology are illustrated in the flowchart (Figure 5.15). The levels of the flowchart are colour coded with black being the main process and blue being the looping process to optimise the IAQ using the methodology.

- Stage one: Model construction

The first stage of the assessment methodology entailed building an air quality assessment model (AQSM) of the lecture theatre in the software. This involved drawing a scale model of the lecture theatre in FloVENT. The software allowed the definition of the material properties of the building fabric. It was assumed that the lecture theatre modelled had a conventional brick and block construction. Additional boundary conditions of the model were fixed by selecting values of the ambient and indoor environmental air temperature, relative humidity and carbon dioxide concentrations, and thus a detailed model was created.

- Stage two: Zoning

The second stage of the assessment methodology was the zoning procedure. The occupied zone of the lecture theatre was initially defined, which included the seated areas of the lecture theatre. This occupied zone was then subdivided into mini breathing zones (mbz) as described in Section 5 .8. As a result, the seating regions in the lecture theatre were visualised as an array of mbzs.

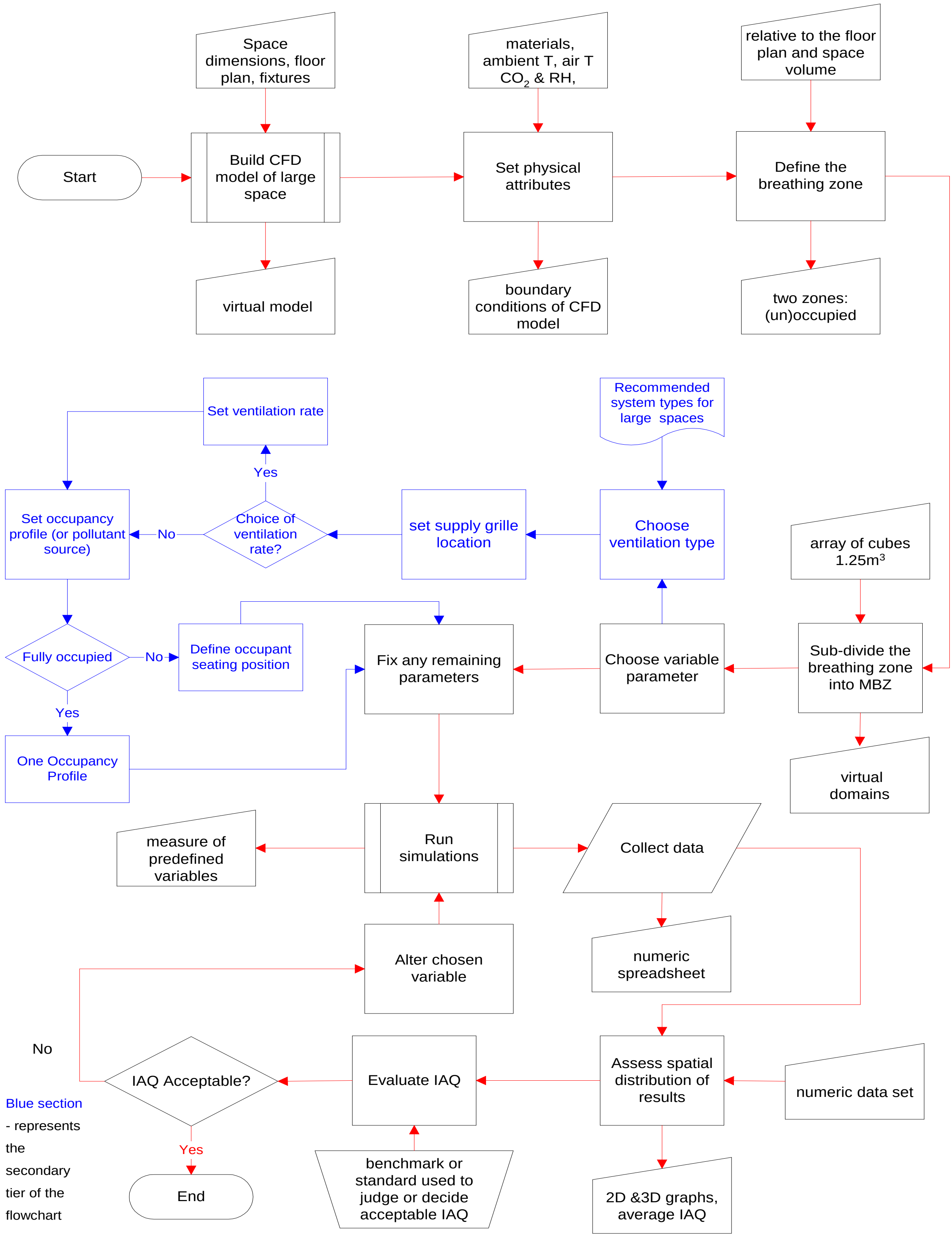


Figure 5.15 Assessment methodology procedure

- Stage 3: Define variables

In the model of the lecture theatre, a number of different parameters could be altered according to the variable of interest and the component of IAQ that was being assessed. This process of setting variables was flexible, as there were both constant and variable parameters, depending on what factor was being assessed. In this study of IAQ in a lecture theatre, the important variables for investigating the IAQ and the occupant comfort were the method of air distribution, the ventilation rate, the occupancy profile, and the location of supply air grilles. The influences of these variables on IAQ are assessed in detail in Chapter 7.

- Stage 4: Simulation

Stage four of the IAQ assessment methodology was the simulation process of the AQSM. The model was initially checked for any diagnostic errors, such as part of the model lecture theatre lying outside the solution domain. The number of repeat solutions of the fluid dynamic equations was set, and the program run until the solution had converged. The output was a worksheet of CO_2 concentration and LMA values for the individual mbzs.

- Stage 5: Determination of an IAQ distribution

The IAQ distribution was determined in stage five. The raw simulation data from the AQSM consisted of the contaminant concentration distribution and local mean age of air in the modelled lecture theatre. This output was processed to display the spatial IAQ distribution via charts and tables in order to assess the IAQ. As a result, the spatial variation of the IAQ distribution in the lecture theatre was simulated.

- Stage 6: IAQ evaluation

The final process was the IAQ assessment. The simulation results were further analysed statistically, and described in tables to assess the IAQ. The numeric results of the simulation of a model lecture theatre were summarised using the spatial coverage and maximum IAQ level represented by the CO_2 concentration (Table 5.7). This outcome could then be compared against recommended concentration limits in a lecture theatre such as 1000 ppm.

The IAQ maps portray the pattern of IAQ in the lecture theatre and illustrate the variation of IAQ in the room. The simulation output was statistically tested to determine the effect on the IAQ distributions from different variables in the lecture theatre. For instance, the effect that a lecture theatre seating occupancy pattern has on the IAQ distribution can be assessed using the methodology. Thus, the methodology can provide an IAQ assessment for different lecture theatre parameters.

Measure	Description
Spatial average IAQ level	Average CO_2 concentration
Maximum IAQ level	Maximum CO_2 concentration
Vertical or horizontal IAQ distribution	LMA and CO_2 distribution

Table 5.7 Summary of measures used in the IAQ assessment

5.9.2 Assessment criteria

In order to perform an IAQ assessment of a lecture theatre, criteria were required to decide whether the IAQ predicted by the methodology was acceptable. The methodology developed used three assessment criteria as follows.

In order to decide whether the IAQ was acceptable in the breathing zone, the CO_2 concentration was used as a representative measure of the spatial average IAQ level in the lecture theatre. This average CO_2 concentration was compared to a recommended level, for example, the ASHRAE CO_2 concentration of 1000 ppm. In addition, the maximum CO_2 concentration was a criterion reported from the simulation output to illustrate the peak CO_2 concentrations in the breathing zone. The peak concentration similarly can be compared to the ASHRAE level. Using a maximum CO_2 concentration along with an average CO_2 concentration in the breathing zone indicates the acceptability of the predicted IAQ.

An even distribution of fresh air in the breathing zone from the ventilation arrangement is preferable, as this means that all the occupants of the room would equally receive fresh air. With this in mind, the distribution of LMA should ideally consist of the freshest air in the breathing zone. Low values of LMA indicate that there is a good delivery of “fresh” supply air to the room. Considering the LMA provides information on how effective the ventilation system is in removing stale air and supplying fresh air, and was therefore included as a criterion in the assessment methodology.

The graphical distributions of CO_2 concentration were also used as a criterion to assess the IAQ. Examinations of the planar and three-dimensional portrayal of CO_2 concentrations allow the identification of regions in the lecture theatre breathing zone that have unacceptable IAQ levels. Such CO_2 plots can be used in conjunction with other modelled data to make a comprehensive assessment of IAQ in the lecture theatre.

The outcomes from the IAQ assessment methodology are a combination of graphical display and numeric results. The graphical display is capable of illustrating the effect on the spatial IAQ distribution produced by the different variables being assessed. For example, the planar and vertical IAQ distribution in the occupied zone can be portrayed using the CO_2 concentration or the LMA values from which, regions of unacceptable IAQ can be identified.

5.10 Chapter conclusions

Computational fluid dynamics software was selected as a measurement tool, because of its ability to simulate airflow and additional parameters at all points in a space. The selection of the CFD software FloVENT was justified by comparable results of the modelling and the pilot study of Mayfield House. The pilot study supported the non-homogenous premise and led to the development of the IAQ assessment methodology. In order to reflect the non-homogenous conditions in lecture theatre and simulate an IAQ distribution a set of measure parameters were required. As a result of a review, the CO_2 concentration and LMA values were selected as suitable measures to portray IAQ distribution in a lecture theatre.

The modelling of the distribution of IAQ in the lecture theatre needed to be focused on the breathing zone. In order to portray the variation of CO_2 concentrations and LMA values, the procedure of zoning was used. Subzone volumes of the lecture theatre breathing zone were determined using simulation. This procedure showed that a mini breathing zone volume of 1.95 m^3 was appropriate to simulate the IAQ variation in the breathing zone for use in the assessment methodology.

A typical university lecture theatre was chosen as a room template. This choice was made because lecture theatres have a range of room sizes and occupancy profiles. This means that there will be inherent variation in IAQ in lecture theatres, due to the way such rooms are used. In addition, lecture theatres are generally expensive facilities to run, and are often under-used (Tutt and Adler, 1998). Thus, as lecture theatres have such specific characteristics this room type requires a particular IAQ assessment procedure.

The tiered geometry design and arrangement of furniture in a lecture theatre allows the students to clearly hear and see the lesson delivered by the tutor. The regular arrangement of seating and bench space means that the recommended space per occupant is smaller in a lecture theatre ($1m^2$/space), when compared with the workstation space recommended for a general office

(4-6m^2/per person). This tighter occupant density reflects the typical activities of note taking and transient occupancy that occur in such a teaching space. This characteristic also applies to other large spaces such as cinemas, auditoria and theatres in which the audience sit in a regular plan for a few hours at a time. Therefore, the proposed assessment methodology may also be applicable to such rooms.

The outcome of this work was a computerised simulation methodology that provided a spatial IAQ distribution from which the IAQ could be assessed. The preliminary CFD model of the pilot study of Mayfield House indicated that the modelling simulated the real world. In order to further evaluate the assessment methodology, it was applied to another lecture theatre on the university campus. This larger lecture theatre was used for large-scale monitoring of carbon dioxide concentration and enabled further testing of the outcomes of the assessment methodology. The measurement of IAQ and further validation of the assessment methodology in a larger lecture theatre is described in the next chapter.

CHAPTER SIX

Validation of the air quality simulation model

6.0 Description of test lecture theatre

Lecture theatre one (LT1) is located on the Mouslecomb campus of the University of Brighton. It is part of the original University site, which has buildings dating from the 1960s and was constructed according to past building conventions. Refurbishment of the lecture theatre, and the ventilation system occurred approximately 10 years ago.

A survey of LT1 was performed. The dimensions of the lecture theatre were 11.9 m x 11.9 m x 5.8 m. Lecture theatre 1 has three outside walls, one of which has non-opening windows. The room has a capacity of 138-seated occupants. Unlike the pilot study, LT1 has a larger room volume, with a different type of ventilation system installed. There is a small projector room at the back of the lecture theatre, which leads to the outside ventilation and heating plant.

6.1 Room characteristics

The lecture theatre has two blocks of seating separated by a middle aisle. The floor has a tiered arrangement of steps with fixed desks and seating. In addition to the middle aisle, there is access to the seating at the sides of the room, with walkways at the opposite end of the rows of benches (Figure 6.1).

Figure 6.1 LT1 layout

The ventilation system in LT1 is a high-level mixing arrangement of air grilles. Air is supplied at the front and extracted at the back of the room (Figure 6.2). It has been reported (Appleby, 1990) that in some cases this type of arrangement can produce short-circuiting of ventilating air, where the supply air moves directly to the exhaust region instead of movement through the breathing zone of the room. Potentially this is a problem as it can lead to the inefficient ventilation of the room, and therefore compromise the comfort of the occupants.

The lecture theatre has a suspended tiled ceiling, which forms the service void that accommodates the ventilation ducts, and other building services. The ventilation grilles are in the ceiling of the lecture theatre. The ceiling is in two sections. The back section is horizontal, with a sloping front section. A row of four extract grilles is at the back of the room. Eight supply grilles are in the remaining ceiling area close to the luminaires (Figure 6.3).

A Building Management System controls the ventilation and heating in the lecture theatre. The heating and ventilation system is operational during Monday to Friday but not at the weekends. The system is active from 8 a.m. to 6 p.m. and the first lecture time is at 9am. This means that the volume of air (approximately 800 m^3) in the lecture theatre has one hour to reach the room comfort-design requirements. During cold periods, as the heating is off over the weekend, the first lectures on Monday are prone to be below the comfortable room temperature.

Issues with heating in the lecture theatre have led to remedial actions. To address the problem of the room being too cold at the beginning of the day, and to mitigate any short-circuiting of ventilating air, two heaters were fitted at the front of the lecture theatre. However, the effectiveness of the extra heaters is questionable in relation to the inadequate thermal comfort of the room or correct any short-circuiting of airflow.

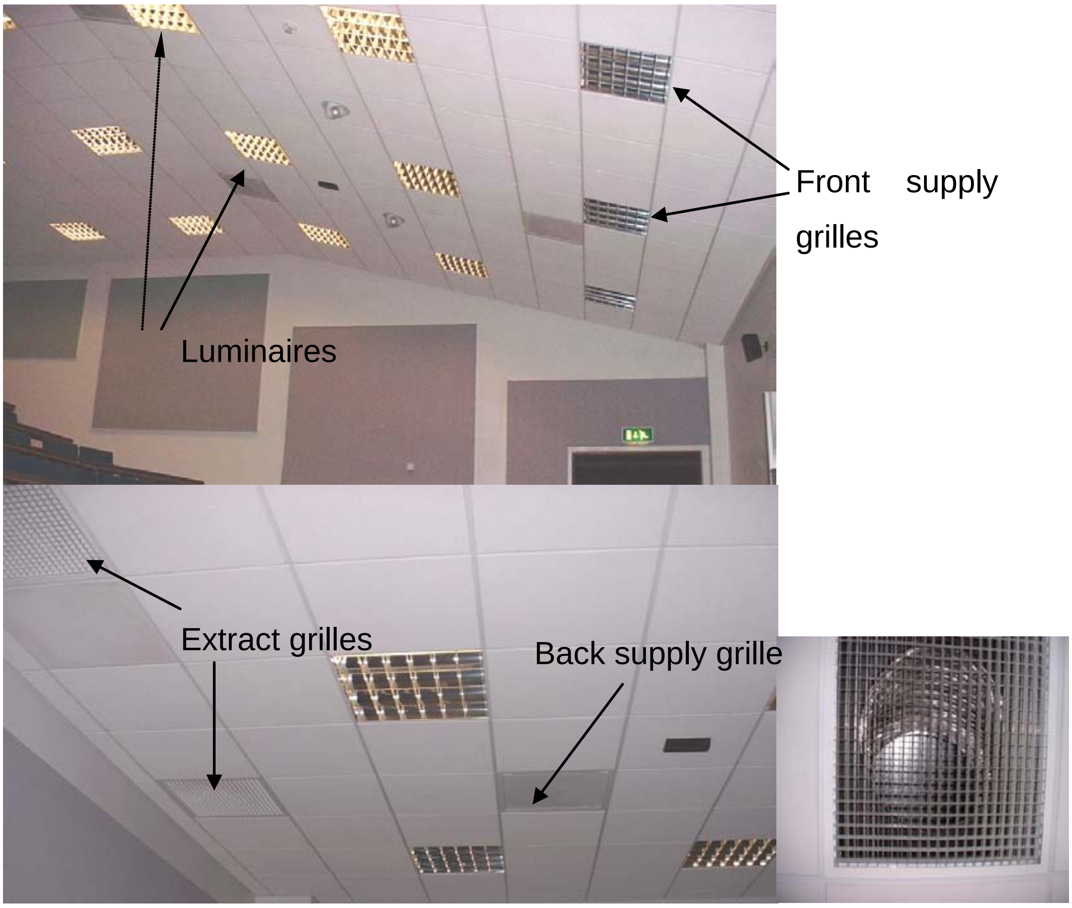


Figure 6.2 Location of ventilation grilles

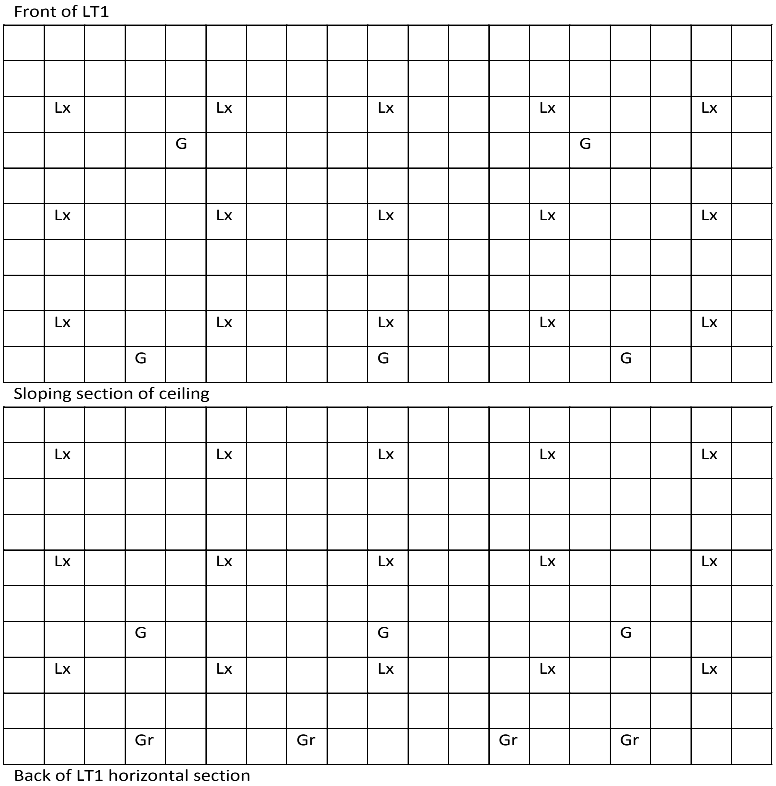


Figure 6.3 Plan of the supply grilles (G), extract grilles (Gr) and luminaries (Lx)

6.2 Study of the air conditions in a lecture theatre

In order to investigate the idea of non-homogeneity, measurement of CO_2 concentrations in a second lecture theatre (Lecture theatre 1) took place. The hypothesis was tested in two ways using a mechanical fan. Air was sampled at seating locations in the lecture theatre with and without the operation of a mechanical fan. The aim of the fan was to force the mixing of air, thus ensuring well-mixed conditions.

The study involved air sampling in Lecture Theatre 1 for three periods (Figure 6.4). Two periods of sampling using differing sides of the room occurred without a fan. During the last monitoring period, a fan was installed at the back of the lecture theatre. This produced three different sampling sites that were analysed to investigate and validate the non-homogeneity hypothesis.

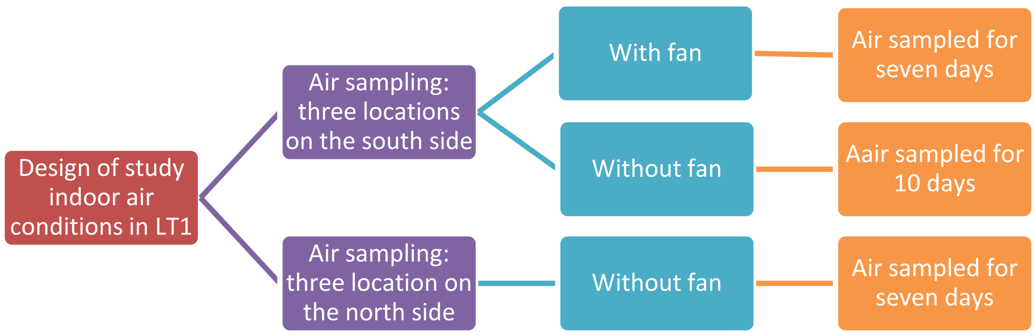


Figure 6.4 Sampling strategy for the study

6.3 Carbon dioxide study

Monitoring of carbon dioxide concentrations occurred at different locations in a second lecture theatre (Lecture Theatre 1). This lecture theatre was selected because of its capacity (larger space), and room geometry (conventional tiered floor lecture theatre design). The lecture theatre was a secure site with easy access to the room, both in and out of working hours. Therefore, it was a suitable choice for locating the monitoring equipment.

The monitoring exercise was carried out in winter, same as the pilot study. This was important as the outside temperature affects the ventilation system heating controls for the room temperature. The ambient CO_2 concentration was assumed to be the same as the average background level for the UK. Thus, the ambient outdoor conditions for the two lecture theatres were similar.

The monitoring period in Lecture Theatre One (LT1) lasted for three weeks. The sampling schedule was programmed into the equipment. Monitoring points were fixed at six locations in the lecture theatre. Carbon dioxide was measured at each location for set times. The data collected from the monitoring points consisted of CO_2 concentrations matched against a time stamp from the equipment data logger. Downloading of data took place at 07:30 hrs (air sampling was resumed at 08:30 hrs) at the beginning of each teaching week, to avoid any disruption to teaching.

As is normal the lecture theatre had a variable teaching schedule. Both the number of occupants and the duration of lectures varied widely during the monitoring periods. Therefore, for each study the characteristics of the lectures were a variable in the assessment methodology.

6.4 South side air sampling

The monitoring in Lecture Theatre 1 (LT1) began on the 17th November 2008 for three weeks. During the monitoring period, the number of students in each lecture was recorded, where possible. The monitoring incorporated three complete teaching weeks. The lecture schedule timetable was the same for each week consequently lectures on Monday, Tuesday and Wednesday morning were monitored twice.

Data was also recorded overnight and throughout the weekend when the lecture theatre was unused. This was to investigate the behaviour of the

CO_2 concentration in the unoccupied lecture theatre. The ventilation system does not operate overnight and at weekends. The CO_2 concentration of the empty room should also provide a baseline measurement for a well-mixed scenario.

Monitoring points were positioned on the south side for 10 days with measurement starting on a Monday and finishing on Wednesday afternoon (Table 6.1). The monitoring points were placed in a line at the front, middle and back, on the south side of LT1 (Figure 6.5). This was to replicate the slope of the seating in the lecture theatre and the physical position of the occupants. The monitored CO_2 at these points should reflect the characteristics of the indoor air inhaled by the students sitting in this location in the lecture theatre.

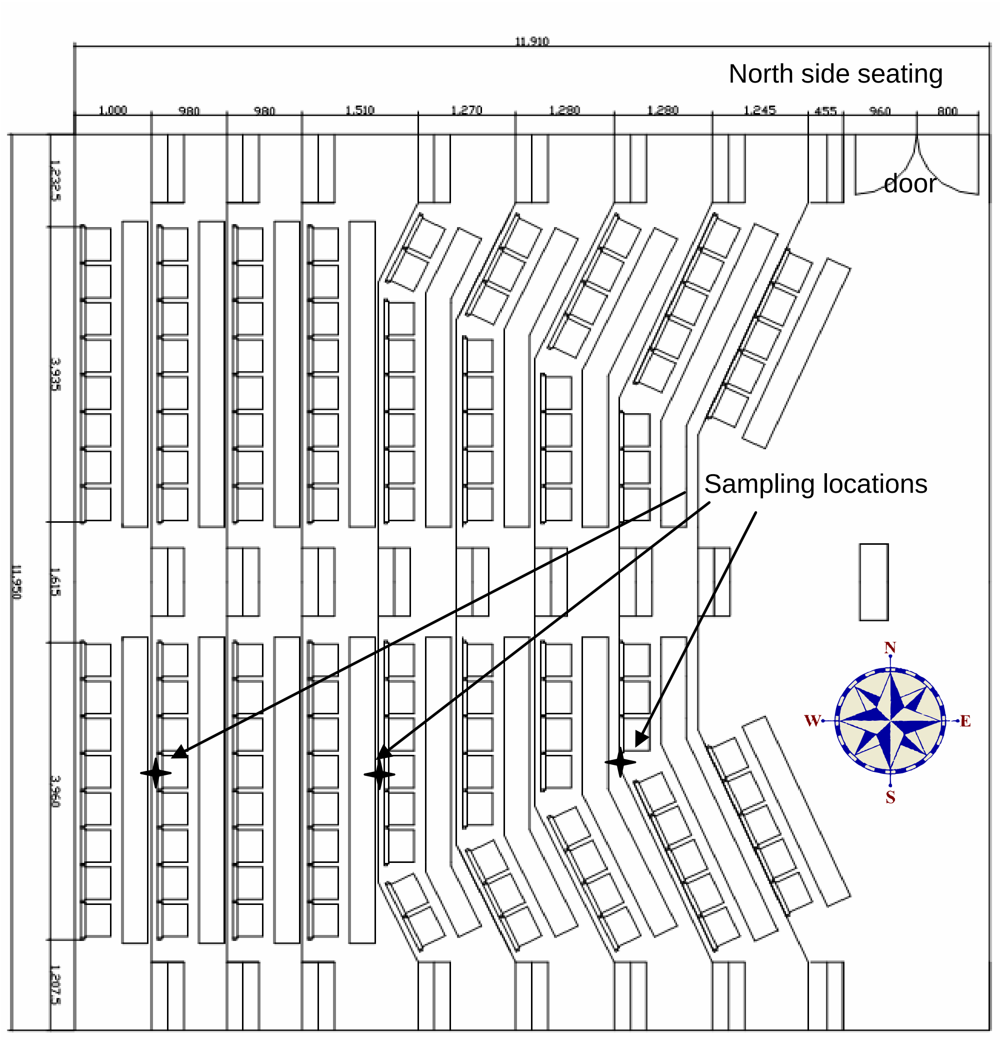


Figure 6.5 Position of monitoring points

Measurement	17/11/2008 to 26/11/ 2008
Started at	17/11/2008 08:00 Monday
Ended at	26/11/2008 14:55 Wednesday
Duration:	10 days, 6 hours, 55 minutes

Table 6.1 Monitoring period at south side of LT1

The air sampling measuring equipment was the same Dantec air-sampling unit used in the pilot study of Mayfield House with three monitoring points. During the first monitoring period, the sampling points were positioned at the south side of the lecture theatre. This was to determine if the sampling tubes were long enough to reach the intended sampling positions. The location of the fire exit was a problem and the tubes were placed around the door to avoid obstructing the escape. They were found to be long enough to reach the front sampling location.

6.4.1 Observations

The CO_2 concentrations monitored on the south side of the lecture theatre are shown in Figure 6.6. During this period there was no fan positioned in the room. The results demonstrated that concentrations of CO_2 increased and decreased consistently with the occupancy times of the lecture theatre.

Variations of CO_2 concentration were observed. The maximum (3485 ppm) CO_2 concentration at 12:53 hrs on Monday 17th November was measured at the back of the lecture theatre. The highest CO_2 concentration peaks occurred on Monday (12:53 hrs), Tuesday (12:20 hrs) and Thursday (19:29 hrs). These concentration peaks corresponded to lectures that had different numbers of students. The maximum number of students registered for the lectures that were scheduled for LT1 were below the room capacity; so the CO_2 concentration approaching 3500 ppm cannot be explained by high room occupancy. However, this high concentration is significant as the occupants in this region of the lecture theatre would be uncomfortable.

The maximum-recorded occupancy of the room was 110 people (80% occupied) for a two-hour lecture on the 25th November the second Tuesday measured. This lecture had a maximum CO_2 concentration of 782 ppm, but it did not result in abnormally high CO_2 concentrations. This is in contrast to lectures with fewer students that recorded extremely high CO_2 concentration peaks. The inconsistency is likely to be due to the operation of the ventilation system.

The CO_2 concentration peaks on Monday 17th of November and Tuesday 18th November occurred in the middle of the lecture theatre on the south seating block. These two CO_2 concentration spikes (3485 ppm and 2612 ppm) were between 12:00 hrs and 13:00 hrs when the ventilation system was operating. The CO_2 peak on Thursday 21st November (2135 ppm) was the lowest peak of the three and occurred at the front of the lecture theatre. However, this CO_2 peak was recorded after the ventilation system had been switched off.

The unoccupied periods in the room had a relatively stable CO_2 concentration. The CO_2 concentrations recorded at all monitoring points approached the ambient concentration over the weekend. Thus, the observations demonstrate that well mixed CO_2 concentrations could only occur when the lecture theatre was unoccupied and when the ventilation system was switched off.

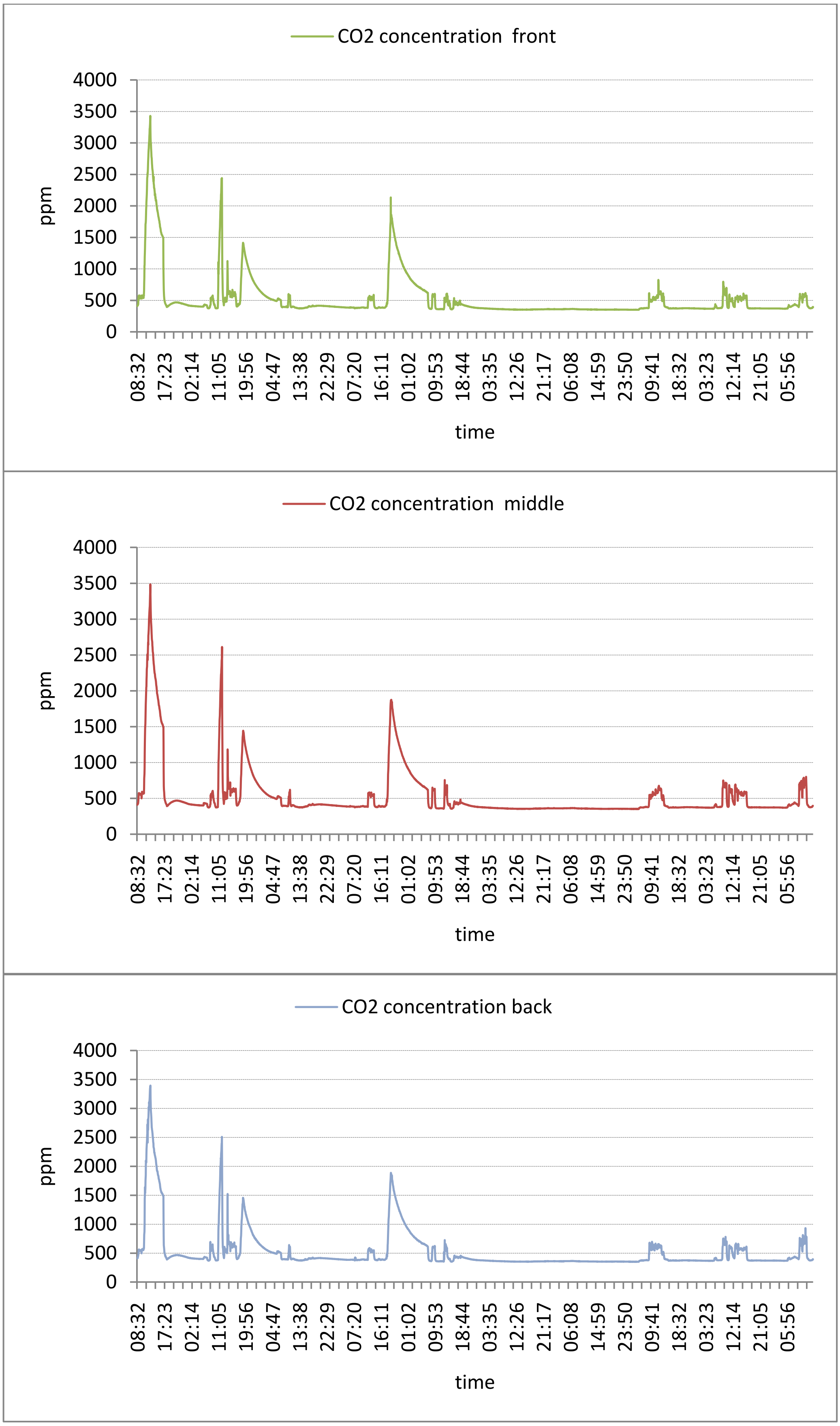


Figure 6.6 Carbon dioxide concentrations at the south side of LT1

To examine whether variation in CO_2 concentration existed between the monitoring points positions in the lecture theatre, the measurements from three points were compared using a day where the extreme CO_2 concentration peaks were not measured. This was Friday 21st November. Three lectures were scheduled from 09:00 to 10:00 hrs, 13:00 to 16:00 hrs and 14:00 to 18:00 hrs. Figure 6.7 illustrates the CO_2 concentrations measured at the front, middle and back of the room.

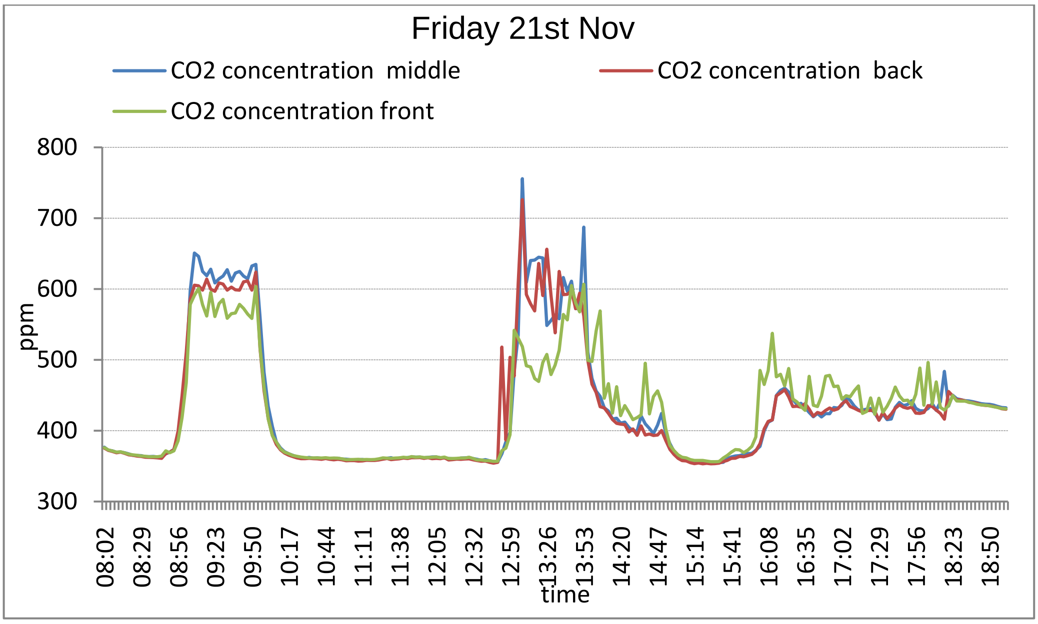


Figure 6.7 Differences in CO_2 concentrations during one teaching day

Friday 21st November had a range of measured concentrations between 550 to 650 ppm. The first set of concentration peaks corresponded to a one-hour lecture with 82 occupants (59% occupancy). For this lecture, the CO_2 concentration in the middle region of the room had the highest concentration peaks.

The room was then empty for the next three hours until 13:00 hrs, when a three-hour lecture with 84 occupants took place. The variation between the front and the other sampling points was pronounced during the first hour of occupation. From 14:00 hrs onwards, the measured concentrations began to decrease but the concentration of the front of the room did not decrease as much as the concentrations at the back and middle regions.

The last lecture started at 16:00 hrs and was for two hours. Eighteen students attended. This was the smallest class that day; with CO_2 concentrations recorded around 450 ppm. The monitoring point at the front of the lecture theatre recorded the highest CO_2 concentrations for the duration of the lecture. This was in contrast to the earlier lectures where the front of the room had the lowest CO_2 concentrations.

6.4.2 Discussion

Well-mixed carbon dioxide concentrations were not measured at the south side of LT1. An analysis of variance of the monitored results indicated (at a 95% confidence level $p<0.05$) a significant difference in CO_2 concentrations at the sampling locations. The concentration of CO_2 varied simultaneously at different locations in the lecture theatre. As a result, the CO_2 concentration cannot be assumed as homogenous on the south side location of the lecture theatre.

Peaks of CO_2 concentration coincided with the time that lectures occurred. During each day, the CO_2 concentrations increased and decreased in accordance with the different lecture occupancy characteristics. The measurements therefore illustrated that well mixed CO_2 concentrations did not occur during the periods when LT1 was occupied, and supported the view that assessing IAQ, the absence of well-mixed conditions should be appreciated.

In addition to non-homogenous conditions, the results illustrated that there were issues with the ventilation in the lecture theatre. The first Monday 17th of November and Tuesday 18th November sampled had CO_2 concentration peaks around 12:30 hrs. On Monday, the first lecture for three hours typically occupied 60% of the seating, which was below the design capacity of the lecture theatre. Similarly, the lectures before 12 pm on Tuesday had an occupancy between 50 to 70%; again below the design capacity of the room. As a result, the numbers of occupants alone does not explain the measured CO_2 concentrations above 2000 ppm.

The exact reasons for high peaks around midday at the beginning of the week are debatable. The peaks around midday could have been due to a time lag in the system exhausting the ventilating air as it operates from 8 a.m. to 6 p.m. The peak on Thursday at 19:30 hrs occurred when the ventilation system was off, and was due to the lecture theatre being occupied for an external meeting causing the CO_2 concentration spike. Nevertheless, the CO_2 concentrations approaching 4000 ppm are remarkable and indicate an issue with the ventilation in the lecture theatre.

In one lecture, 80% of the seats were occupied. This was the lecture with the highest occupancy rate during the period of observation in LT1. During this two-hour lecture, abnormally high CO_2 concentrations were not measured, even though it had the majority of occupied seats relative to less occupied lectures. The reason for this discrepancy cannot be explained without a full examination of other parameters such as the ventilation system in LT1.

The CO_2 concentrations from each sampling location for Friday 21st November for the entire teaching period were analysed to established how uniform the concentrations were in the lecture theatre.

To examine the degree of non-homogeneity in LT1, a complete teaching day that had CO_2 measurements without extreme concentration peaks was studied on Friday 21st November (Figure 6.7). The Friedman statistical test was used to analyse the CO_2 concentrations. The results suggested that there was sufficient statistical evidence ($p<0.05$ at 95% significance level) of differences in CO_2 concentrations throughout the day and during each lecture. Therefore, the observations showed that a spatial variation of CO_2 concentrations existed throughout the day for all lectures, and between the three monitoring points.

6.5 North side air sampling

The information gained from the first sampling period indicated that variation in CO_2 concentration occurred in the south side of the lecture theatre. To investigate whether there was variation in CO_2 concentrations on the north side of LT1, the line of monitoring points were moved (Figure 6.8). Sampling occurred on the north side seating of the lecture theatre at similar positions to the south side.

Sampling on the north side of the lecture theatre took place without a fan. The second monitoring period was for seven days (Table 6.2). The results were analysed to determine the extent to which the CO_2 concentrations varied on that side of the room.

Measurement	26/11/2008 to 03/12/ 2008
Started at	26/11/2008 14:55 Wednesday
Ended at	03/12/2008 15:30 Wednesday
Duration:	7 days, 35 minutes

Table 6.2 Monitoring period on the north side of LT1

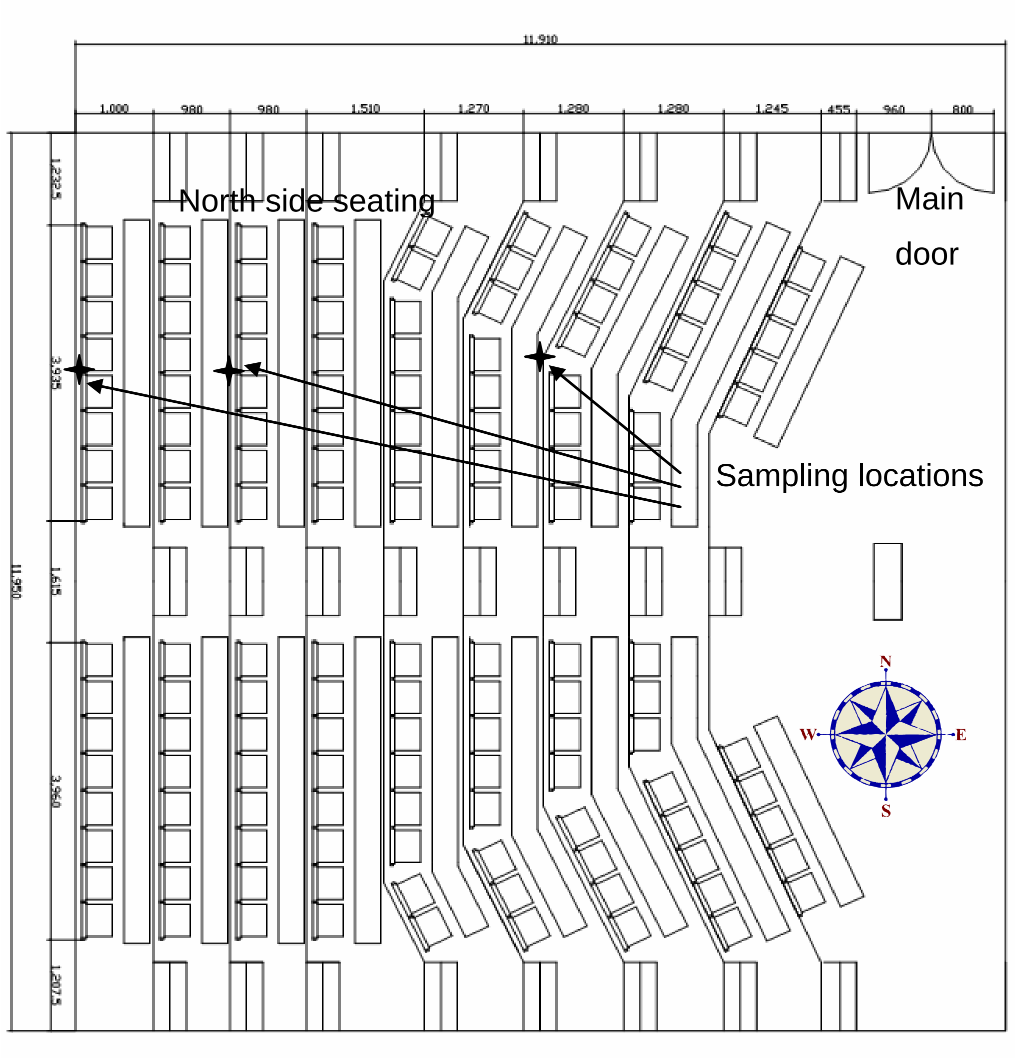


Figure 6.8 Position of monitoring points on the north side of LT1

6.5.1 Observations

General observations from the north side monitoring period (Figure 6.9) indicated that the CO_2 concentrations at the sampling locations followed a similar pattern of increase and decrease to that observed during the first monitoring period. Again, the CO_2 concentrations responded to the varying occupancies of the lecture theatre.

Table 6.3 summarises the duration of lectures that were used in the north side sampling period. The colours represent blocks of teaching, with the numbers of students that were counted entering the lecture. For some lectures it was not possible to physically record the number of students this is shown as a blank in the colour block.

Northside sampling 09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
week 2									
Wednesday 26th Nov		students: 97 = 70% occupancy							
Thursday 27th Nov	35 = 25%			74 = 54%	77 = 56%				
Friday 28th Nov	82 = 59%				71 = 51%			26 = 19%	
Saturday 29th Nov									
Sunday 30th Nov									
week 3									
Monday 1st Dec	81 = 59%			40 = 29%	20 = 16%	38 = 28%			
Tuesday 2nd Dec	102 = 74%		62 = 45%		64 = 46%	70 = 51%		69 = 50%	
Wednesday 3rd Dec		81 = 59%			37 = 27%				

Table 6.3 Timetable of the student number and percentage occupancy

On the Friday 28th November for the first class of the day, no high levels of CO_2 were measured. A peak in CO_2 concentrations of approximately 2500 ppm for all three monitoring points occurred during the second lecture at 15:00 hrs. This lecture had a similar number of students as in the first lecture that day. However, such a peak in concentration was not observed in the morning lecture.

Higher concentrations of CO_2 occurred at all three monitoring points on Monday 1st December and Tuesday 2nd December. On Monday, the highest CO_2 concentration of 3293 ppm was between 11:50 to 12:30 hrs. The morning lecture was the longest lecture of the day and had the greatest number of students, so a higher CO_2 concentration should have been expected. Nevertheless, the measured CO_2 concentration substantially exceeds the recommended 1000 ppm and would have implications for the comfort of the occupants.

On Tuesday 2nd December, the concentration peaks occurred between 16:30 to 17:00 hrs. The maximum CO_2 concentration of 4965 ppm at 16:45 hrs on Tuesday 2nd December was measured at the back sampling point. In contrast, to the maximum peak on Monday, this was measured at the middle sampling point and indicates that the area in the room where students sit, levels of IAQ appears to vary.

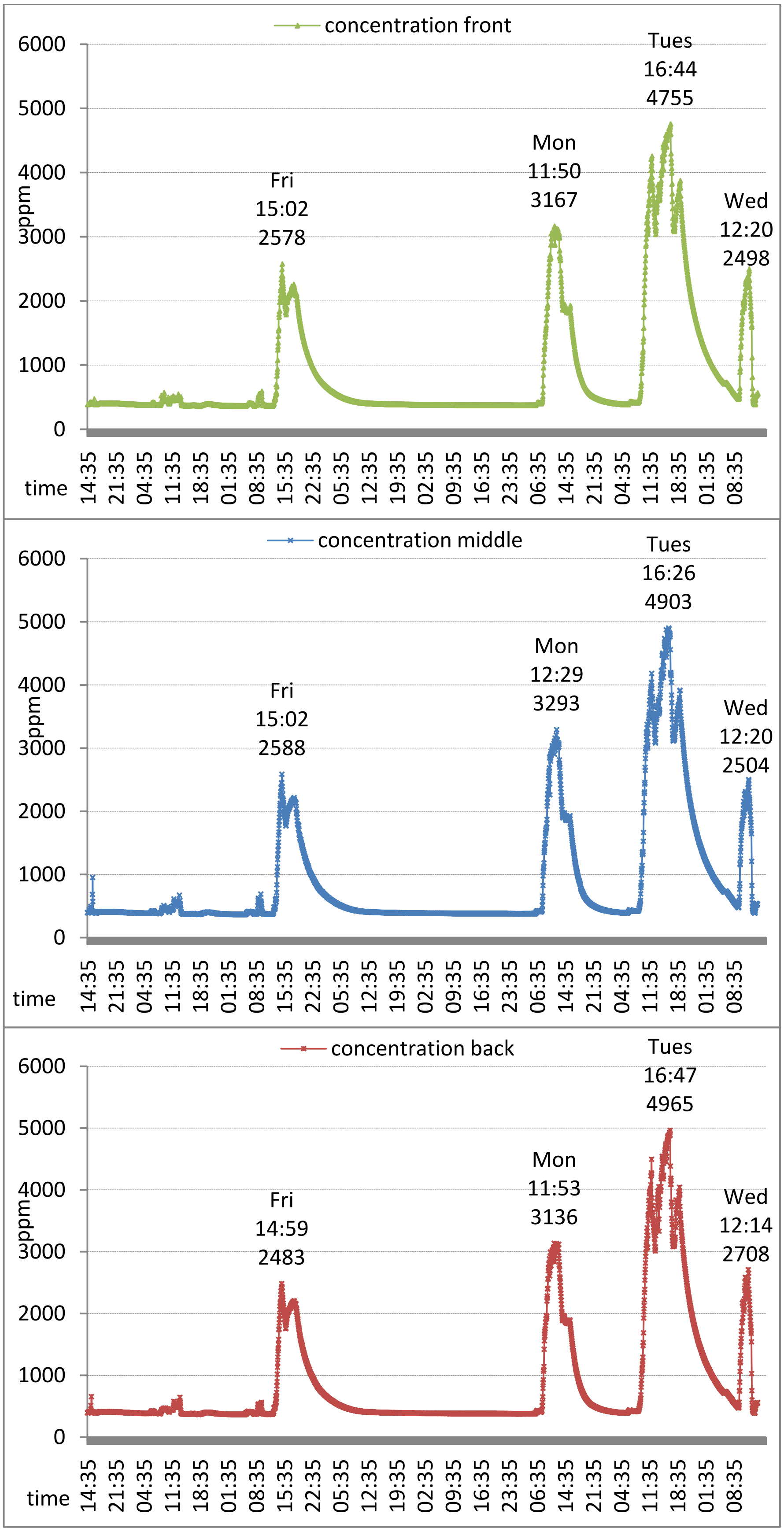


Figure 6.9 Carbon dioxide concentrations at the north side of LT1

6.5.2 Discussion

In the study of LT1, the air was sampled using a Vivo Trigas monitor. This directly measured the concentration of CO_2 (in ppm) using photoacoustic spectroscopy. Once the sampling times were programmed into the equipment, it continuously sampled the air. The monitor unit itself is calibrated annually by the manufacturer hence no external calibration was required.

Carbon dioxide concentrations on the north side of LT1 were not well mixed. Statistical analysis of variance of the raw data for this monitoring period indicated at a 95% confidence level, that there were significant differences between the CO_2 concentrations at the various monitoring locations. This reiterates the findings from the sampling of the previous week that homogenous conditions did not occur during the occupied times of the lecture theatre. Furthermore, the variation of CO_2 measurements between monitoring points in the lecture theatre was examined over one working day (Friday 28th November). The data analysis additionally showed that well mixing of CO_2 concentrations did not occur during individual lectures. Hence, no well mixed conditions were measured during the times the theatre was used.

As in the previous week, high CO_2 concentrations were also recorded on Monday and Tuesday at the north side of LT1. These concentrations suggest that students sitting in both North and South seating areas would experience high CO_2 concentrations and some other discomfort related to IAQ. The maximum CO_2 concentration of 5000 ppm on Tuesday indicates an issue with the ventilation of the lecture theatre, as it is unusually high and nearly 4000 ppm above the recommended ASHRAE level of 1000 ppm. Therefore, the occupants in this area of LT1 would experience discomfort due to the poor IAQ, with insufficient ventilating air to remove body odour or other contaminants.

Carbon dioxide levels build up in the lecture theatre because of occupancy, only to be vented to ambient concentration overnight. The extreme concentration of 5000 ppm suggests that the ventilation system was not efficiently exhausting the stale air during the day. It could also have been that during the monitoring period the ventilation system may have been malfunctioning. However, the arrangement of the ventilation system supply and extract grilles suggests that there is likely short-circuiting of the ventilating air occurring, which would affect the IAQ and comfort of the occupants in the lecture theatre.

Further to variations in CO_2 concentration between monitoring points, differences between the lecture theatre sides were additionally found. Sampling on Friday 21st November on the south side of the lecture theatre had CO_2 concentrations less than 1000 ppm, with the largest concentration measured at approximately 13:00 hrs. This was in contrast to measurements taken on the north side of the lecture theatre on Friday 20th November, where the maximum CO_2 concentrations were approximately 2500 ppm. However, the number of students for both Friday lectures was similar. Therefore, the differences between the observed carbon dioxide concentrations were because of some other factor other than the occupancy number of the room.

6.6 Outcome of sampling with forced air mixing

For the final monitoring period (1st to the 8th December), a mechanical fan was placed at the back of the lecture theatre, facing the seats, in an attempt force the mixing of air. A pedestal fan (with a blade diameter of 40 cm) was positioned at breathing level. The sampling tubes were placed on the south side for seven days. This location was chosen to enable comparison with previously sampled data.

The results analysed in relation to variation in CO_2 concentration between the monitoring points. A Friedman test showed that at 95%

significance level ($p < 0.05$) concentrations in the front middle and back were different during sampling. Analysis of the CO_2 concentration measured at the monitoring points for each lecture again indicated (at 95% confidence level) that there was significant spatial variation between the CO_2 concentrations. Thus, the addition of a fan did not make a significant difference to the mixing of air in the lecture theatre. However due to the volume of the lecture theatre several fans would be necessary to make any difference to the mixing of the air.

6.7 Summary of findings

Figure 6.10 shows the variation in CO_2 during the entire monitoring period. Several peaks in concentration exceed the ASHRAE recommended level of 1000 ppm. These peaks were measured at both sides of the lecture theatre. It thus appears that there are problems with the IAQ and potentially worse occupant comfort for both the seating areas.

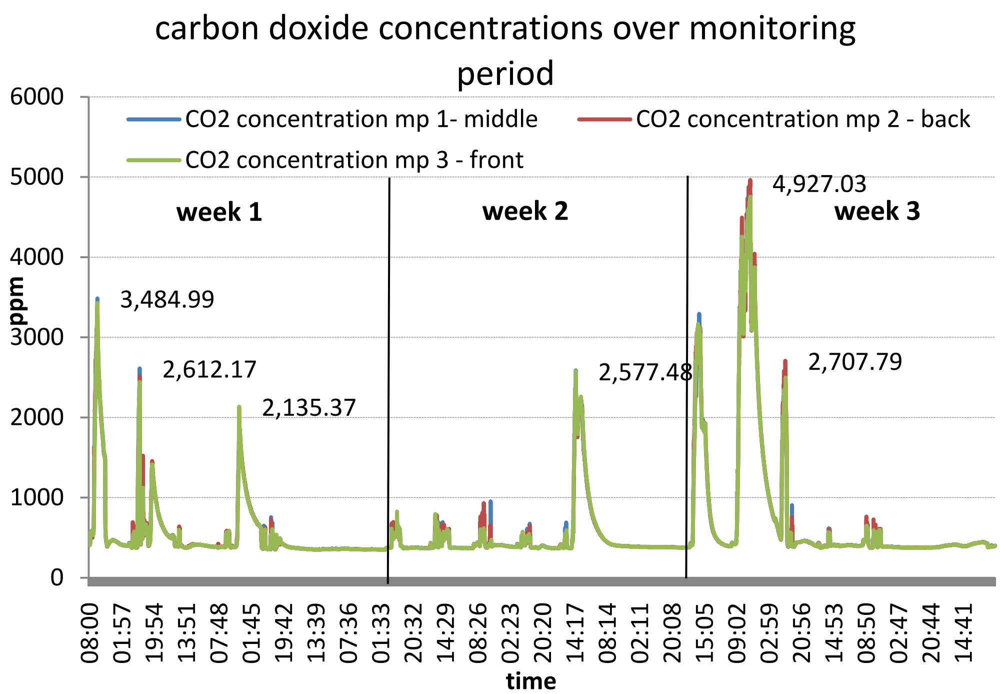


Figure 6.10 CO_2 concentration during the entire monitoring period.

It was found, overall, that the patterns of CO_2 concentration were different for each lecture, even when comparing lectures that had similar numbers of occupants. Carbon dioxide concentration differences were pronounced between both sides of the lecture theatre. These observations suggest that there are basic issues with the ventilation of the room, which was beyond the focus of this research.

It is important to note that these differences do not result from the sampling strategy. The sampling tubes were positioned at the back of the seated occupant, and not directly in the line of exhalation and the high CO_2 concentrations were not recorded just for short time periods. This shows that the readings were not due to an occupant exhaling in the vicinity of the sampling tube.

The spatial variation demonstrated in the example from LT1 is important when assessing IAQ, as it cannot be assumed that pollutant levels are equal at all points throughout a room. The outcomes from the increased amount of empirical data from LT1 verified the non-homogenous theory underpinning the development of the assessment methodology. In order to investigate the applicability of the AQSM to use in a real setting, the following section describes the simulation of two lectures that were monitored in this theatre.

6.8 Examination of the performance of the AQSM

The Mayfield House pilot study findings indicated that indoor air conditions were not well mixed. This was an important observation, as assessment of IAQ in lecture theatres should not assume that air conditions are the same throughout the room. The non-homogenous premise therefore led to the development of an IAQ assessment methodology.

The IAQ assessment methodology formed the basis of an air quality simulation model (AQSM). The AQSM was performed on two separate lectures BE 225 and BE311 that were held in LT1 during the observation period (24th November to 8th December). These two lectures were selected as they corresponded to when the sampling was done on different sides of the theatre (BE 225 sampling on north side, BE 311 sampling on south side). This was in order to have measurement and AQSM data from both sides of the room. For both lectures, the numbers of students were known in addition to their seating location, as it was possible to photograph the class before the start of the lecture (permission from all the occupants was granted). The position where the students sat was needed for entry into the AQSM. The validity of the AQSM was examined by comparing the outcome from the simulations to the measured data. The comparability of the simulation and real data is discussed.

6.9 Operation of the AQSM

The AQSM has different components, which can be fixed or varied according to the parameter being tested. The ventilation rate and supply air temperature can be set in the model and in this instance, for the two lectures used in testing the AQSM, the model variables were the number of occupants and the occupants' seating position.

The AQSM can test what effect changing the ventilation rate has on IAQ in the lecture theatre. A particular airflow velocity can be input into the AQSM and a simulation run. The level of IAQ provided by the chosen airflow velocity can be assessed using the CO_2 concentration output. This operation of the AQSM allows the user to examine, in detail, the effect on IAQ, by experimenting with changing ventilation rates. A ventilation rate can be selected that provides an optimum level of IAQ in the lecture theatre.

The effect on IAQ from the seating position of the students can also be modelled. The AQSM permits the students to be placed in any of the seats in order to model the occupancy profile. The effect on IAQ from different occupant seating densities can thus be assessed. Furthermore, the seating locations in the lecture theatre that receive poor IAQ and are uncomfortable for the students can be importantly identified.

The AQSM required a measured survey of LT1. This survey included the position of the steps, the benches and the seats in addition to the room dimensions. These are detailed measurements were required to construct a replica model of LT1 using the FloVENT software.

In the simulation model of LT1, the properties of the construction material for the walls, floor and ceiling ventilation were assigned. The walls were modelled as plaster covered blocks and the location of the ventilation system grilles, along with the lecture theatre seats and desks were also included.

The CIBSE design guide values for the ventilation rate and supply air temperature were set in the simulation of the LT1 model. These parameter settings were six air changes per hour and 20˚C respectively. Therefore, the indoor conditions in the model represented the design conditions of the lecture theatre.

As part of the data collection the number and position of students was plotted on a room plan and photographed for a back up reference. The occupant positions for both lectures were entered into the model of LT1. This created two versions of the AQSM replicating the student's sitting in each lecture. Thus, two computer models were constructed to provide data to verify the output from the AQSM against the measured values from the lectures. In the following sections, the simulation results from the computer models are compared with the monitored results from the observations.

6.9.1 IAQ Assessment results for lecture one

The initial lecture that was assessed (BE225) using the methodology lasted for two-hours. The lecture started at 11:00hrs on Tuesday 25th November. This lecture occurred during the first sampling period when sampling was on the south side of the theatre. Sixty-three students were seated with one lecturer standing at the front (Figure 6.11). The lecture theatre was 46% occupied and substantially below its design capacity. Accordingly, the IAQ and occupant comfort should have been acceptable.

Figure 6.11 Occupancy seating profile in lecture BE225

The assessment methodology resulted in 64 mini breathing zones (mbzs). These subzones (Figure 6.12) covered the occupied seats and the non-occupied regions of the room (including the middle aisle between the seating blocks). The red line in Figure 6.12 corresponds to the positions where the monitoring points were located when the CO_2 concentrations were measured. Regions that were unoccupied were included in the AQSM because they were in a modelled subzone.

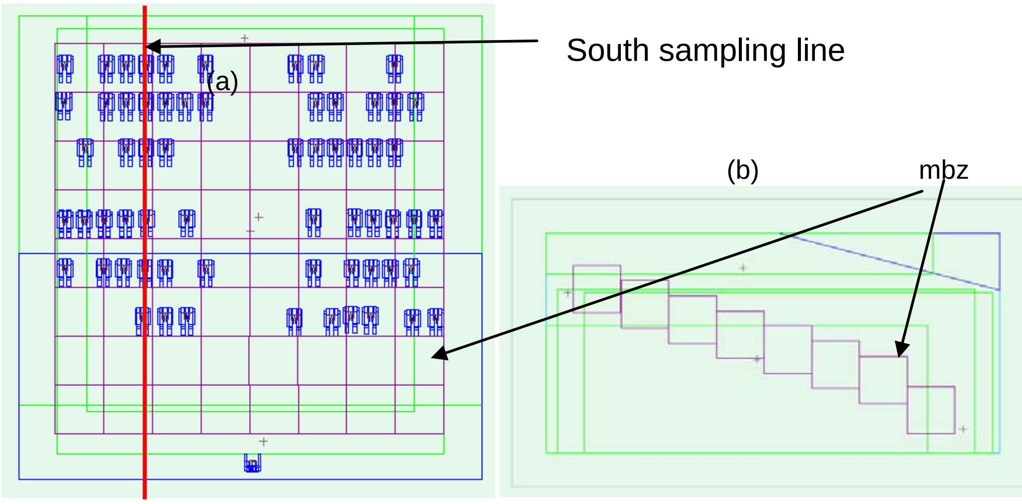


Figure 6.12 Plan (a) and side view (b) of occupants and mbz in model

The IAQ assessment outcomes for lecture one are detailed in the following subsections one and two.

1. Carbon dioxide concentrations

The concentration of CO_2 in a lecture theatre provides an indication of IAQ and an estimation of the occupants' comfort. In addition, CO_2 levels provide information on the effectiveness of the ventilation system in a room.

Applying the AQSM to the lecture resulted in a simulation of the distribution of IAQ. This distribution was reported in terms of CO_2 concentrations and the age of the ventilating air (LMA). The spatial average, maximum and minimum CO_2 concentrations simulated in the model were used to assess the IAQ in the lecture against selected criteria.

The AQSM results for the BE225 lecture in terms of the spatial average maximum and minimum CO_2 concentrations are given in Table 6.4. The maximum and minimum CO_2 concentrations were reported to illustrate the range of concentrations in the breathing zone. To determine which measure of central tendency to use as an average IAQ measure, a frequency plot of the data was constructed (Figure 6.13.).

Variable	Mean	StDev	Variance		
CO_2ppm	489.00	57.84	3345.98		
	Median	IQR	Maximum	Minimum	Range
	389.78	502.39	599.24	94.25	209.47

Table 6.4 CO_2 simulation results summary

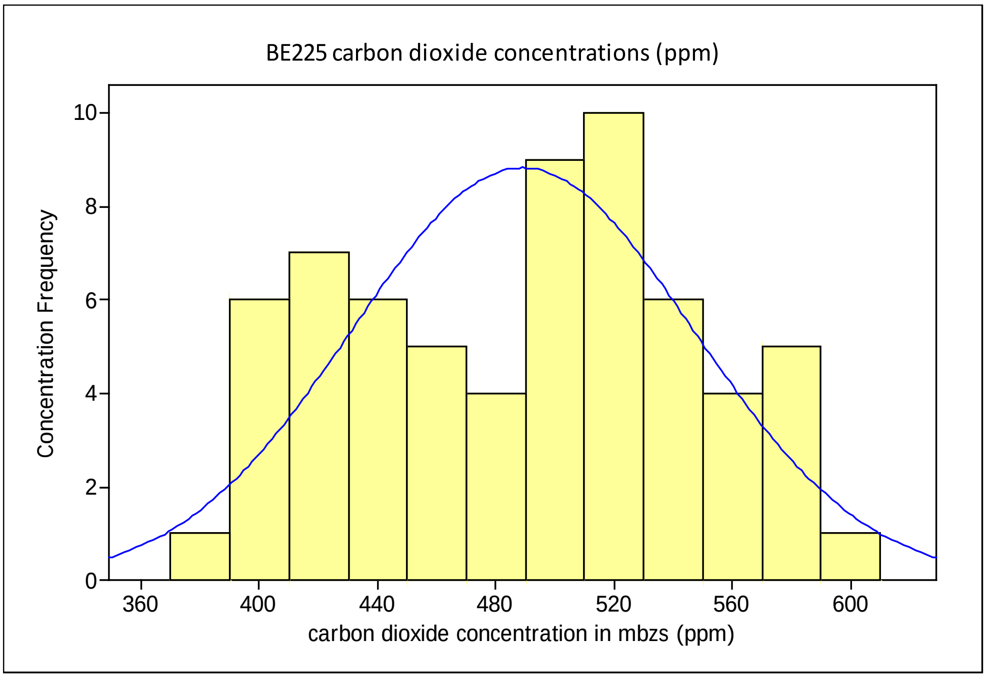


Figure 6.13 CO_2 frequency plot for lecture BE225

The frequency plot (Figure 6.13) of the CO_2 concentrations over the breathing zone showed that the data was not symmetric. The range between the maximum (599 ppm) and minimum (390 ppm) CO_2 concentrations highlighted the spread and uneven distribution of concentrations. This non-symmetric distribution was confirmed by using an Anderson Darling test for normality at a 95% confidence level ($p < 0.05$), which indicated that the data was nonparametric. For this reason, the median was used as the measure of central tendency.

The occupancy of the lecture theatre was 46% with a spatial average CO_2 concentration in the breathing zone of 503 ppm. This was within the recommended ASHRAE guideline of 1000 ppm. Using the average CO_2 concentration from the AQSM, the predicted IAQ was therefore acceptable.

The variation of the CO_2 concentrations in the different regions in the lecture theatre was examined further by plotting the data in three dimensions. The occupants were located approximately equally in both seating blocks. However, the front two rows of the lecture theatre were unoccupied, while the middle to back regions had the highest occupant density.

Examination of the spatial distribution (Figure 6.14) highlighted locations with high CO_2 concentrations. Given, however, that the occupants were sitting in roughly similar positions on each side of the lecture theatre, the south side had higher CO_2 concentrations. Despite similar occupant seating patterns in this lecture, occupants sat on the north side of the room received better IAQ, and therefore were more comfortable.

During this lecture, the theatre was approximately half-full, so the expected IAQ should have been acceptable. The AQSM confirmed that the IAQ was acceptable as the predicted CO_2 concentration was within the recommended ASHRAE guideline of 1000 ppm. Importantly, even though the students were sitting symmetrically in the lecture theatre, the IAQ distribution was asymmetric. Thus, students sitting on the north side seating block experienced lower CO_2 concentrations.

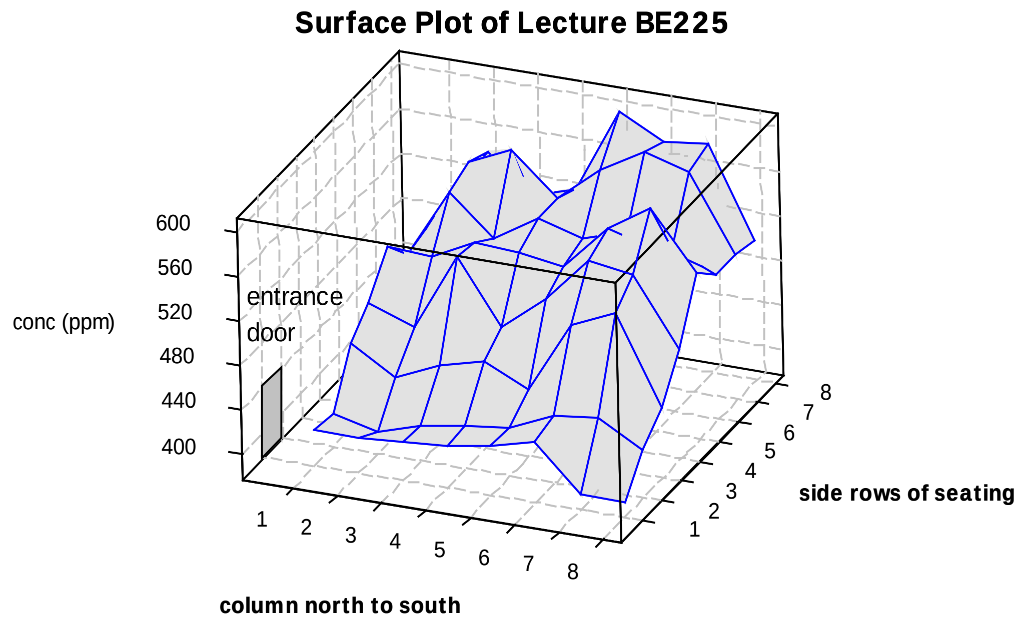
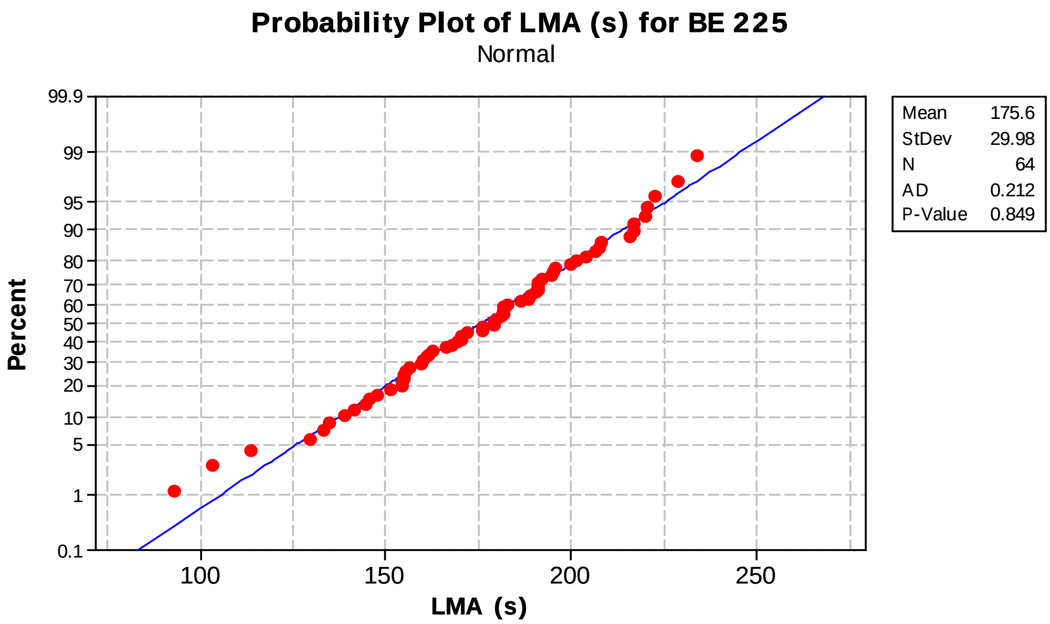


Figure 6.14 Spatial distribution of CO_2 in the lecture

2. Local mean age of air (LMA)

An ideal ventilation scenario was for the students in the lecture theatre to receive outside fresh air that had ambient concentrations of CO_2. In order to measure the ventilation system efficiency, the delivery pattern of fresh air to the breathing zone was examined using the LMA. The LMA distribution in the lecture was analysed to indicate the regions in the lecture theatre that received the freshest air.

The supply and exhaust grilles in LT1 are symmetrically arranged in the ceiling. Analysis of the LMA distribution using an Anderson Darling test (Figure 6.15) found that the distribution was normal at a 95% confidence level (p=0.849). Therefore, in theory the supply air was delivered symmetrically to both sides of the lecture theatre. This LMA simulation outcome and the symmetrical arrangement of ventilation grilles was not however reflected in the LMA three-dimensional plot (Figure 6.16).



population is normal

Figure 6.15 Normality test of LMA for lecture BE225

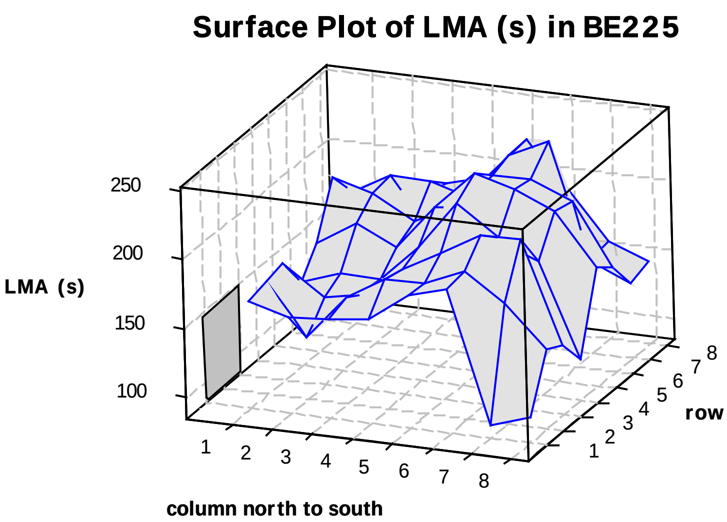


Figure 6.16 Three-D plot of LMA

The influence occupants have on the delivered air was seen in the spatial LMA three-dimensional plot. The oldest air in the breathing zone occurred in the seating south of the aisle from the middle to the back of the lecture theatre. The south side of the lecture theatre had more pronounced peaks and troughs of LMA. Therefore, air on this side of the lecture theatre had a relatively uneven age, and occupants sitting here would receive variable levels of IAQ and comfort.

The IAQ assessment of this lecture satisfied the ASHRAE threshold CO_2 concentration of less than 1000 ppm. Students were sitting in similar positions at both sides of the lecture theatre but the assessment illustrated that the freshest air, with lower carbon dioxide concentrations, occurred in the north side seating area. Thus, the LMA distribution findings backed up the CO_2 observations and indicated that students sitting in the north side received the freshest air and that the ventilation was the most efficient in this region of the lecture theatre.

6.9.2 Comparison of modelled and monitored CO_2 concentrations

The capabilities of the AQSM for indicating IAQ and occupant comfort in a lecture theatre were evaluated. The AQSM output from the modelled lecture BE225 was compared with CO_2 measurements taken during the actual lecture. The comparability of the model output to the actual measurements is reported.

The performance of the AQSM for BE225 was compared with monitored data. The existing CO_2 data was sampled from the south side of LT1 previously described in Section 6.4. Lecture BE225 occurred on Tuesday 25th of November and had 64 occupants (46% occupied). The lecture theatre therefore was only half-full, and the IAQ should have been acceptable.

The variation in CO_2 concentrations between the three monitoring locations are illustrated in the graph (Figure 6.17). During this lecture, the lowest CO_2 concentrations were measured at the front of the lecture theatre, with the middle and the back locations having higher concentrations. As a result, students sitting towards the front of the south side of the lecture theatre received air to lower CO_2 concentration compared with the other locations. This suggested that these students were sitting in a location where IAQ would be better.

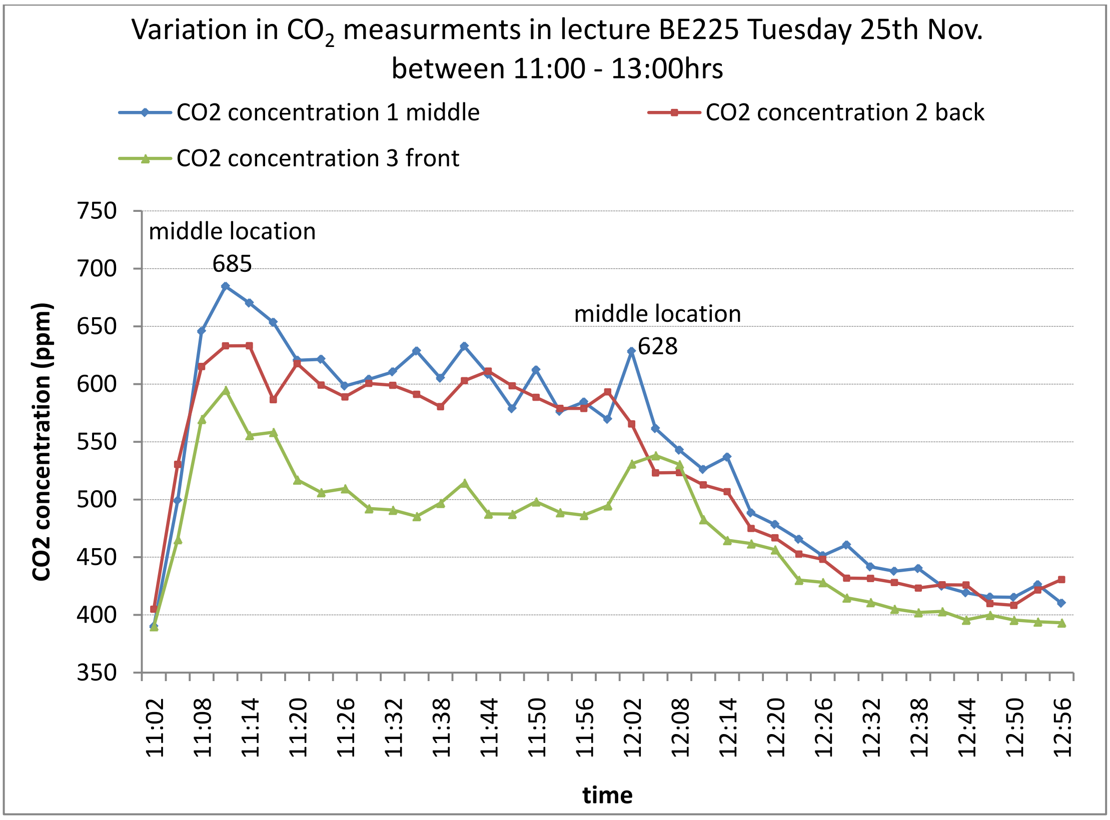


Figure 6.17 Variation of CO_2 between monitoring points

The AQSM results were arranged in a spreadsheet format that represented the grid of mini breathing zones (mbz). In order to investigate whether the results from the AQSM showed a similar pattern to the actual results, a contour plot was drawn. The resultant two-dimensional plot of CO_2 concentrations for each mbz therefore represented the breathing zone plane in the lecture theatre.

The corresponding monitoring points were superimposed onto the contour plot of simulated CO_2 concentrations to compare with the measured CO_2 concentrations (Figure 6.18). This contour plot illustrated that the middle and back seats on the south side of the lecture theatre had the highest CO_2 concentrations (>560 ppm). These seating regions received less ventilation compared with the rest of the lecture theatre. Although the CO_2 concentration is not a health issue, the simulation indicated that there is non-uniform ventilation of the room which could lead to occupant discomfort.

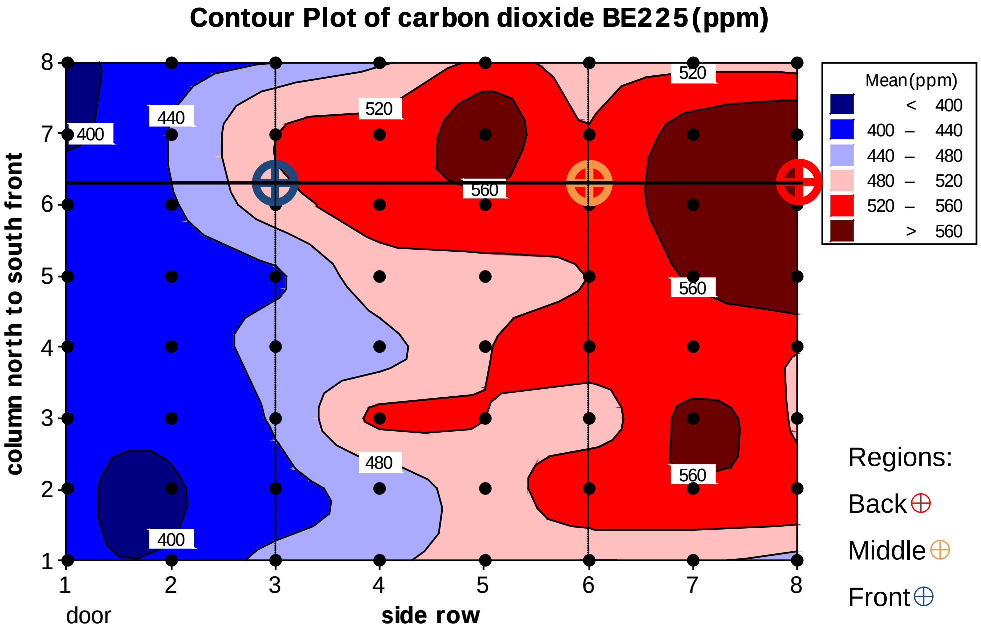


Figure 6.18 Planar CO_2 concentrations plot from AQSM

The comparison of measured and simulated CO_2 concentrations is summarised in Table 6.5. The average CO_2 concentrations were calculated from the measurement during the two-hour lecture. The median was used to represent the measured data due to the unsymmetrical CO_2 concentration distribution.

The range of the CO_2 concentrations at the front and middle of the lecture theatre simulated by the AQSM agreed with the monitored data. The measured CO_2 concentration at the back was slightly below the predicted range. Nevertheless, the AQSM results were within the same order of magnitude, and hence comparable with the measured results.

Monitoring location	Measured CO_2 Average, interquartile range	AQSM CO_2 range
Front	486, 412-509	480-520
Middle	552, 441-611	520-560
Back	530, 432-597	>560

Table 6.5 Comparison of CO_2 data for BE225

Further verification of the AQSM is demonstrated by the comparison of the average CO_2 from the monitoring points, with the simulation result for the overall CO_2 concentration in the breathing zone. The AQSM calculated the overall CO_2 concentration for the breathing zone as 503 ppm. The average CO_2 concentration for the sampling on the south side was 499 ppm. These two concentrations were close in value and indicated that the AQSM results were comparable with the measured CO_2.

The AQSM results for the LMA were able to give an indication of the pattern of the ventilating air. The variation of LMA on the south side of the lecture theatre was consistent with the pattern of CO_2 concentrations. Although the grille configuration was symmetrical about the room centre on the south side of the room, the simulated airflow pattern from the ventilation system was clearly different. Students were sitting in similar positions on both sides of the lecture theatre, and therefore presented similar obstructions to airflow. However, the LMA plot indicated that fresh air and thus the IAQ, was more variable on the south side.

The empirical data and results from the modelling of this lecture were comparable. The measured data illustrated the variation in CO_2 between locations in the lecture theatre over time. The assessment methodology allowed the IAQ to be represented in different formats, described statistically and portrayed in spatial plots.

In conclusion, the performance of the AQSM in a real world situation was examined using lecture BE225. The CO_2 concentrations predicted by the studies suggest that the AQSM were comparable to those measured in the real lecture. The AQSM was therefore capable of indicating the IAQ and the comfort of the occupants in the lecture theatre.

6.9.3 IAQ assessment results for lecture two

In order to investigate further the operation and validity of the AQSM in predicting IAQ in a lecture theatre, a different lecture was assessed. The developed assessment methodology was applied to a lecture that occurred in LT1 on the final Friday of the monitoring period. An AQSM was made of this lecture in order to assess the IAQ in the theatre during this class.

The lecture that was assessed started at 16:00 hrs and was timetabled for two hours. This lecture BE331, was the last class for that day so the room would have been effectively ventilated throughout the day. The total number of occupants was 59, which again meant that the lecture theatre was approximately half-full as was the case for BE225. Thirty-one students were sitting at the north side of the room (Figure 6.19) and 26 students sat at the south side. The number of students was similar between the seating sides but their spatial pattern was irregular.

The details of the lecture BE 311 were entered into an AQSM. The positions and volumes of the mini breathing zones were the same as the previous assessment of lecture BE225. The physical room characteristics were not altered. The AQSM for BE311 was similar to the model of BE225 except for a different occupancy seating profile, in terms of the position and number of students. Hence, the main difference between the models for each lecture was the positions where the students were sitting, as all the other variables and settings in both models were the same.

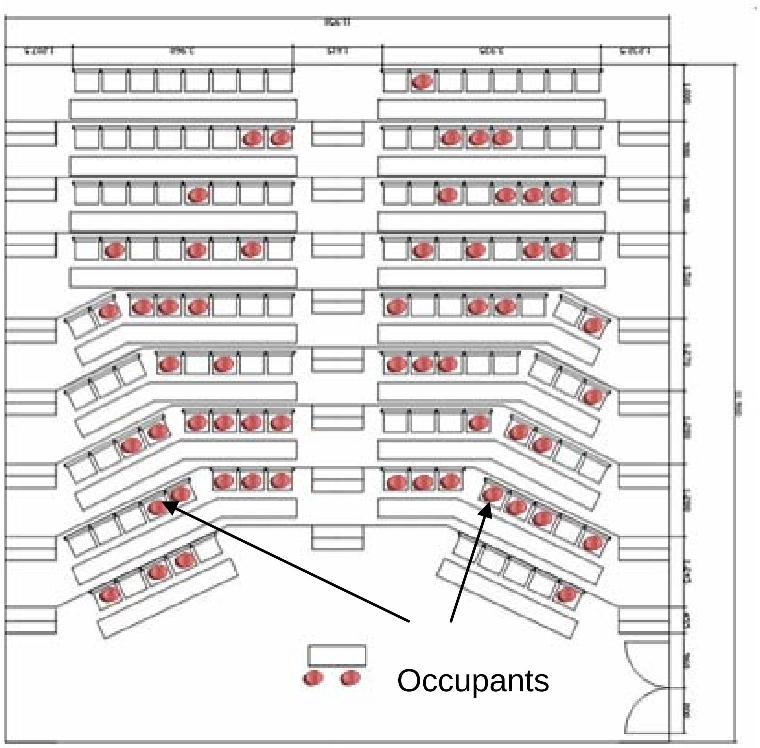


Figure 6.19 Occupancy seating profile for BE 311

A simulation for BE311 was performed. The CO_2 and LMA values for this lecture scenario were calculated by the software in the AQSM. A prediction of the IAQ and airflow pattern in the breathing zone for lecture BE311 was determined. The analysis of the data follows in subsections one and two.

1. Carbon dioxide concentration

A statistical analysis of the carbon dioxide concentrations found that the CO_2 concentration in the mini breathing zones was normally distributed. The symmetry of the distribution is shown in the concentration frequency histogram (Figure 6.20).

The AQSM for the lecture BE311predicted the overall CO_2 concentration in the breathing zone as 498 ppm. This satisfied the ASHRAE criteria of 1000 ppm. The IAQ for this lecture was therefore acceptable, and the occupant comfort in the theatre should not be an issue.

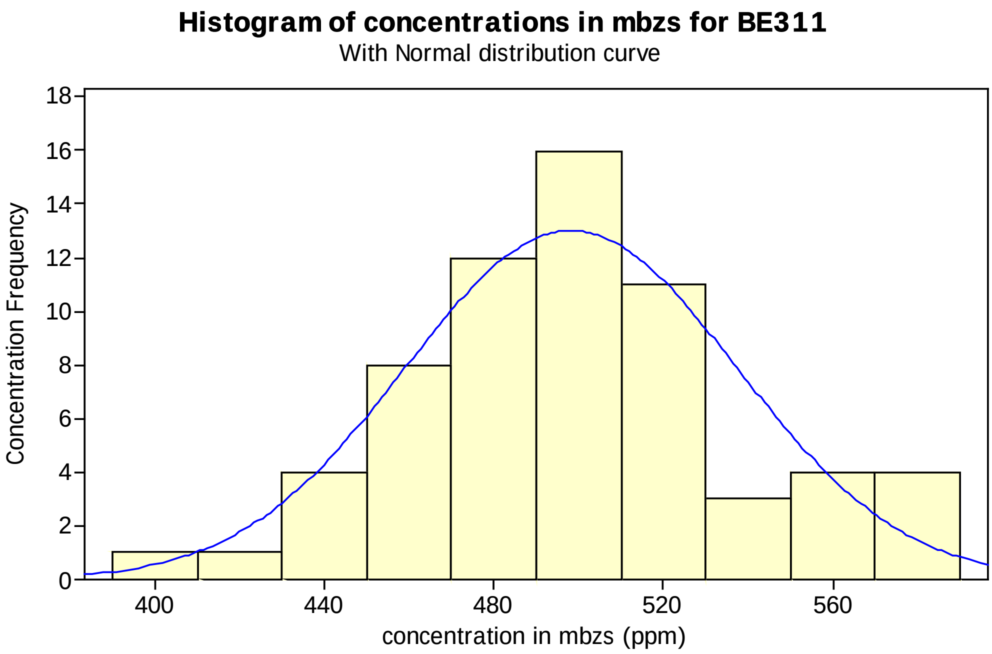


Figure 6.20 Distribution of carbon dioxide concentration in mbzs

The raw CO_2 data output from the AQSM was symmetrical. To determine if the CO_2 distribution was symmetrical in relation to the students seating position, a three-dimensional spatial graph was plotted from the AQSM output (Figure 6.21). This plot illustrated the variable CO_2 distribution in relation to the occupant seating positions. That meant that the IAQ was different between seating positions. Because of this, certain seats received a better quality of air with less discomfort.

In this lecture, the second and third rows from the front at the south side of the lecture theatre had the most number of students. This was not reflected in the three-dimensional surface concentration plot as the corresponding regions had relatively low CO_2 concentrations. Hence, in these front rows the ventilation system simulation efficiently moved the air away from the occupants and replaced it with supply air as per its design. Furthermore, even though more students were sat in this location, these seats received better IAQ and the comfort of the individuals setting there was unlikely to be compromised.

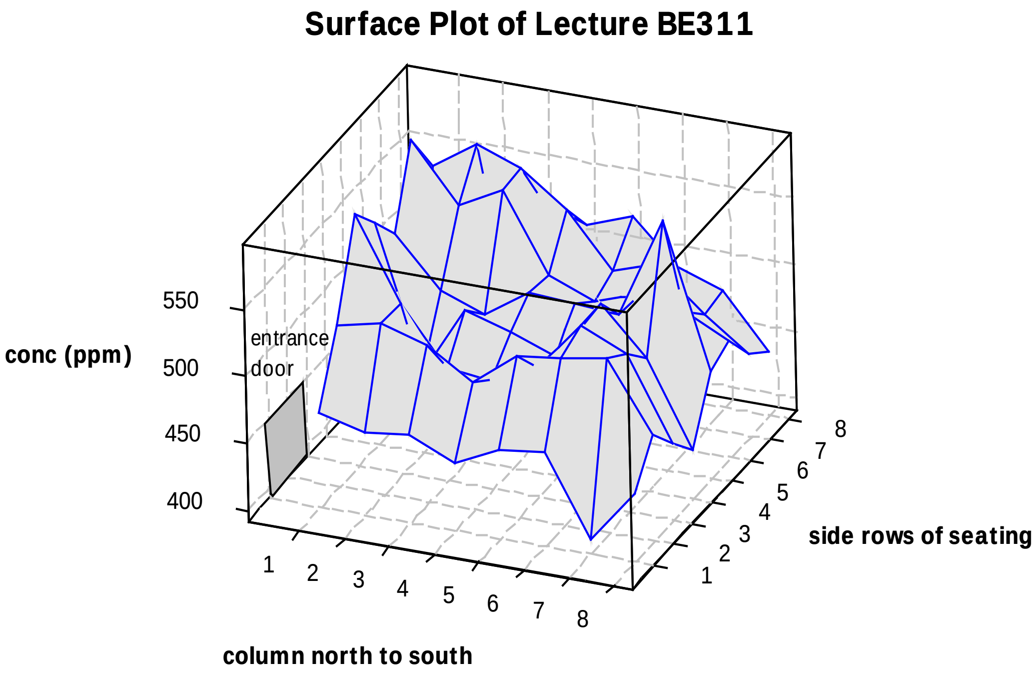


Figure 6.21 3-D representation of CO_2 concentrations

In the case of the densely occupied front rows in lecture BE331, the IAQ mapping from the AQSM results clearly illustrated an advantage of this assessment methodology. Using a homogenous assessment approach would miss the observation of acceptable IAQ in the densely occupied seating region; as such, an approach assumes that the level of CO_2 is uniform throughout the room. This importantly demonstrates the potential of the developed assessment methodology as a practicable tool for designing lecture theatres with efficient ventilation arrangements to deliver acceptable IAQ and occupant comfort.

2. Local mean age of air

The airflow from the ventilation system was examined using the local mean age of air (LMA). The LMA pattern in the breathing zone during the lecture BE311 was plotted in three dimensions. The simulation allowed the areas of seating that received the freshest air to be identified.

In the model of the lecture theatre, the major variable was the occupant seating pattern. During the modelling of this lecture, the ventilation rate remained at six ACH. Thus, any difference in the LMA pattern would be expected to result from a change in obstructions to airflow resulting from the different seating pattern.

The distribution of LMA for BE311 was normal, as it was for the previously assessed lecture (BE225). There was sufficient statistical evidence, ($p = 0.229$) at a 95% confidence level to suggest that both lecture LMA distributions were the same. This indicated that the ventilation system was consistently supplying the same levels of fresh air to the lecture theatre.

Air with the lower age is the freshest as it has occupied the room for the least amount of time. From the LMA plot (Figure 6.22) it can be seen that the densely occupied front rows of the lecture theatre had relatively low LMA values. Examination of the less sparsely occupied regions towards the back of the room showed that these locations also received similarly fresh air.

On the other hand, the CO_2 three-dimensional plot suggested that the regions toward the back of the lecture theatre were less comfortable even though they had a low LMA value. This result indicated that an IAQ judgement therefore cannot be solely based on the age of air. Thus, the assessment of IAQ must be made by examining both the LMA and CO_2 concentration simulation data.

The outcome from applying the assessment methodology to this lecture was a representation of the spatial IAQ in terms of LMA and carbon dioxide concentration distribution. The overall spatial IAQ average indicated an acceptable level of IAQ in the room during the lecture, and regions of possible discomfort were importantly identified from the AQSM output. Consequently, a detailed IAQ assessment was performed.

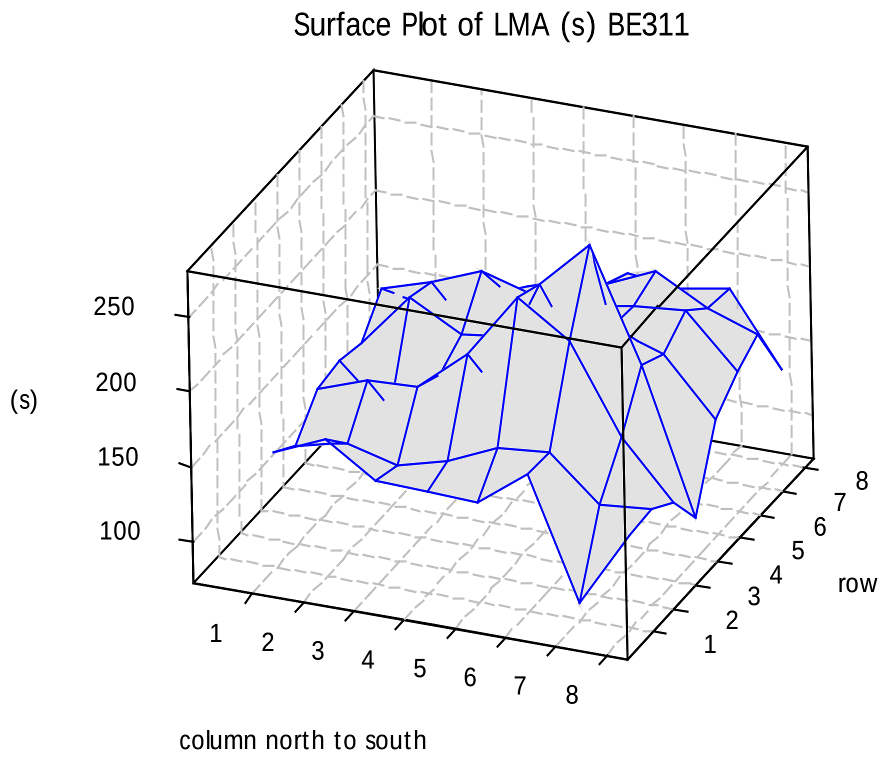


Figure 6.22 3-D plot of LMA for BE311

6.9.4 Discussion

The assessment methodology was applied to lecture BE311 to investigate further the validity of the methodology in an actual, but different situation. A corresponding AQSM was made of BE311, and a simulation was conducted. The output from the model is discussed as follows.

As with the assessment of lecture BE225 the performance of the AQSM for BE311 was compared to actual measured data. The lecture was timetabled for two hours, but it did not last that long. This can be seen from the CO_2 measurements (Figure.6.23) which increased from 16:00 hrs, then decreased after 17:05 hrs. For this reason, it was assumed that the lecture lasted for an hour.

Figure.6.23 shows that the sampling point in the centre of the seating block had the highest CO_2 concentrations with time. Nevertheless, all three measurements followed a similar pattern with a narrow band of CO_2 concentrations (550 to 600 ppm) that lasted for approximately one hour. The CO_2 measurements during this hour appeared stable and accordingly, this period was used in the comparison of the AQSM results with the measured data.

For lecture BE311, sampling occurred with a fan present on the south side of room. The fan was included this week in an attempt to force an increased mixing of the air in the lecture theatre as an aid to the installed ventilation system. During this lecture, the back and middle locations followed a similar CO_2 concentration pattern. The front sampling location however, showed lower concentrations. As a result, occupants sitting at the front of the lecture theatre would have received a better IAQ.

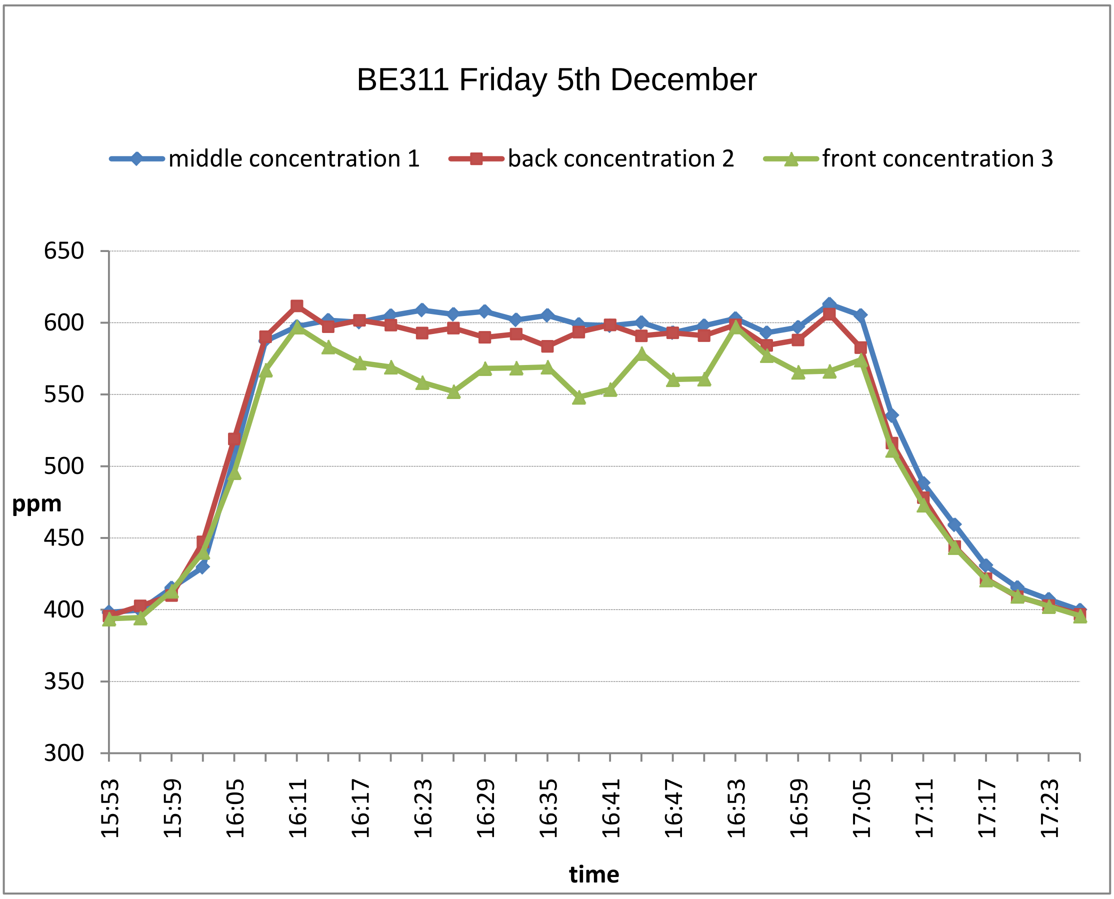


Figure.6.23 Monitored CO_2 concentrations at the sampling points

The data set for the lecture BE311 showed that the average spatial CO_2 concentration was 531 ppm. The AQSM predicted a spatial average CO_2 concentration for the breathing zone as 498 ppm. Both these results indicated that the IAQ was acceptable during the lecture but they differ by 33 ppm. However, the result from the AQSM was for the entire breathing zone in the lecture theatre, whereas the monitored CO_2 concentrations were sampled from the breathing zone on one side of the room.

The spatial average CO_2 concentration simulated by the AQSM, was not much higher than the measured breathing zone concentration. The comparison is not straightforward however, as there the real measurements are recorded against time, whereas the time component in the modelled results is a parameter included in the fluid dynamic equations. Nevertheless, the AQSM predicted acceptable IAQ in agreement with the measured results.

In order to explore the AQSM output further, a comparison of the simulated and actual results was made by plotting the AQSM output as a planar contour plot (Figure 6.24). The monitoring locations were marked onto matching positions on the contour plot in order to determine if the AQSM results agreed with the measured CO_2 concentrations.

Using the sampled measurements, the one-hour lecture duration was used to average a CO_2 concentration at each of the three locations. The average CO_2 concentration at each monitoring point was compared with the corresponding AQSM results indicated on the contour map (Table 6.6). The simulated CO_2 concentration ranges from the AQSM for the monitored locations corresponded to the measurements at the front and middle of the theatre, but the range at the back location was slightly below the measured result. Nonetheless, the simulated CO_2 concentrations were generally come parable to the measured data. The contour map of CO_2 concentrations determined by the assessment methodology illustrated a spatial variation that corresponds to the non-homogenous principle.

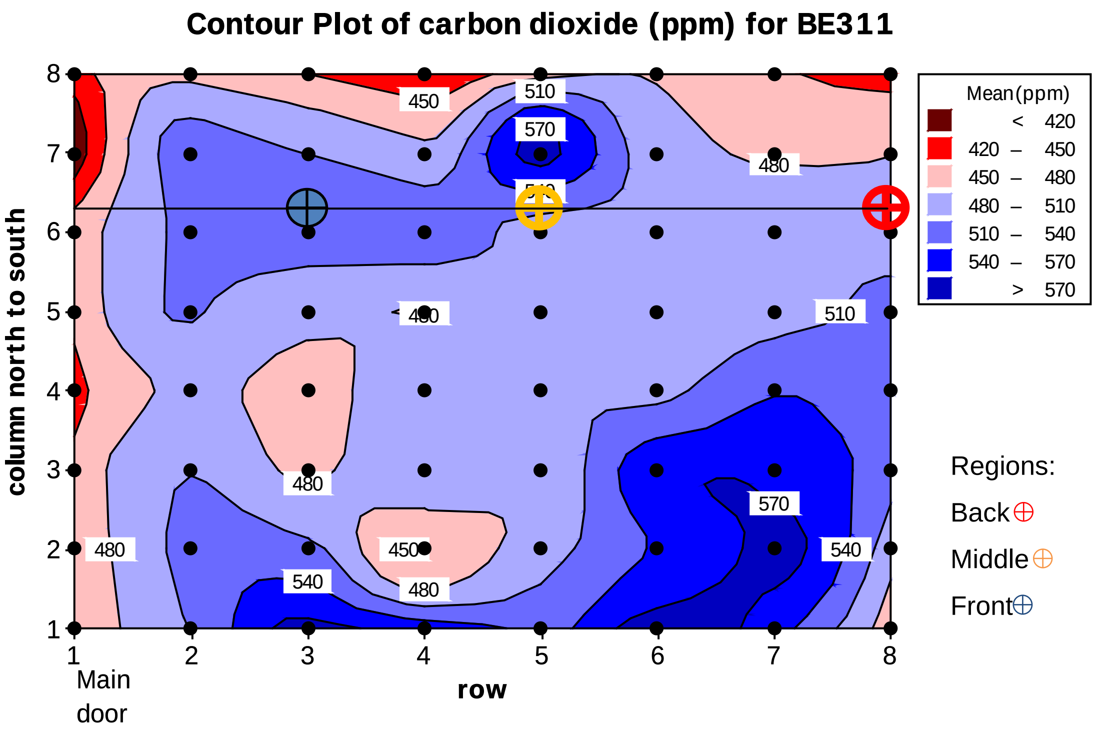


Figure 6.24 Planar contour plot of mbz carbon dioxide concentrations

Monitoring point location	Average measured CO_2 concentration and interquartile range	Corresponding AQSM CO_2 concentration range
Front	518, 394-568	510 - 540
Middle	541, 395-601	510 - 540
Back	535, 393-593	480 - 510

Table 6.6 Comparison of CO_2 data for BE311

The modelled CO_2 concentrations were of the same order of magnitude as the measured data. It is argued that the modelled output is as accurate as the measured concentrations. Thus, the AQSM produced a simulated representation of the CO_2 concentrations for this lecture, which were similar to the assessment outcome of the monitored CO_2 concentrations.

6.10 Appraisal of the AQSM

In order to examine the AQSM output against an established IAQ assessment approach (the decay equation), two IAQ assessment exercises were carried out. The reliability of the established IAQ assessment methodology to a lecture theatre was investigated by comparing its IAQ assessment result to the data measured in LT1. Furthermore, the results from the developed assessment methodology were compared with the results from the decay equation approach in order to further verify the developed AQSM.

6.10.1 Comparison of the measured findings with the decay equation

The decay equation IAQ assessment methodology uses a simple mass balance formula. This equation is an exponential decay equation and was discussed in Section 2.7.1.2. The equation assumes that air in the space being assessed is homogenous. This equation is a recognized method for assessing IAQ. However, the validity of this approach to a lecture theatre is challenged in this research. The following subsections describes the IAQ assessment using this approach to a monitored lecture session.

1. IAQ assessment using the decay equation

The aim of this exercise was to compare the CO_2 concentration calculated by the decay equation to the CO_2 measured during monitoring in LT1. The particular formula used was Equation (3). This mathematical relationship assumes that the room is initially free of respiratory CO_2. The number of occupants, room volume and ventilation rate are the variables, which are entered into Equation 3. The equation outcome is a single CO_2 concentration for the room, which therefore represents the IAQ for the room assessed.

$$c = \left[\frac{10^6 V_c}{Q'} + c_a \right] \left(1 - e^{-n}\right)$$ Equation 3

The decay equation terms can be rearranged for the conditions that occur in the room. For instance, if the initial CO_2 concentration was c_0, a number of people were present, and the ventilating air had a CO_2 concentration of c_a then the equation can be written including these parameters (Appendix A contains further detail). However, Equation 3 does not include the initial CO_2 concentration of the lecture theatre that is being assessed. This is because the initial CO_2 concentration in the lecture theatre is considered as an unknown. A generic ambient CO_2 concentration (c_a) of 350 ppm was used in the calculation as the background level of CO_2 in the lecture theatre. However, this concentration was used for figurative purposes only, as an ambient concentration of around 400 ppm or higher is frequently quoted.

During the air quality-monitoring period in LT1, the number of occupants in each lecture was recorded where possible. Before the lecture began, a head count of students and staff entering LT1 was made. In order to include late students, counting continued for 20 minutes into the lecture.

The occupancy profile of LT1 was established for two purposes. The number of occupants was required to calculate (using Equation 3) a theoretical carbon dioxide concentration for each lecture. The second reason for recording the occupant number and seating position was for inclusion in the two AQSMs.

The theoretical CO_2 concentrations for separate lectures were calculated by inputting the number of occupants for each lecture into the equation. The results from Equation 3 were compared with the average measured CO_2 concentrations recorded from the three monitoring points in LT1. The data comparisons were to assess whether the CO_2 concentrations from the decay equation reflected the real CO_2 concentrations measured in the lectures, and therefore establish the validity of this assessment approach to a lecture theatre.

2. Results and discussion

The three-week monitoring period in LT1 illustrated the variable nature of the CO_2 concentrations (Figure 6.25). The high CO_2 concentrations measured on the Monday in week three suggest a problem with the performance of ventilation system and make it problematic to compare the monitored and calculated CO_2 concentrations. The data however did illustrate the variability of the CO_2 concentrations caused by the characteristics of the room, and that concentrations occurred that were substantially above the design ideal.

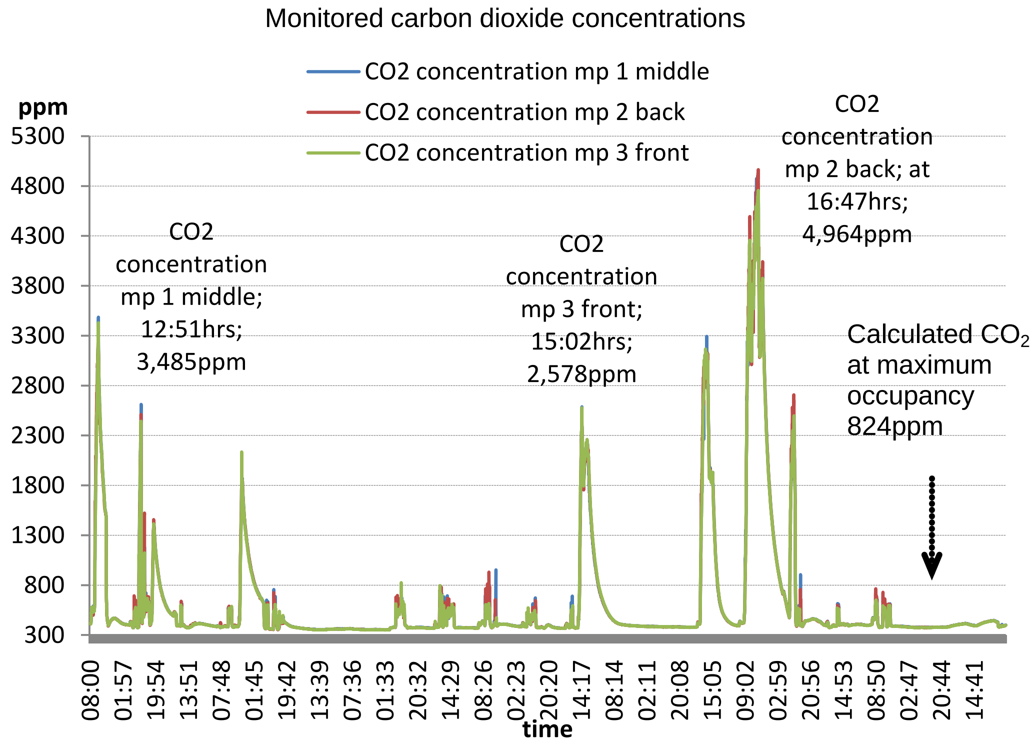


Figure 6.25 Monitoring period showing the calculated maximum CO_2 concentration

Lecture theatre 1 has a maximum occupancy of 138. Using this number of occupants in the decay equation, the maximum CO_2 concentration in the room was calculated as 824ppm. This concentration was calculated using the recommended ventilation rate of six air changes per hour.

However, approximately half the number of lectures had measured CO_2 concentrations that exceeded the maximum concentration calculated using an occupancy of 138 in Equation 3 (Figure 6.25).

As some of the monitored lectures had extremely high CO_2 concentrations, certain lectures were used in the comparison of the decay equation IAQ assessment to that measured. Figure 6.26, shows the contrast between the calculated and measured concentrations for lectures where the occupancy number was known and where the CO_2 monitored concentration was not excessively high. The discrepancy between the calculated concentrations and the average measured values can be seen in the graph (Figure 6.26). The decay equation either over or under reports the CO_2 in the lecture theatre when compared to the average concentration measured in the separate lectures. Therefore, the difference between the measured and calculated CO_2 concentrations for the lectures highlighted an uncertainty in the IAQ assessment using Equation 3.

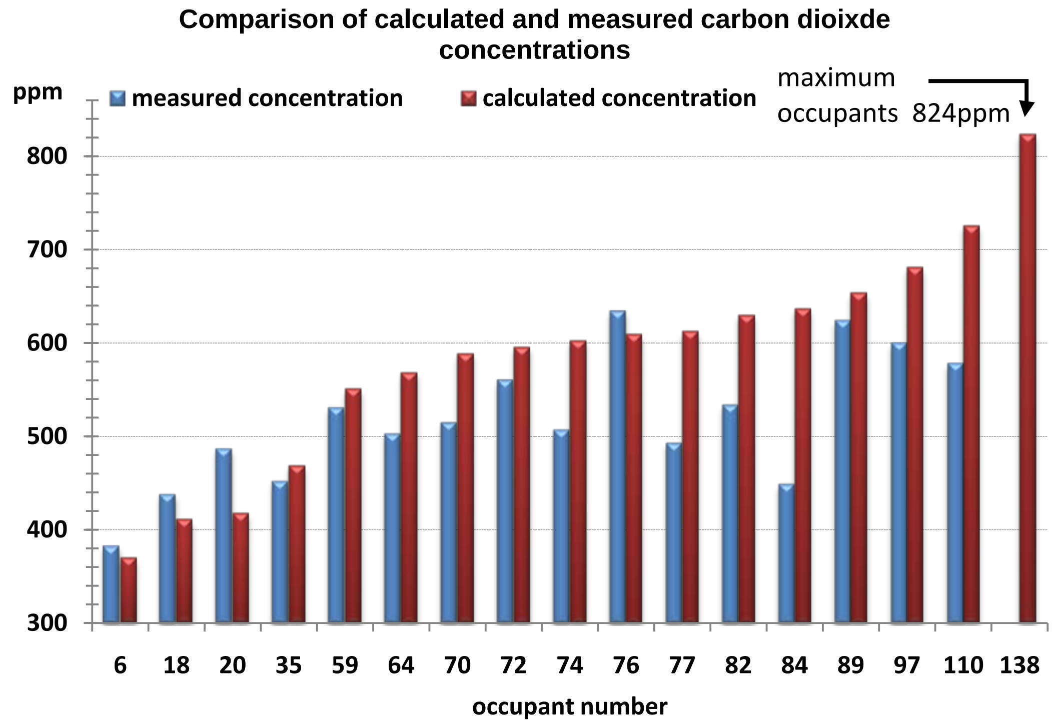


Figure 6.26 Comparison of measured and calculated CO_2 concentrations

The decay equation assessment methodology (using Equation 3) assumes the entire lecture theatre has a uniform CO_2 concentration. Applying this IAQ assessment methodology to LT1 gave an assessment outcome which either over or under estimated the measured CO_2 concentrations. For this reason, using the decay equation in an IAQ assessment of lecture theatres is inappropriate, as the IAQ, and hence comfort of the occupants, would be inaccurately assessed.

6.10.2 Comparison of IAQ assessment methodologies

The performance of the AQSM was further examined to substantiate its validity in an IAQ assessment of the lecture theatre. The IAQ assessments from the AQSM for lectures BE225 and BE311 were compared with the IAQ assessment of these lectures using Equation 3, and the measured CO_2 concentrations. The comparison was conducted to establish a benchmark for judging the accuracy of the results from the AQSM against an established IAQ assessment methodology.

The lecture theatre was occupied by other classes before the modelled lectures (BE225 and BE311) took place. The occupancy numbers for the preceding classes were known. Thus, it was possible to calculate the level of CO_2 using Equation 3 for the modelled lectures.

The results from each of the assessment methodologies are shown in (Table 6.7). The measured CO_2 concentrations were included as a baseline for the comparison of data. The CO_2 concentration calculated using the decay equation (Equation 3) was consistently higher than the measured CO_2 concentration for each of the five lectures, on the two different days. It appeared that assessing the IAQ using this methodology over calculated the measured IAQ level.

As Equation 3 over predicts the CO_2 concentration, using this IAQ assessment method to specify a ventilation rate capable of delivering acceptable IAQ, would lead to over ventilation of the lecture theatre. A higher than required ventilation rate would increase the energy demands of the ventilation system, whereas a lower ventilation rate would still provide acceptable IAQ.

The CO_2 concentrations from the AQSMs are closer to the measured concentrations than the concentrations calculated using Equation 3. This is especially the case for lecture BE225 where the average measured and predicted IAQ was different by four ppm. The results from the AQSM were more comparable to the measured results than the calculated outcomes. This demonstrates the capability of the AQSM to provide a realistic IAQ assessment.

Number of occupants	Calculated CO_2 concentration from equation 3	Average measured CO_2 concentration at locations in the breathing zone	AQSM spatial average CO_2 in breathing zone
Tuesday 25th Nov			
110	728	634	-
64 BE225	570	499	503
Friday 5th December			
76	611	436	-
70	590	532	-
59 BE311	553	498	531
Max 138	824	-	

Table 6.7 Carbon dioxide concentration by assessment method

The variation in IAQ that was found to occur in lecture theatres was not portrayed using Equation 3. Additionally, the AQSM considers the IAQ assessment in the breathing zone and allows the spatial pattern of CO_2

concentration to be assessed in detail. As a result, the use of the assessment methodology gave a more representative prediction of expected air quality in the lecture theatre and thus an improved prediction of the occupant comfort.

6.11 Conclusions

The measurement over a period of three weeks of CO_2 concentrations in LT1 showed a clear pattern of variation. The empirical data showed that there was a spatial variation of IAQ in the lecture theatre, and reinforced the non-homogenous premise that underpins the IAQ assessment methodology.

The measured CO_2 concentrations at each location varied. Each location only approached steady CO_2 concentrations, when the CO_2 concentrations decayed close to ambient levels during extended periods of non-occupancy. These periods occurred overnight, and at weekends, but never during occupied times. For this reason, to base any form of IAQ assessment on the assumption that there is an instantaneously even distribution of CO_2 concentrations is a flawed approach and can compromise the occupants' comfort in the lecture theatre.

The AQSM developed in this study was capable of portraying a spatial IAQ pattern in a large lecture theatre (LT1). The portrayal of a spatial IAQ pattern was not practical use in physical data, as the number of sampling points was a limitation when collecting empirical data. The AQSM does not have this constraint; as if more simulation points are required, additional subzones can be added to the model.

For this reason, the AQSM has an advantage over a measurement procedure. If required, a very detailed spatial portrayal of IAQ can be produced, which would be useful if assessing the IAQ at the local level, for instance, where occupants are seated in proximity to potential pollutant sources such as printers. Thus, the AQSM can be tailored to specific IAQ assessment needs without necessary requiring complex physical environment monitoring.

Importantly, the assessment of the IAQ using Equation 3 does not reflect any spatial variation in the CO_2 concentration or illustrate those regions in the space where maximum IAQ values occur. Additionally Equation 3 was shown to either over or under estimate the CO_2 concentration in the lecture theatre. In addition, this assessment method does not give an indication of the variability of the CO_2 concentration in the room. The calculated carbon dioxide concentrations are for the entire space, including the unoccupied regions, which do not need assessment. In contrast, the AQSM assesses the breathing zone, which is the most important region of the room.

The methodology focuses entirely on assessing IAQ in the breathing zone. Regions outside of this zone are not important from the point of view of the occupants comfort and experience of IAQ. For this reason, when compared with mass balance calculations, the assessment methodology improves the approach to IAQ investigations in lecture theatres.

Given the layout and size of lecture theatres, the extent of inaccuracy using Equation 3 suggests that this approach is inappropriate for such spaces. Assessing IAQ using this method may be acceptable for small rooms but large spaces are outside its boundary of accuracy. Thus using Equation 3 in an IAQ assessment of a lecture theatre can lead to problems with under ventilation and hence issues with occupant comfort, or over ventilation, which will increase the operational costs of the lecture theatre.

Application of the AQSM to two typical lectures in the lecture theatre LT1 enabled the portrayal of predicted IAQ distributions. It illustrated the pattern of air delivery to the breathing zone, and gave an overall assessment of the average CO_2 concentration that was comparable to the actual concentrations measured. The results from the AQSM were similar to the measured concentrations and illustrated the applicability and apparent accuracy of the methodology. Furthermore, the assessment methodology uses carbon dioxide concentration as a surrogate for occupant comfort. Thus, using the AQSM developed in this research enables the prediction of IAQ and hence indirectly assesses the occupant comfort in lecture theatres.

This chapter has illustrated that the results from the developed non-homogenous methodology were in agreement with the measured data. The methodology was in particular capable of the detailed spatial assessment of IAQ in lecture theatres. This is important for the design of lecture theatres and the specification of their ventilation systems. For that reason, the development of the assessment methodology has provided a practicable AQSM to predict the IAQ in lecture theatres and similar large spaces.

The next chapter discusses the use of the IAQ assessment methodology to determine the effect on IAQ of changing ventilation rates, methods of air distribution, occupancy profiles, and supply air grille locations.

CHAPTER SEVEN

Application of the developed IAQ assessment methodology

7.0 Lecture theatre model

The lecture theatre used in the modelling was LT1 (see description in Section 6.1). Using the AQSM, the effects on IAQ in the model lecture theatre from four different scenarios were investigated. From the survey data of LT1, a scale model template of the lecture theatre was built in the software and used to assess the IAQ in the four cases mentioned earlier.

The simulated model lecture theatre had a conventional staged design with a sloping ceiling at the front of the room for acoustics. Using the methodology described in Chapter 5, the occupied zone of the lecture theatre was subdivided into the mini breathing zones (mbz). The zones were offset from the wall and floor by approximately 0.5 m as this region would not be occupied. The division of the breathing zone produced 63 mbzs consisting of seven horizontal rows and nine vertical columns (Figure 7.1), which covered the seating and aisle region of the lecture theatre. The mbz encompassed both occupied and unoccupied seats (Figure 7.2). This array of mbz enabled the portrayal of the IAQ distribution in the simulations.

The boundary conditions in the AQSMs are described below. The simulations were performed using the assumption that the environmental conditions indoors and outdoors were steady, in that they did not change over time. The ventilation system in the lecture theatre AQSM was a simple design that did not use techniques such as pressure differentials (advective flow) to extract room air. It was therefore simulated as operating under a balanced state where the volume of air in equalled the volume of air out. Furthermore, the metabolic rate of the occupants was set in the simulation as a constant that corresponded to a sedentary activity level. At this sedentary level of activity the body heat output was taken as 70W. In actuality, individuals' metabolic rates change due to their physiology and activity. Finally, it was assumed that there was no variation in the ambient CO_2 concentration. In reality, the CO_2 concentration outdoors varies slightly for a number of reasons. However, the purpose of the AQSM was to provide a snapshot of the significant conditions that occur indoors, in order to predict the IAQ in the model lecture theatre.

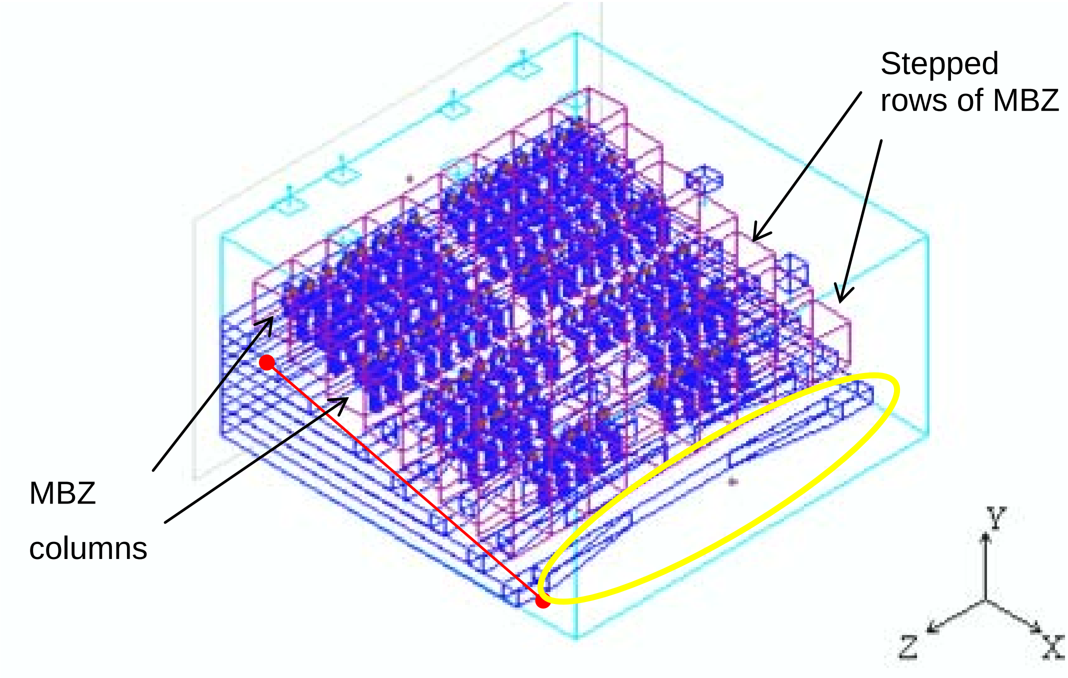


Figure 7.1 Row and column arrangement of mbzs in the template

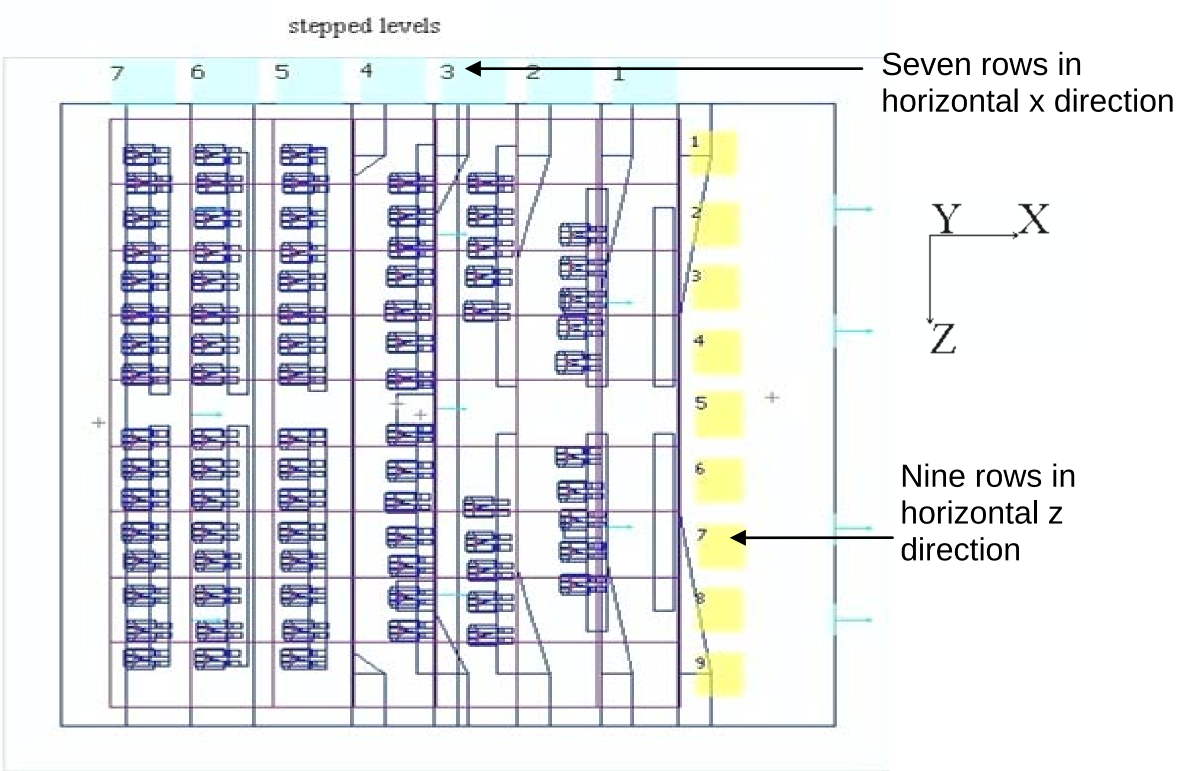


Figure 7.2 Plan view of symmetrical occupancy profile

7.1 Details of the cases investigated

The variables that most affect IAQ in a lecture theatre were discussed in Chapter 3 (Section 3.2). Where it was suggested that there were four key characteristics that significantly influence the IAQ in a lecture theatre. These characteristics were the method of air distribution, the ventilation rate, the occupancy-seating pattern (source location) and the arrangement of the ventilation grilles.

Figure 7.3 summarises the cases that were simulated to represent typical scenarios that occur in lecture theatres. The blue entries in the diagram indicate the main ventilation scenarios that were assessed. The white entries in the diagram represent the AQSMs produced by changing the parameters being assessed. The assessment methodology was applied to three different methods of air distribution that are found in lecture theatres.

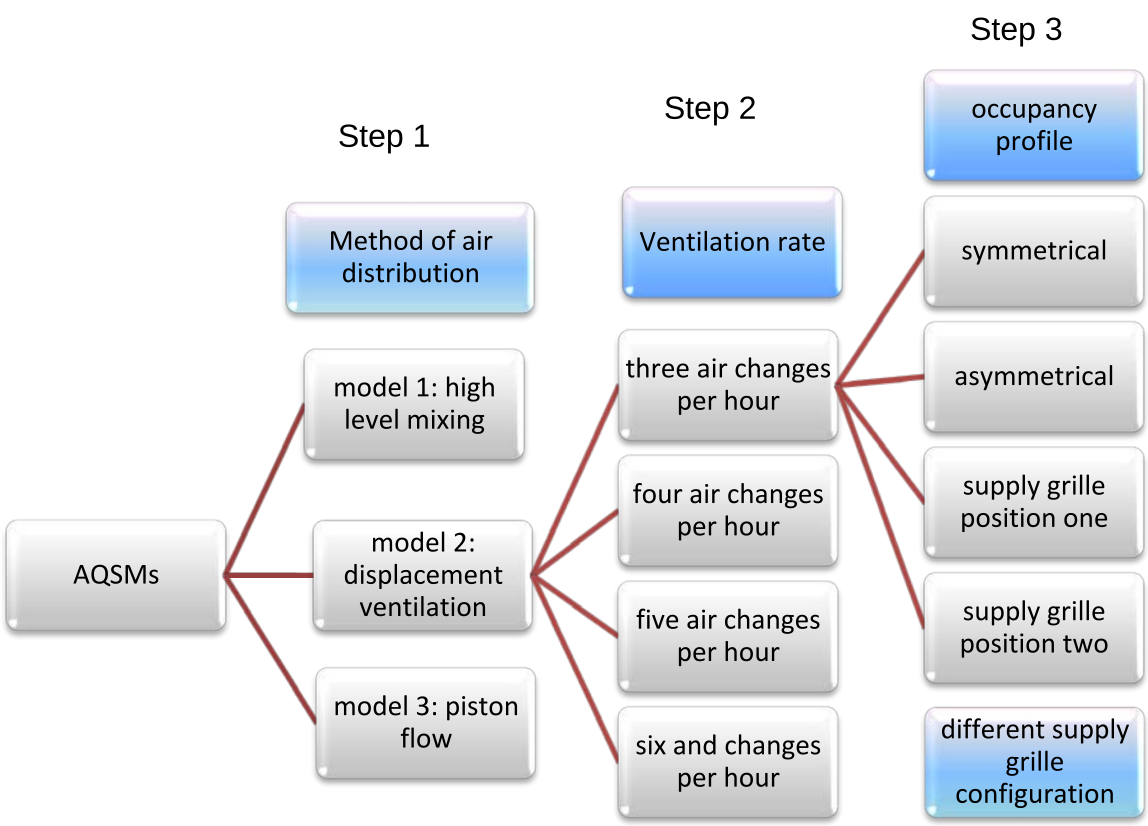


Figure 7.3 Summary diagram of the simulations

Using an existing AQSM of a displacement ventilation (DV) system, four ventilation rates were assessed for their effect on IAQ. This DV system was used in subsequently simulations because this ventilation type is widely recommended as an energy efficient ventilation strategy for lecture theatres and other spaces with large room volumes. Thus, the AQSM of a displacement ventilation system was also used to investigate the effect on IAQ of differing occupancy profiles and different configurations of the ventilation supply grilles. Consequently, there were eight different AQSMs constructed to investigate the IAQ resulting from the four different cases.

7.2 Simulation of IAQ for different air distribution methods

The model lecture theatre template was used in predicting the IAQ delivered by different air distribution methods. In the lecture theatre AQSM the occupants were simulated as a combination of solid blocks (with heat output) to represent body mass. The desks and seats were simulated in the model, as these are noteworthy obstructions to airflow pattern.

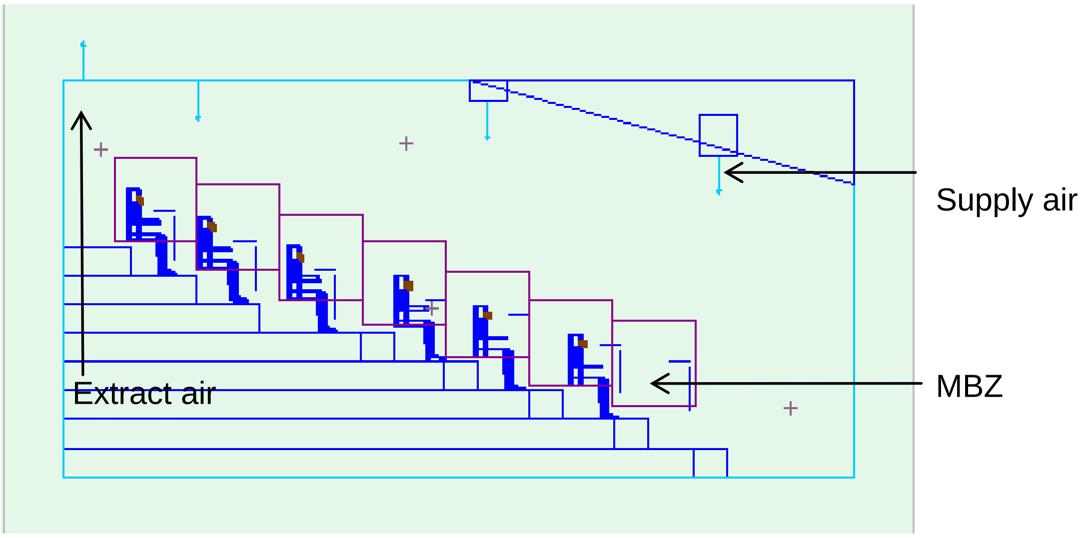
The AQSMs used in all eight simulations consisted of a κ-ε turbulence CFD model. The software solves a set of three partial differential equations repeatedly until a solution is calculated (converged). The CFD model grid used approximately 250,000 cells. In each cell, the software calculates (from the partial differential equations) the value of the parameter of interest. The number of iterations performed in the simulation to obtain a convergence for each AQSM was typically ten thousand, and took approximately two days on a desktop personal computer.

7.2.1 Selection of air distribution methods

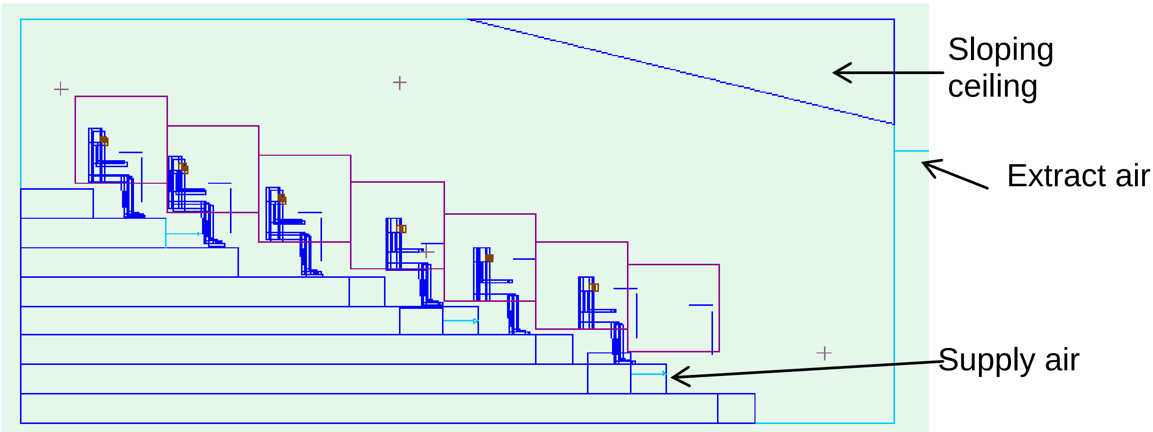
The purpose of this assessment was to establish which of the three common air distribution methods typically found in lecture theatres delivered the best IAQ. The air distribution methods or ventilation arrangements (VA) that were assessed were a high-level mixing ventilation system, displacement ventilation (DV), and piston flow. The assessment methodology consequently produced models that corresponded to each ventilation arrangement.

The images (Figure 7.4) show a cross-sectional view of the differing air distribution arrangements as seen from the drawing board component in the software. The position and number of occupants was kept constant in each model, along with the ventilation rate and supply air temperature. Therefore, the only variable was the configuration of the supply and extract grilles in the ventilation arrangement.

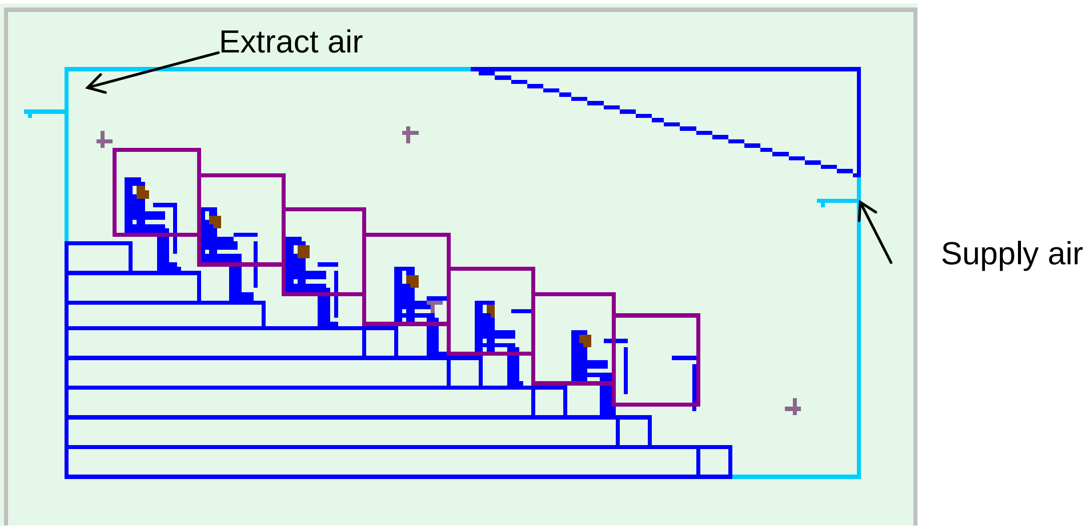
The configuration of the lecture theatre with the students seated tiered towards the front of the space presents specific design considerations, both in the positioning the air grilles (as draughts should not occur) and in selecting an appropriate quiet ventilation system. Model 1 uses higher-level mixing of supply and exhaust air. Model 2 was a displacement ventilation arrangement. The recommendations from ASHRAE suggest placing supply diffusers at the front of the space and the returns at the back (Appleby, 1990). This arrangement was consequently used in model 3.



Model 1 High-level mixing supply and extract



Model 2 Displacement arrangement



Model 3 Piston flow

Figure 7.4 Cross-section of the three air distribution methods simulated

7.2.2 Ventilation rate used in the models

The ventilation rates used in the three simulations were within the CIBSE recommended range for a lecture theatre. The three ventilation arrangements have different recommended rates for use in lecture theatres. A displacement arrangement with air supplied at floor level beneath the seats uses low velocity air (≤0.5 ms^{-1}) to avoid draughts. The recommended range of ventilation rates for a DV arrangement is 3-6 air changes hour (ACH). The recommended ventilation rate for a high-level mixing and piston flow arrangement in a lecture theatre is 5-8 ACH (Vent-Axia, no date).

Ventilation rates can be described by two methods. The first relates to the number of people in the design capacity of the room and is expressed as a volumetric rate per person. The second is based on the size of the space and is expressed as air changes per hour (Equation 4). For this investigation, the air change per hour representation of the ventilation rate was used.

$n=\frac{QV}{t}$ Equation 4

where n is air changes per hour (ACH)

Q is volumetric airflow rate (m^3/s)

V is room volume (m^3)

t is time (s)

The recommended supply air rate for a lecture theatre according to CIBSE is 10 L/s per person (CIBSE, 2006). In a lecture theatre, the recommended ventilation rate is three to six ACH. The supply air temperature for all simulations was set at 18ºC the recommended temperature for a DV system. The ventilation rate used in each model was set at the lower recommended rate (three ACH) to represent a worst-case scenario for the least amount of supplied fresh air.

7.2.3 Symmetrical Occupancy Profile

The occupancy pattern in lecture theatres is often variable in terms of the numbers of students seated, their position, and in the period of occupancy, namely *"dense but intermittent, or extended and sparse"* (BRECSU, 1997) p,5). However, according to Tutt and Adler (1998, p 270) a typical audience number in a lecture ranges from *"30-60 students"*.

The occupancy profile used in the lecture theatre simulations was quantified as a percentage occupancy of the total seating capacity. The occupancy profile was kept constant in all simulation scenarios to compare the IAQ performance of the ventilation arrangements. The occupants were seated in a symmetrical pattern with fully occupied rows from the middle to the back of the room and an empty front row. The lecture theatre was modelled using 60% of the design capacity as a common occupancy number giving an occupancy number of 82 people.

The assessment methodology was applied individually to the three ventilation arrangement scenarios. The number of iterations performed in the simulations to obtain a convergence for the solution was typically ten thousand. The outcome of the simulations consisted of data from each of the mini breathing zones. The results are described in the following sections.

7.2.4 Analysis of simulation data

The output from each of the simulations consisted of data from each of the mini breathing zones, and not from all the grid cells produced by the Cartesian grid that the software uses, as that totalled into the tens of thousands. The CO_2 concentration output for each of the mbz regions (63 in total), was used to calculate the spatial average IAQ and portray its distribution within the breathing zone for each of the three AQSMs. The output from the simulations was manipulated further in order to assess the IAQ from each of the distribution methods.

The simulation resulted in a spreadsheet of 63 datasets, one for each mbz. The data on the spreadsheet was manipulated to summarise the results of the CO_2 concentration simulation for the entire breathing zone (made up of 63 mbzs) for each method of air distribution (Table 7.1). The table includes values for the mean and median carbon dioxide concentration in order to select a midpoint in the data to describe the spatial average IAQ. However, to decide whether to use the medium or the mean CO_2 concentration to represent a spatial average IAQ in the breathing zone, the data required statistical testing.

Ventilation system									
Model	Mean	s.d.	Min.	Q1	Median	Q3	Max.	Range	IQR
1	542.6	30.3	486.4	516.1	540.2	571.0	607.0	120.6	54.2
2	473.6	87.5	365.0	400.8	448.6	528.1	675.5	310.5	127.2
3	508.8	49.3	426.8	466.3	509.4	544.2	612.2	185.5	77.9

Table 7.1 Breathing zone CO_2 concentrations for the three AQSMs

Table Legend

Mean	arithmetic mean of mbzs sample
s.d.	standard deviation of mbzs sample
Q1	first interquartile range
Median	middle number for central tendency
Q3	third interquartile range
IQR	interquartile range
Range	difference between the maximum (max.) and minimum (min.)

The summary of the CO_2 concentration predictions from the three AQSMs illustrated that the three methods of air distribution gave different CO_2 concentrations. Models 1 and 3 had a degree of symmetry in the CO_2 concentration pattern, whereas model two did not. Methods 1 and 3 produced similar results however, the systems performed differently.

7.2.5 Statistical testing

The purpose of the IAQ assessment was to determine which of the three air distribution methods delivered the best IAQ in the modelled lecture theatre. The CO_2 concentration simulation results, for the different methods of air distribution, illustrated that each method gave different representations of CO_2 in the breathing zone. To assess the IAQ the distribution throughout the breathing zone needed to be examined. In order to do this, the shape and pattern of the CO_2 concentrations for each air distribution method AQSM were analysed statistically.

The data outputs for each of the three AQSMs were independent as the data sets were from separate AQSM. In order to establish whether the data was normally distributed or nonparametric, an Anderson - Darling, normality test was performed (Figure 7.5). The outcome of this normality test was that at a 95% confidence interval ($p<0.005$) the CO_2 concentration distribution for AQSM three, piston flow, the CO_2 concentration distribution was normal, but AQSM one, high-level mixing ventilation, and AQSM 1, displacement ventilation, were nonparametric. This result for AQSM 1 was not clear from the summary of data in Table 7.1, as the mean and median CO_2 concentration were similar which suggested a normal distribution.

The three AQSM CO_2 results were individually compared, by using a test of variance, to establish whether there was any similarity between them. The outcome from testing the variance was that they were different at a 95% confidence interval (Table 7.2). To examine further this result, an analysis of variance of the medians for the three AQSM confirmed that there was a difference between at least two of the median concentrations for the CO_2 simulations from the methods of air distribution (Table 7.3). The result was that there was a significant difference between the median concentrations for the distributions at a 95% confidence interval. Thus, the ventilation arrangements did not have the same CO_2 distribution.

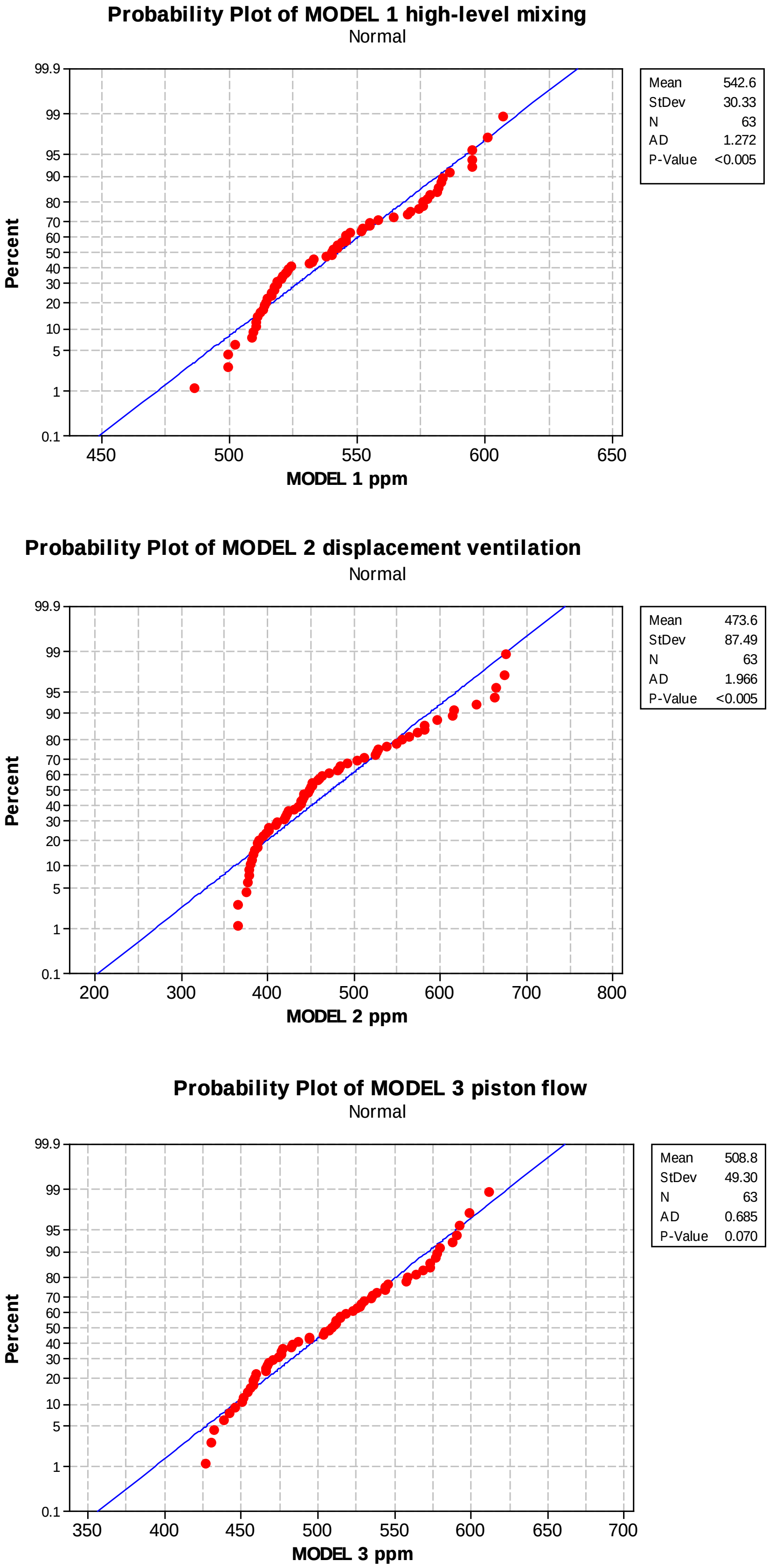


Figure 7.5 Normality test of the distribution of data for methods of air distribution

Assessment of different methods of air distribution on IAQ (CO_2) distribution

One-way ANOVA: MODEL 1 high-level mixing ventilation, MODEL 2 displacement ventilation, MODEL 3 piston flow

```
Source   DF      SS     MS      F      P
Factor    2  150242  75121  20.48  0.000
Error   186  682314   3668
Total   188  832556

S = 60.57   R-Sq = 18.05%   R-Sq(adj) = 17.16%
p is less than 0.05 at 5% significance level hence reject Ho
                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level         N    Mean  StDev  -------+---------+---------+---------+--
MODEL 1 ppm  63  542.64  30.33                              (-----*-----)
MODEL 2 ppm  63  473.58  87.49  (-----*-----)
MODEL 3 ppm  63  508.77  49.30                (------*-----)
                                -------+---------+---------+---------+--
                                     475       500       525       550

Pooled StDev = 60.57
no overlap of CIs hence reject Ho
```

Table 7.2 Results from the test of variance for the carbon dioxide distribution

Kruskal-Wallis Test on CO_2 concentration

H0: the population medians are all equal versus H1: the medians are not all equal

MODEL	N	Median	Ave Rank	Z
MODEL 1 ppm	63	540.2	125.3	5.39
MODEL 2 ppm	63	448.6	66.5	-5.07
MODEL 3 ppm	63	509.4	93.2	-0.32
Overall	189		95.0	

H = 36.55 DF = 2 P = 0.000

Table 7.3 Results from the non-parametric test of variance

7.2.6 IAQ assessment results

The output from the AQSM developed in this thesis assesses the predicted IAQ in a lecture theatre against three criteria. The spatial average CO_2 concentration in the breathing zone should be less than a chosen limit (for example a thousand ppm). The maximum predicted CO_2 concentration should also be less than this chosen limit. The final assessment criterion is that the ventilation system should deliver fresh air equally throughout the entire breathing zone of the lecture theatre. These assessment criteria were applied to the variables that were investigated namely the distribution of CO_2

concentrations and the local mean age of air (LMA) from each AQSM. The results are described separately in the following four subsections.

1. Simulated carbon dioxide distributions

The purpose of the IAQ assessment was to establish which of the three air distribution methods delivered the most appropriate IAQ in the lecture theatre. The statistical tests of the CO_2 concentration simulations in the previous section illustrated that the three methods of air distribution delivered different levels of CO_2 in the breathing zone.

The box plots (Figure 7.6) illustrate the differences in CO_2 concentrations for each method of air distribution simulated. The AQSM of high-level mixing flow and AQSM of piston flow have a more symmetrical distribution of concentrations. This symmetry is reflected by the closeness of the respective mean and median CO_2 concentrations. The AQSM of the displacement ventilation system has the lowest mean and median, but has the largest spread of concentrations. The CO_2 concentration distribution from the displacement ventilation AQSM therefore suggests that this air ventilation method has the greatest degree of variation of CO_2 in the breathing zone.

A limit of CO_2 was chosen as 600 ppm for this theoretical IAQ assessment. The individual mbz CO_2 concentration plot (Figure 7.7) shows the spatial variation in the CO_2 concentrations. Of the three methods of air distribution, the displacement ventilation has the largest range of values (reflecting the most varied CO_2 distribution), and the maximum value. However, it also has the lowest overall average CO_2 concentration. The simulated concentrations from the AQSM for high-level mixing ventilation has the closest grouping or smallest spread values of the different air distribution methods, between 500 and 600ppm and indicates a relatively uniform distribution of CO_2. This is in contrast to the displacement ventilation AQSM which has the most variation in simulated CO_2 concentrations

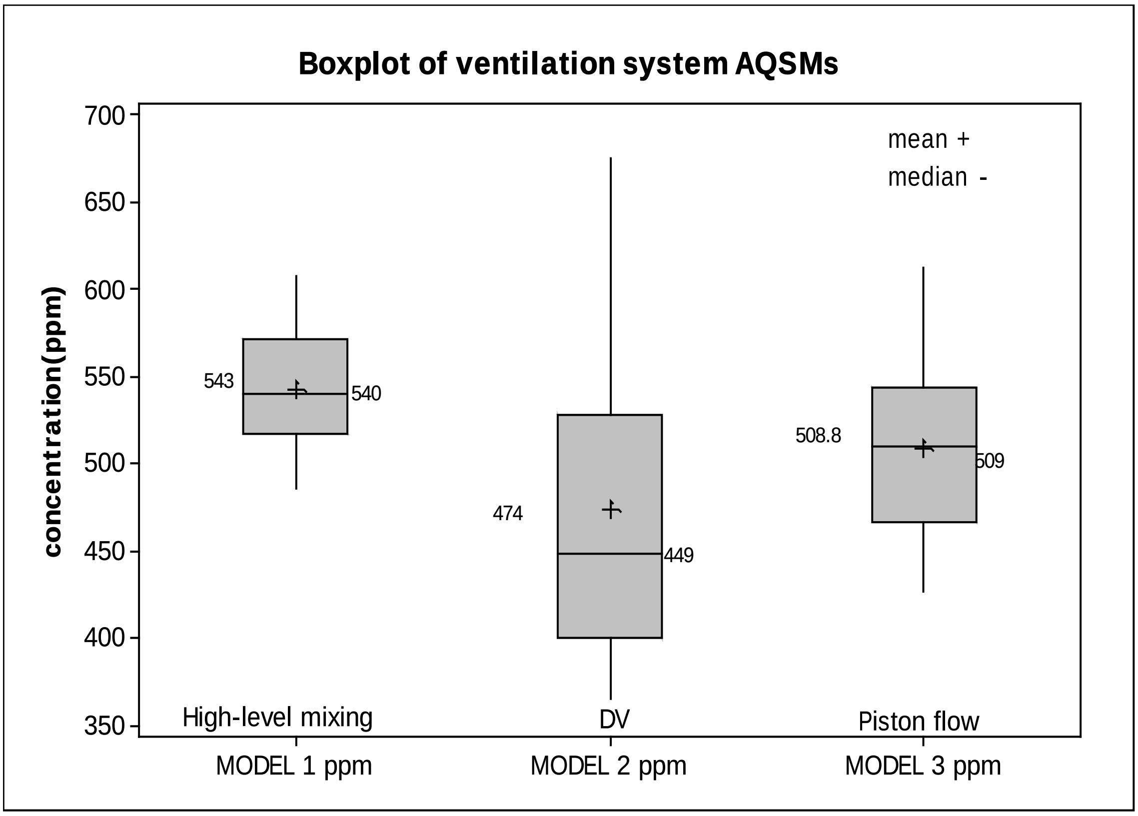


Figure 7.6 Summary of CO_2 concentration plots for each AQSM.

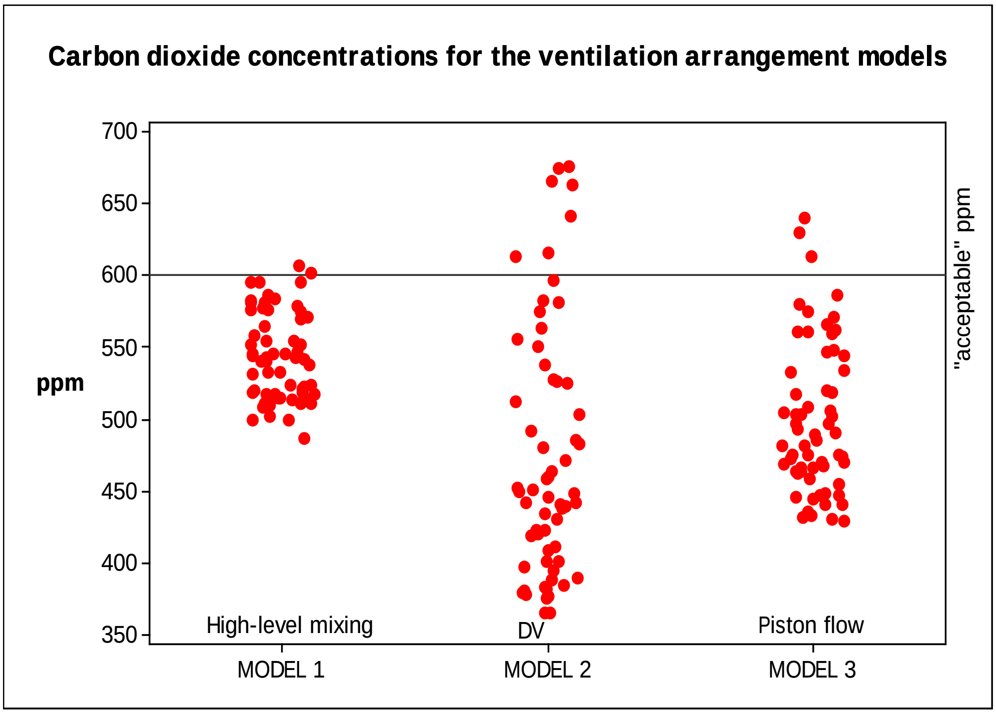


Figure 7.7 Individual mbz plots of CO_2 concentration at 3 air changes an hour

The above figures visually portray regions higher than or below the threshold level of CO_2. In the cases modelled, using a hypothetical maximum concentration of 600 ppm, the high-level mixing ventilation method of air distribution satisfies the criterion as the majority (97%) of mbzs are below this level. The piston flow air distribution method has 95% mbzs below this level whilst the displacement ventilation system has the lowest IAQ performance (89%) mbzs under 600 ppm).

Using 600 ppm of CO_2 as a measure of a maximum concentration, the displacement ventilation system performed least well according to the criterion. Based on a maximum concentration of 600 ppm CO_2, the high-level mixing system (AQSM 1) is the air distribution method that best satisfied this criterion.

2. Planar CO_2 distribution

Figure 7.8 shows contour plots of the CO_2 concentrations in the breathing zone plane for the three simulations. From the contour plots, the regions in the lecture theatre where high CO_2 concentrations exist can be predicted. For all three methods of air distribution modelled, the region at the rear corners of the breathing zone had the highest CO_2 concentrations in all cases. Consequently, occupants sitting here would experience higher levels of CO_2 and less comfort.

From the contour plot (Figure 7.8), the AQSM 1, high-level mixing, had the most even distribution of CO_2 concentrations in the breathing zone. This simulation did however have the highest CO_2 concentrations out of the ventilation systems simulated. The displacement system, AQSM 2, had the most varied CO_2 distribution but with the largest areas containing the lowest CO_2 concentrations. The distribution of CO_2 concentrations in the AQSM 3, a piston flow system, was in between the other two AQSM. The method of airflow that consistently supplied the breathing zone with the same standard of IAQ (albeit not the most comfortable) was AQSM 1.

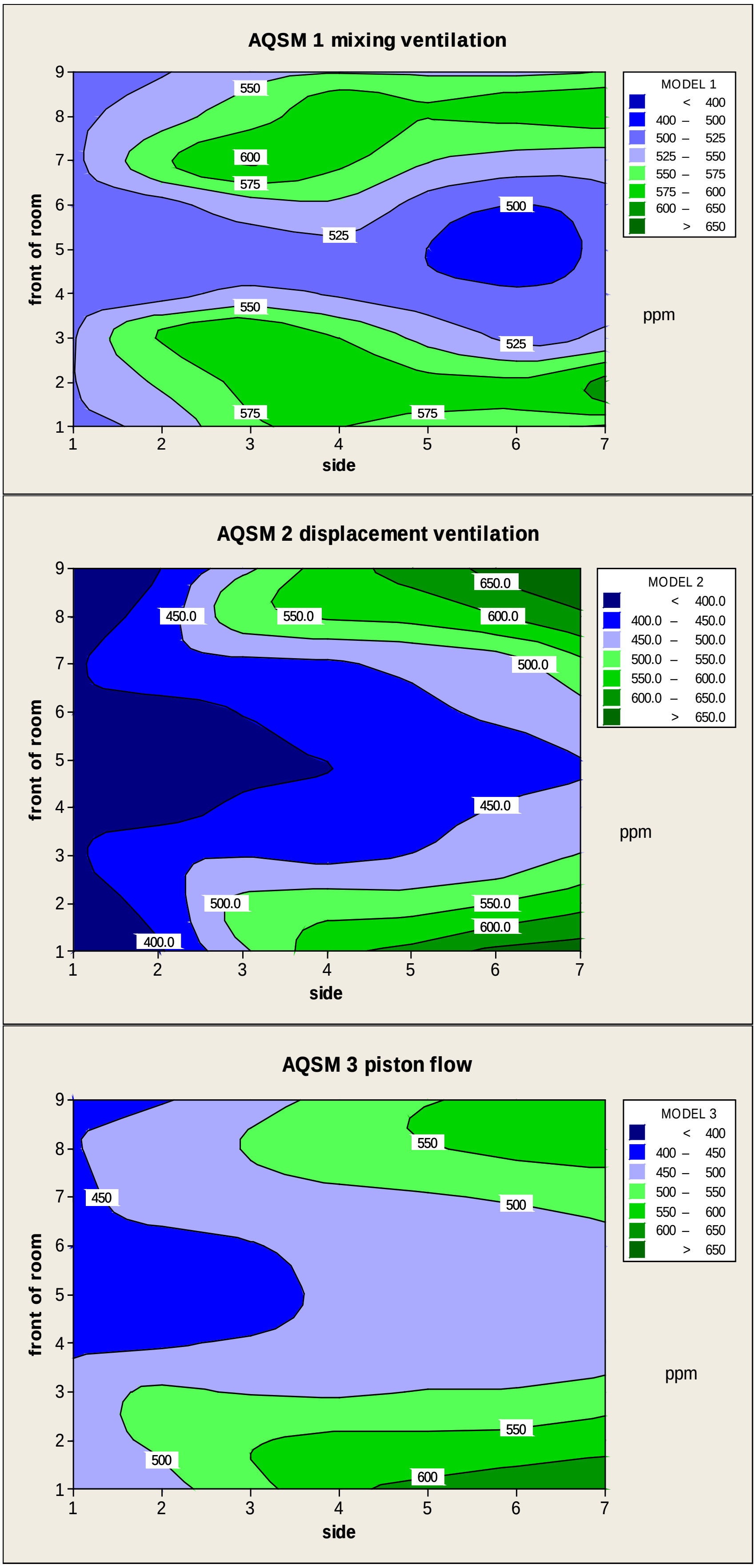


Figure 7.8 Carbon dioxide contour plots for the methods of air distribution.

The distribution of CO_2 can be further portrayed in a three-dimensional view of the breathing zone. To consider the spatial distribution of CO_2 concentrations in this aspect individual three-dimensional surface plots were drawn from the results of each AQSM (Figure 7.9). This allows the complete shape of the CO_2 distribution in the lecture theatre breathing zone to be visualised for an IAQ prediction.

The three-dimensional surface plots of the carbon dioxide concentration for each AQSM provide a clear picture of the CO_2 distribution in the lecture theatre breathing zone. From this visual plot, the difference between the three AQSMs can clearly be seen. The side regions of the lecture theatre seating have peaks in CO_2 concentration. The tiered design of the lecture theatre can be seen from the surface plot display. Using such visual plots can make a component of an IAQ assessment plain to the assessor, as regions of unacceptable IAQ within the breathing zone can be highlighted

The graphical portrayal of the AQSM predictions indicated that the more even CO_2 distribution in AQSM 1, a high-level mixing ventilation system (Figure 7.9) delivered a similar level of IAQ throughout the breathing zone. However, although the high-level mixing method of air distribution simulated provided equivalent IAQ to the lecture theatre occupants, this method gave the highest spatial average CO_2 concentration. Therefore, the high-level mixing type method of air distribution required further consideration in relation to its suitability for use in the modelled lecture theatre.

The variation in CO_2 concentrations throughout the breathing zone is shown as peaks and troughs in three-dimensional plots. The simulated CO_2 concentrations for the AQSM of the high-level mixing ventilation arrangement show that this system has the least variation between the maximum and minimum CO_2 concentrations. The displacement ventilation system and piston flow method of ventilation gave a more variable spatial CO_2 distribution than the high-level mixing method.

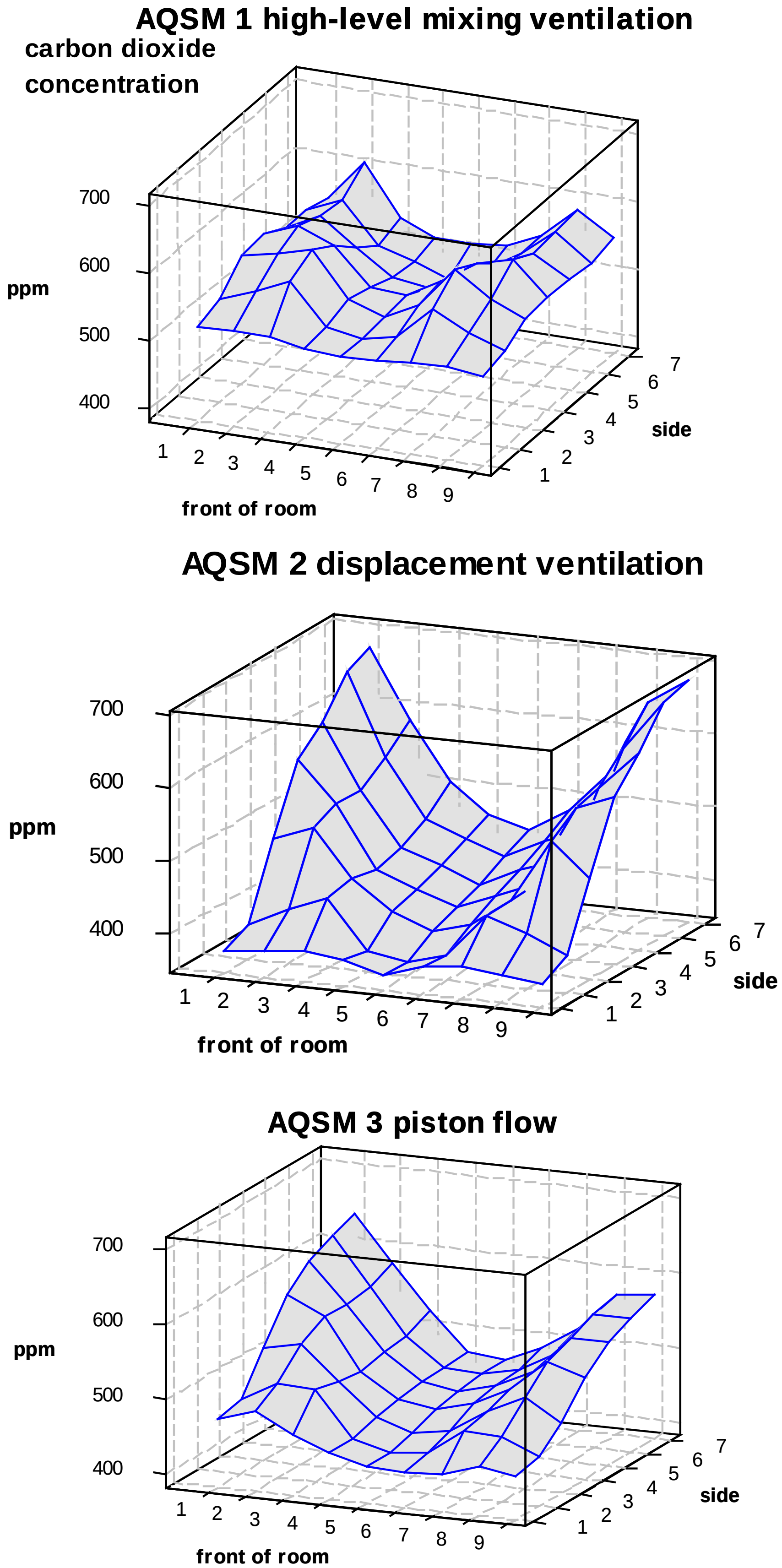


Figure 7.9 Surface 3D plots of CO_2 concentration for each model.

Peaks above the arbitrary 600 ppm maximum occurred most frequently in the displacement ventilation method of air distribution (ASQM 2). However, although this simulated displacement system had the greatest variation of CO_2 in the breathing zone; it also had the lowest spatial average CO_2 concentration. Therefore, like the high-level mixing method of air distribution, the displacement ventilation satisfied some, but not all, of the assessment criteria.

The simulation of a piston flow method of air distribution (ASQM 3) had similar three-dimensional characteristics to that of the displacement system. This method showed a spatial average CO_2 between those of the other two methods of air distribution. The piston flow method however had fewer CO_2 concentrations above 600 ppm than the displacement system, but more than the high-level mixing ventilation method. The AQSM of piston flow method of air distribution occupied the middle ground of the three AQSMs.

3. Vertical CO_2 distribution

The previous section described two different portrayals of the CO_2 distribution in the simulated breathing zone of the lecture theatre. The contour plots provided details of the CO_2 distribution in a plan view, whereas the three-dimensional plot simulated the CO_2 distribution within the breathing zone volume.

The vertical distribution (front elevation) of the CO_2 concentration of each AQSM (Figure 7.10) illustrated the IAQ distribution in the vertical plane and enabled the prediction of any pollutant stratification in the breathing zone. The rows represent the level of mbz, with row one being at the front of the room and row seven at the back of the room. The vertical concentration plot of AQSM one (high-level mixing) was symmetrical either side of the aisle region at mbz number five, with the concentrations closely banded. This plot reiterated the uniform distribution displayed in the 3D surface plot of AQSM 1. AQSM 1, a high-level mixing ventilation arrangement, therefore gave a consistent CO_2 concentration for all the seating rows.

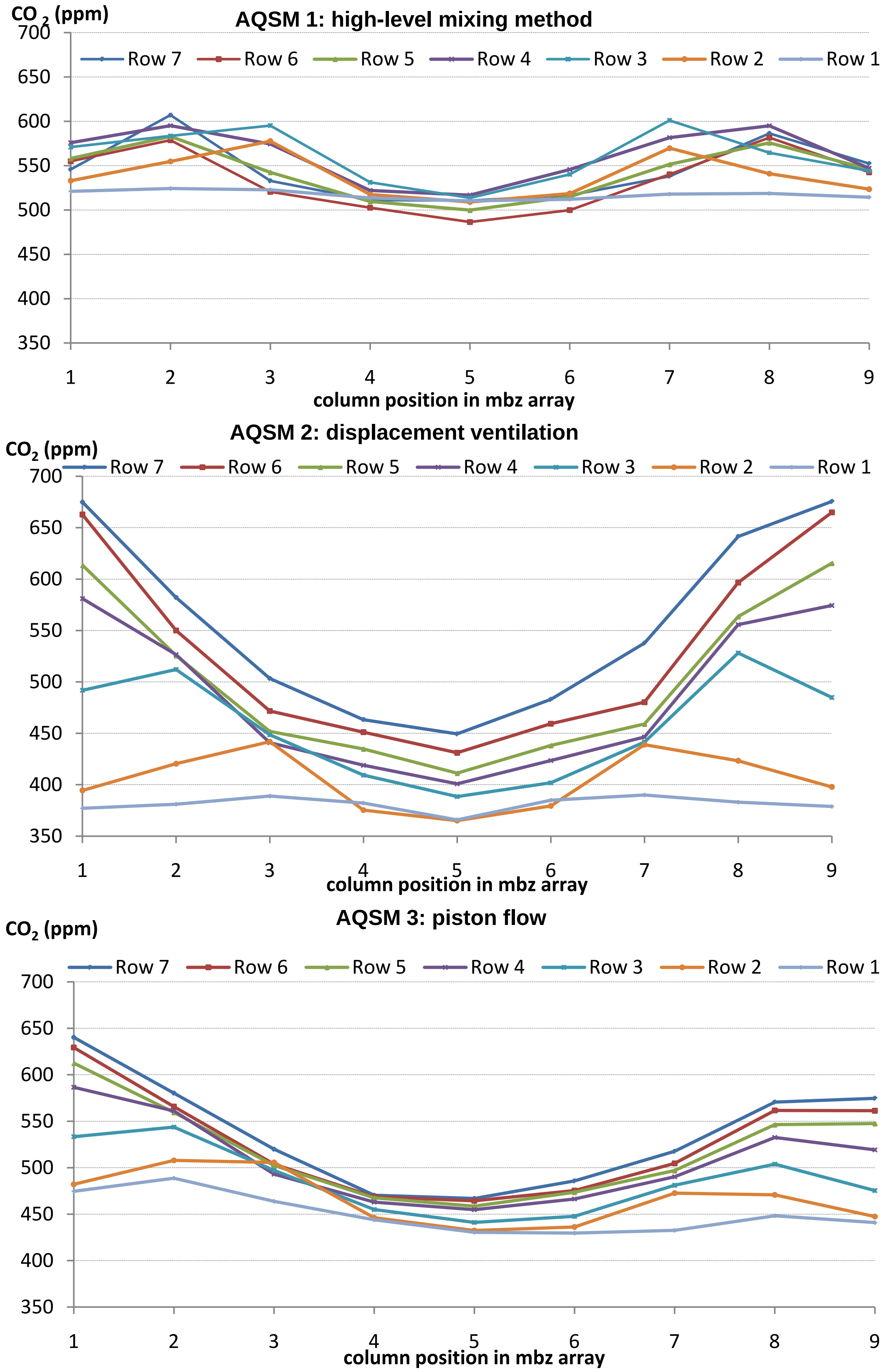


Figure 7.10 Front elevation CO_2 concentration profiles

Similarly, AQSM 2 (displacement system) had a symmetrical vertical pattern with the front two rows experiencing CO_2 concentrations close to ambient. This distribution had the largest range of concentrations (approximately 300 ppm) with the lowest average concentration. Although symmetrical, the concentrations were not however as uniform as AQSM 1 (high-level mixing method of air distribution).

AQSM 3, piston flow, showed simulated CO_2 concentrations that corresponded to the stepwise seating order. This simulation had a range of CO_2 concentrations that were between AQSM 1 and 2. The CO_2 concentrations were closely banded, especially at one side of the room, possibly due to the supply and extract arrangement. However, further investigation would be required to confirm this.

4. Distribution of the local mean age of air

One of the assessment methodology criteria is concerned with the performance of the ventilation system or method of air distribution in the lecture theatre. Ideally, the ventilation system should supply the entire breathing zone with the freshest air. Therefore, as part of the IAQ assessment processes the LMA distribution was also considered.

The performance of the air distribution method was considered using the local mean age of air (LMA) as an indicator of which ventilation system potentially delivered optimum IAQ. The CO_2 simulations described in the previous sections showed that the displacement system and piston flow had higher CO_2 concentrations at the rear corners and sides of the space. The absence of occupants in the middle walkway aisle of the room was indicated by the lower concentrations of CO_2. Comparison with the LMA plots (Figure 7.11) indicates that the rear and side regions of the simulated lecture theatre had corresponding dead zones where the air was older, and hence less fresh. Therefore, this suggested that the higher LMA values in the rear and side of the room corresponded to high CO_2 concentrations.

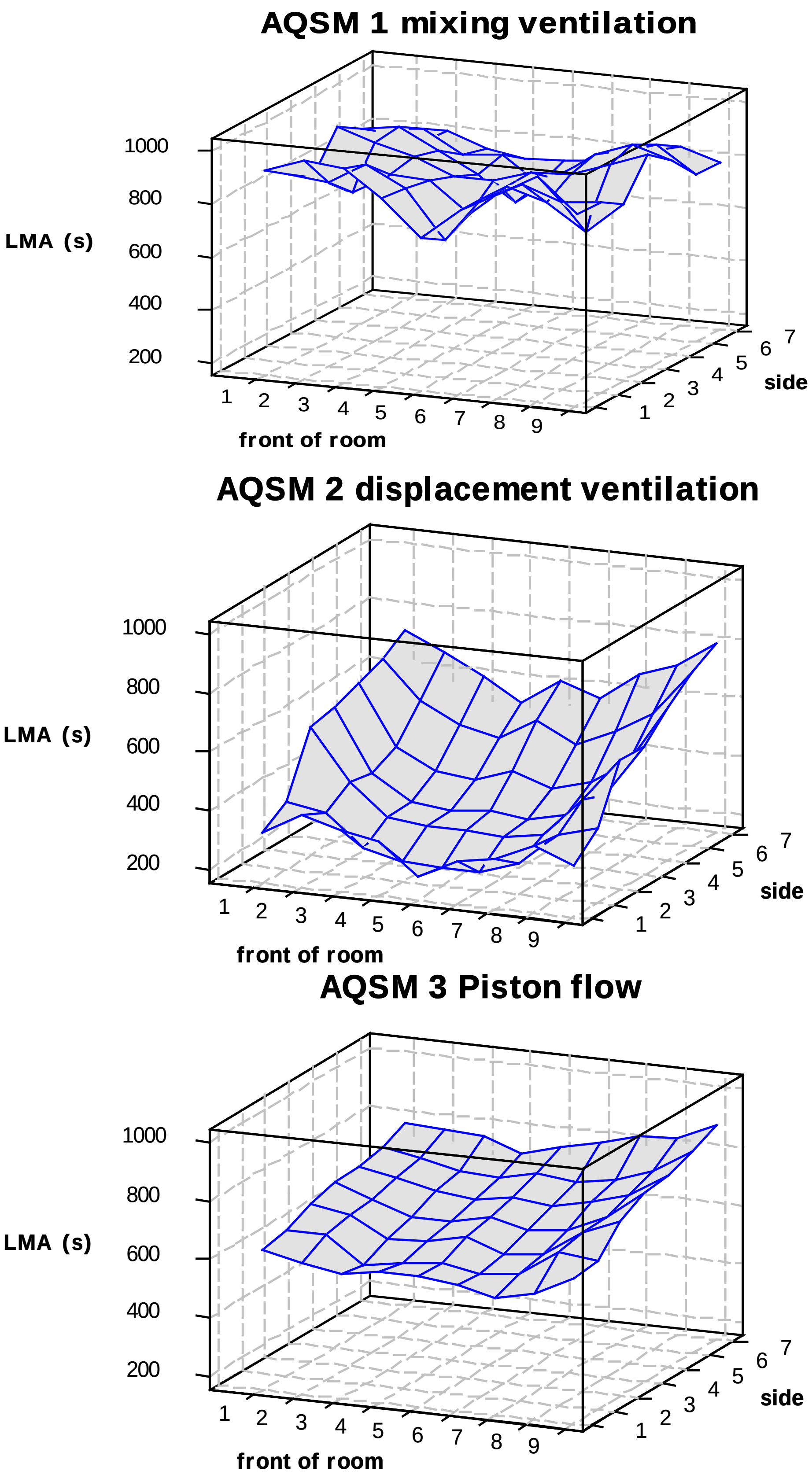


Figure 7.11 Surface 3D plots of LMA each model.

AQSM 1 (high-level mixing method) and AQSM 3 (piston flow) had high LMA values in the walkway area of the lecture theatre. This illustrated that air was being supplied unnecessarily to unoccupied areas. This was in contrast to AQSM 2, a displacement ventilation arrangement, but there was being supplied in seated areas only.

The relatively uniform distributions of airflow provided by AQSM 1, a high-level mixing ventilation arrangement, is shown by the LMA values (Figure 7.11). The effect of the ventilation arrangement (position of supply grilles) on the airflow pattern was shown clearly in AQSM 2, a displacement arrangement. The LMA plots provides an image of the ventilation effectiveness of each of the ventilation methods. This portrayal of the LMA distribution therefore allows regions of stale air to be predicted from the surface plots.

7.2.7 Discussion of the effect on IAQ from air distribution methods

This work importantly argued that a visual portrayal of a predicted IAQ level, in addition to a quantitative description of IAQ is of equal value as a calculated IAQ level from a generic approach. The lecture theatre breathing zone is the volume of air that is being assessed in terms of its IAQ acceptability. Applying the assessment methodology to the selection of air distribution methods was intended to simulate the difference in delivered IAQ by each system. The example IAQ assessment used was based on the following criteria: maximum and average concentration of indicator (CO_2) under a chosen level (600 ppm), and uniform distribution of fresh air (LMA).

Displaying the CO_2 concentration in a two-dimensional contour plot illustrated the distribution of CO_2 in one aspect. In this two-dimensional aspect, the CO_2 concentrations that corresponded to the seating plan of the lecture theatre were identified. Additionally the three-dimensional surface plots and contour maps illustrated the different IAQ distributions in the breathing zone. The maps indicated which method of air distribution gave the most uniform pattern of IAQ. High-level mixing ventilation had the least number of mini breathing zones that were over a selected level of 600 ppm (as an example assessment criterion), and it had the smallest spread of data shown in the box plot. Therefore, this method of a distribution satisfied the CO_2 of the IAQ assessment criteria.

High-level mixing delivered air that had the most uniform IAQ distribution to all the occupant-seating positions but had a higher CO_2 concentration than the other simulated methods of air distribution. The planar local mean age of air plots indicated that displacement ventilation had regions of freshest air but not with a uniform distribution pattern, so this method did not pass this criterion. The vertical distribution of the LMA in the displacement ventilation simulated had the lowest LMA values of all arrangements. This indicates that this type delivered the freshest air to the occupants but at varying CO_2 levels.

Piston flow produced a middle ground between the arrangements, as the horizontal distribution of air was not as even as high-level mixing. However, the vertical CO_2 distribution had the most variable pattern of all the models, albeit with a relatively even LMA three-dimensional plot. Overall, the assessment criteria indicated that high-level mixing was the most appropriate method of air distribution for this lecture theatre.

The results illustrated that the assessment methodology can be used to select an air distribution method appropriate for lecture theatres. It seems clear that this methodology could also be applied to other tiered large spaces such as cinemas and auditoria.

7.3 Simulation of IAQ with varying ventilation rates

The standard of IAQ in a lecture theatre is influenced by the ventilation rate that is used the ventilation system. The ventilation rate was one of four influential variables on IAQ described in Chapter 3. This study will now describe a simulation in which the only variable was the ventilation rate. This enabled the prediction of the effect of different ventilation rates on the IAQ level and its distribution in the lecture theatre.

Displacement ventilation (DV) was used in this simulation. This type of air distribution method is identified by Schild (2004) as being the most effective system where ceiling heights are greater than three metres. In addition a DV system is appropriate in spaces where the resultant airflow is not disturbed much by occupant movement, and where occupants are sedentary for some time is, such as in lecture theatres (Jackman, 1990). An additional reason for using a DV system was that it has the potential to deliver fresh air close to the breathing zone, and is an energy efficient system because of the low ventilation rate that is used in order to avoid draughts.

The displacement configuration in the AQSM had local supply air grilles integrated in the floor at step level, and high-level extracts in the front wall. The lecture theatre was occupied by 82 people seated symmetrically either side of the middle aisle. This was the same occupancy profile as used in section 7.2 where different methods of air distribution were simulated.

7.3.1 Selection of ventilation rates

Ventilation rates were chosen for simulation that were in the recommended range for this particular system. Separate AQSMs were constructed for each of the recommended simulated ventilation rates. The ventilation rates were between three and six air changes per hour (Table 7.4). The supply air temperature was fixed at 18˚C for each simulation.

AQSM	Ventilation rate (ACH)
Minimum airflow rate	3
Low airflow rate	4
Medium airflow rate	5
Maximum airflow rate	6

Table 7.4 Airflow rates simulated

Individual simulations were performed for each airflow rate. The resulting output consisted of mbz values for CO_2 concentration and the local mean age of the air. As for the previous simulation exercise, this output was further examined in order to assess the IAQ in the breathing zone.

7.3.2 Analysis of CO_2 distribution

A frequency plot from the AQSM of the different ventilation rates is shown in Figure 7.12. All of the ventilation rates that were simulated have different CO_2 distributions, but none is normally distributed. From the Figure 7.12 it can be seen that the data set for each ventilation rate is not symmetrical. The ventilation rate that shows the most symmetrical distribution is the maximum airflow rate.

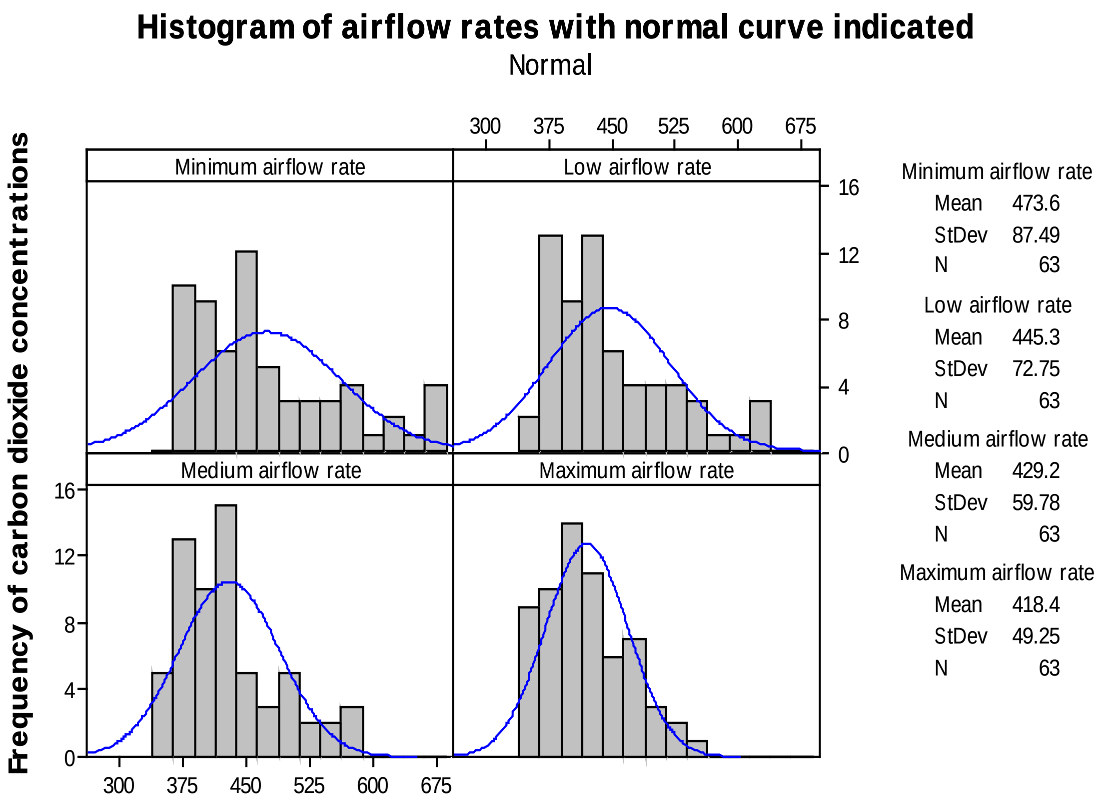


Figure 7.12 Histogram airflow rates resultant of CO_2 concentrations

The overall level of IAQ in terms of the average CO_2 concentration and the maximum level are shown in Table 7.5. The minimum airflow rate has the lowest ventilation rate but with the highest average CO_2 concentration in the breathing zone. As the airflow increase to the maximum rate, the CO_2 concentrations accordingly decrease. This result was expected as increasing the ventilation rate should dilute the concentration of CO_2 in the space as more air is being introduced to the room. However, the purpose of this simulation was to determine how low the ventilation rate could go (to reduce the ventilation energy) within the recommended ranges and still be able to deliver acceptable IAQ in the lecture theatre.

Statistical descriptor	Minimum airflow rate	Low airflow rate	Medium airflow rate	Maximum airflow rate
Arithmetic mean (ppm)	474	445	429	418
Standard deviation	87	73	60	49
Maximum concentration	676	625	577	543
Median	449	430	419	408
Interquartile range	127	104	83	68

Table 7.5 CO_2 concentration summary for the varying ventilation rates.

7.3.3 Application of statistical tests

The spatial average CO_2 concentration in the lecture theatre breathing zone was required for the IAQ assessment. The shape of the data from the AQSMs and the variation between the mean and median values for each airflow rate suggested that the data was not normally distributed. Consequently, the AQSM data was statistically tested to determine which type of spatial measure of central tendency (mean or median) to use.

The data was analysed using the Anderson-Darling statistic. This test determined whether the data followed a normal distribution (Figure 7.13). The Anderson-Darling test was used in the simulations to measure how well the AQSM data followed a normal distribution; the better the distribution fits, the data the smaller the test statistic is. All the distributions were shown to be nonparametric ($p<0.05$), at the 5% significance level. Therefore, the median was used to describe the breathing zone spatial average CO_2 level for each airflow rate AQSM.

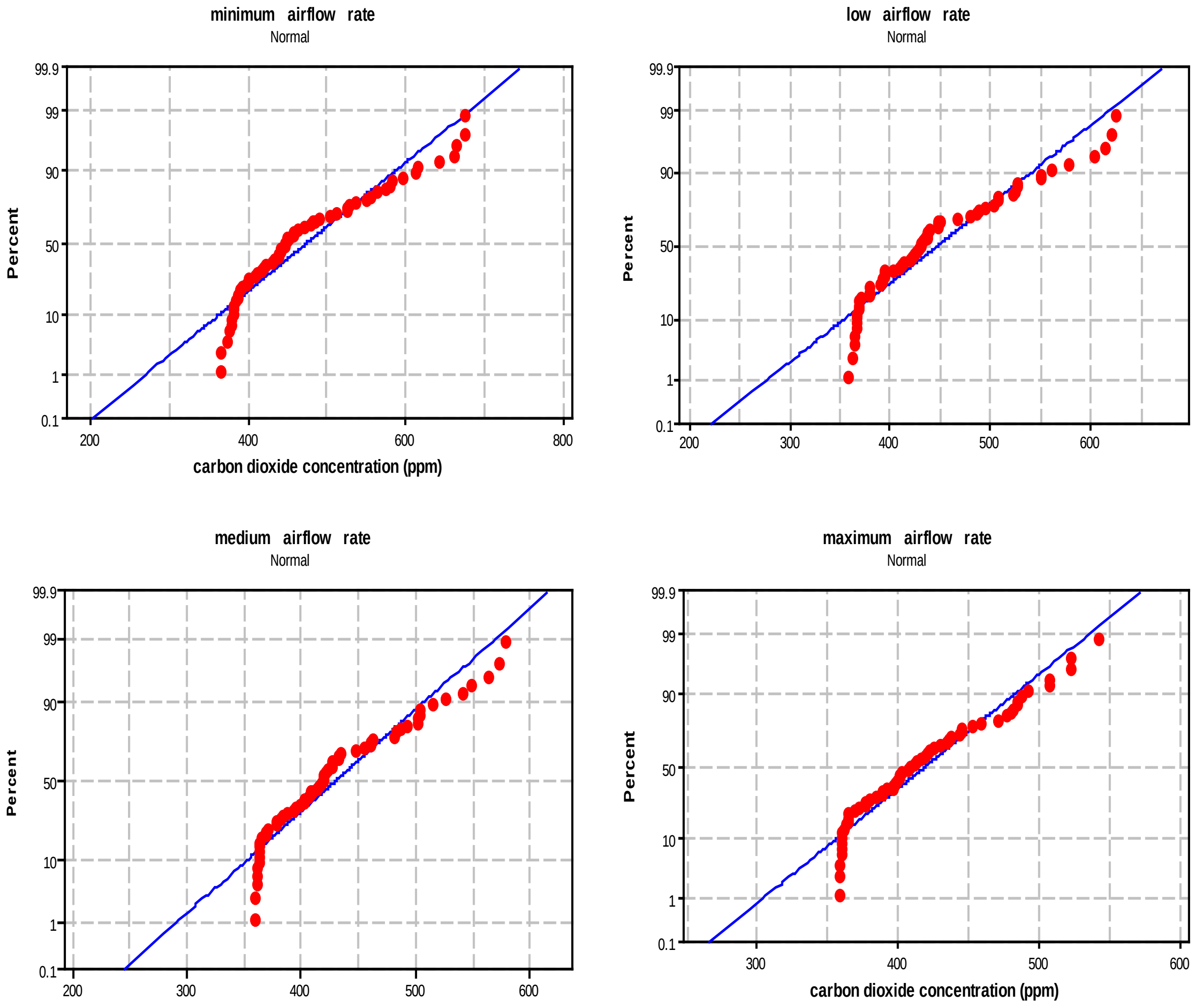


Figure 7.13 Normality tests on the CO_2 distribution for the ventilation rates

Figure 7.14 shows the distribution of CO_2 concentrations for the four airflow rates. The minimum and low airflow rates have the largest spread of concentrations above the average CO_2 concentration. The maximum airflow rate has the smallest concentration spread with the lowest overall average CO_2 concentration.

The four sets of airflow rate data were matched, as the simulation was repeated in the mini breathing zones for the varying ventilation rates. A Friedman nonparametric test was used to determine the significance of changing the ventilation rate (Table 7.6). The statistical test on the four ventilation rate medians' indicated that there was sufficient evidence (at a 95% confidence level, $p<0.05$) to suggest the median CO_2 concentrations were different. Increasing the ventilation rate, besides lowering the spatial average CO_2, changed the distribution of CO_2 in the breathing zone.

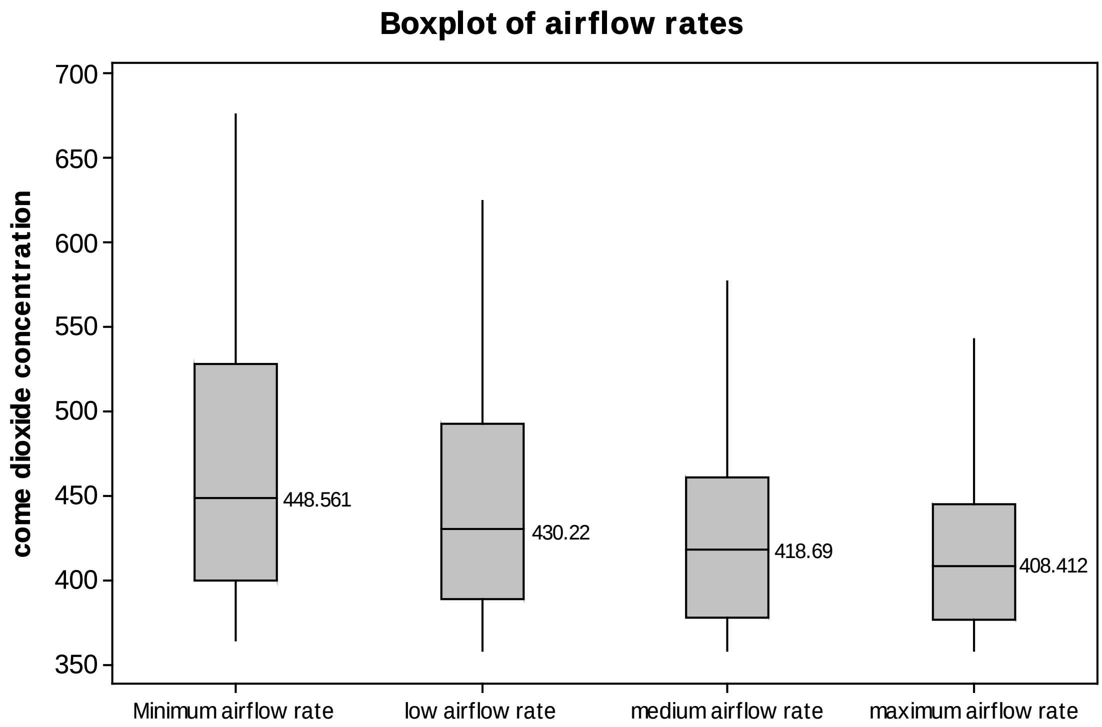


Figure 7.14 Boxplot illustrating the median CO_2 concentrations

S = 165.80 DF = 3 P = 0.000			
Rate	N	Est. Median	Sum of Ranks
Minimum airflow rate	63	453.70	251.0
Low airflow rate	63	429.81	182.0
Medium airflow rate	63	417.89	122.0
Maximum airflow rate	63	414.11	75.0
Grand median = 428.88			

Table 7.6 Results of the Friedman Test on the ventilation rates

Comparing the simulation outcome with the field study of LT1 in Chapter six, a lecture occurred that had the same number of students (82) as that which was simulated in the AQSM of the different ventilation rates. The ventilation rate of LT1 was six air changes per hour, which was the maximum ventilation rate used in the simulation. The average CO_2 concentration measured, on one side of the room, for this lecture was 456 ppm. The AQSM of the maximum airflow rate predicted an average CO_2 concentration of 414 ppm for the entire lecture theatre breathing zone. Even though these two concentrations cannot be directly compared, they are however, of the same order of magnitude and illustrates that the AQSM was predicting concentrations close to that which were measured.

7.3.4 IAQ assessment results

The application of the assessment methodology to the model lecture theatre simulated the effect of different ventilation rates on IAQ and occupant comfort. The CO_2 and LMA output from the AQSM was therefore examined to determine whether a low ventilation rate (airflow rate) could deliver acceptable IAQ. The spatial distribution of CO_2 concentration in the breathing zone and LMA was analysed from two aspects: the planar breathing zone and the vertical direction and described in the following subsections.

1. Planar CO_2 distribution

The simulated CO_2 concentration within the lecture theatre breathing zone was plotted in three dimensions for each airflow rate AQSM (Figure 7.15). The shape of the plots is similar for all four AQSM, but the concentrations decrease as the rate of ACH increases. The AQSM of a minimum airflow rate shows the highest peaks in CO_2 concentration at the back and side regions of the lecture theatre. The AQSM of the maximum airflow rate however, has a relatively smoother plot of CO_2 concentrations with peaks becoming less pronounced as the airflow rate increases, illustrating the effect on the CO_2 distribution of supplying more air in the lecture theatre.

The distribution patterns from all the AQSMs, irrespective of the airflow rate, showed proportionately higher CO_2 levels at the rear sidewall regions; importantly these regions were occupied. The effect of increasing the ventilation rate lowered the maximum level of CO_2 due to more fresh air being supplied to the room. The unoccupied zones as expected had low concentrations of CO_2, which is portrayed in Figure 7.15 as mbzs with CO_2 concentrations close to ambient air concentrations, an example being the stepped aisle region of the lecture theatre. Increasing the airflow rate did not produce an even CO_2 distribution in the breathing zone, which meant that the occupants would experience unequal levels of IAQ and hence comfort. The minimum airflow rate however, had a majority of mbzs below 600 ppm, which suggested that IAQ comfort would only be a problem in the back and side regions of the lecture theatre.

The method of air distribution was the same for all four airflow rates simulated. The contour plots of CO_2 concentrations (Figure 7.16) illustrate the planar two-dimensional map of the CO_2 distribution. As with the three-dimensional plots, the contours follow a comparable pattern for each airflow rate. The simulation shows higher concentrations at the side of the room with lower concentrations at the front of the room, and the middle aisle walkway. The patterns of the contours were similar for all the airflow rates and illustrated the topography of the CO_2 distribution in the breathing zone plane.

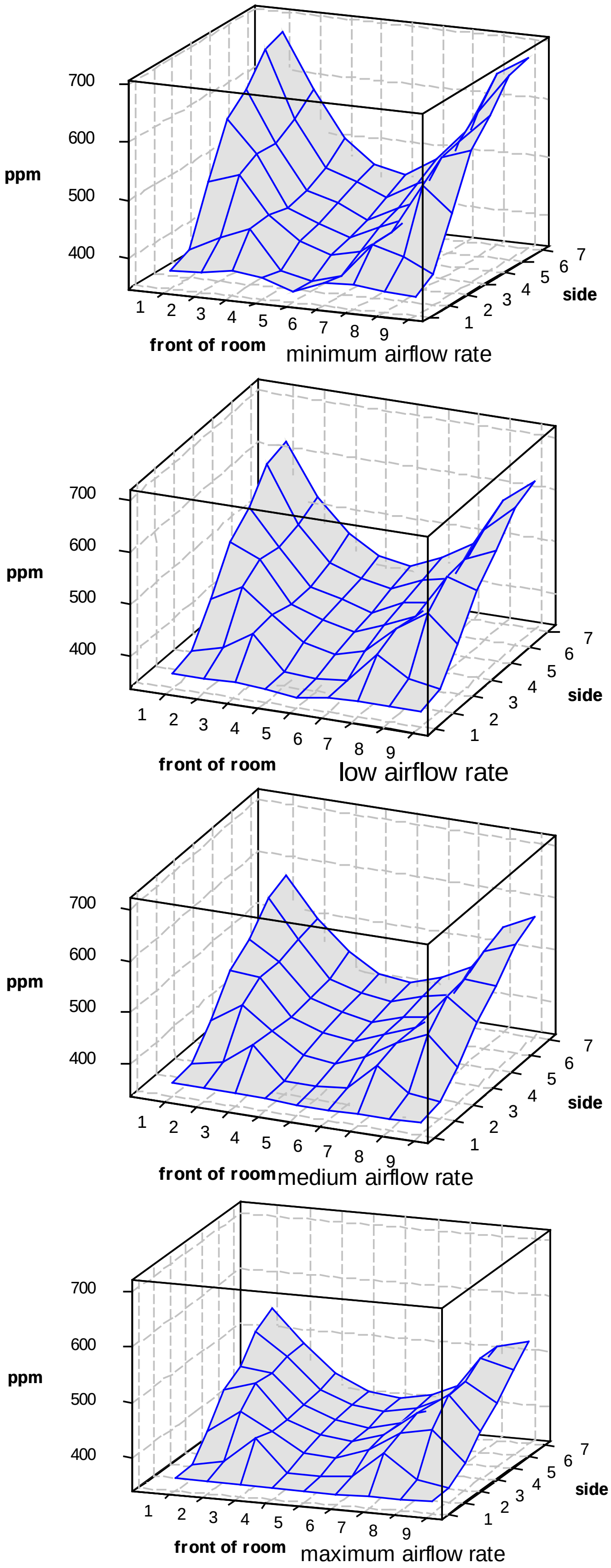


Figure 7.15 3D contour plots of the ventilation rates

Increasing the airflow rate moved the higher value contour lines towards the back of the lecture theatre, illustrating the reduction in the breathing zone CO_2 concentration with increasing airflow rate. Furthermore, the pattern of contour lines illustrated that the airflow pattern was similar for all the airflow rates. Therefore, increasing the airflow rate did not significantly improve the delivery of IAQ for all the occupants sitting in the lecture theatre, but just reduced the overall CO_2 concentration in the breathing zone.

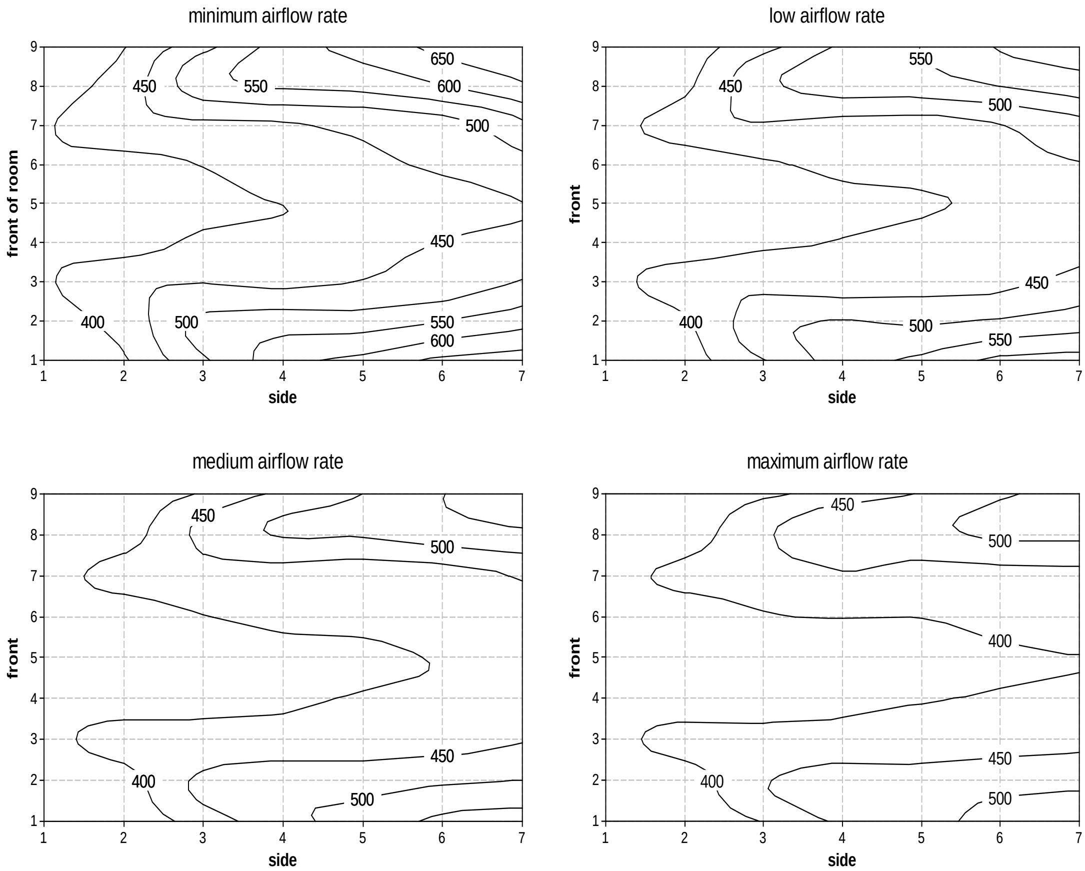


Figure 7.16 Contour CO_2 maps for the different ventilation rates

2. Vertical CO_2 profile

The distribution of CO_2 with height due to the tiered seating arrangement of the lecture theatre was considered. The vertical distributions of the CO_2 levels in the mbzs are shown in Figure 7.17 for the two extreme airflow rates, the maximum and the minimum. The walkway region of the room corresponds to mbz number 5, and the sides relate to mbz numbers 1 and 9. Row 1 corresponded to the lecture theatre front row, and row 7 was at the back.

The vertical distribution of the CO_2 concentration for all the airflow rates had a similar "U" shape. The dip in CO_2 concentrations centred on mbz number 5 and corresponded to the lecture theatre aisle region. This region was unoccupied and hence would have lower CO_2 concentrations than the CO_2 concentrations in the seating regions. Due to the similarity of the vertical distribution graphs for all four airflow rates, only the simulation results for the maximum and minimum airflow rates are reported here.

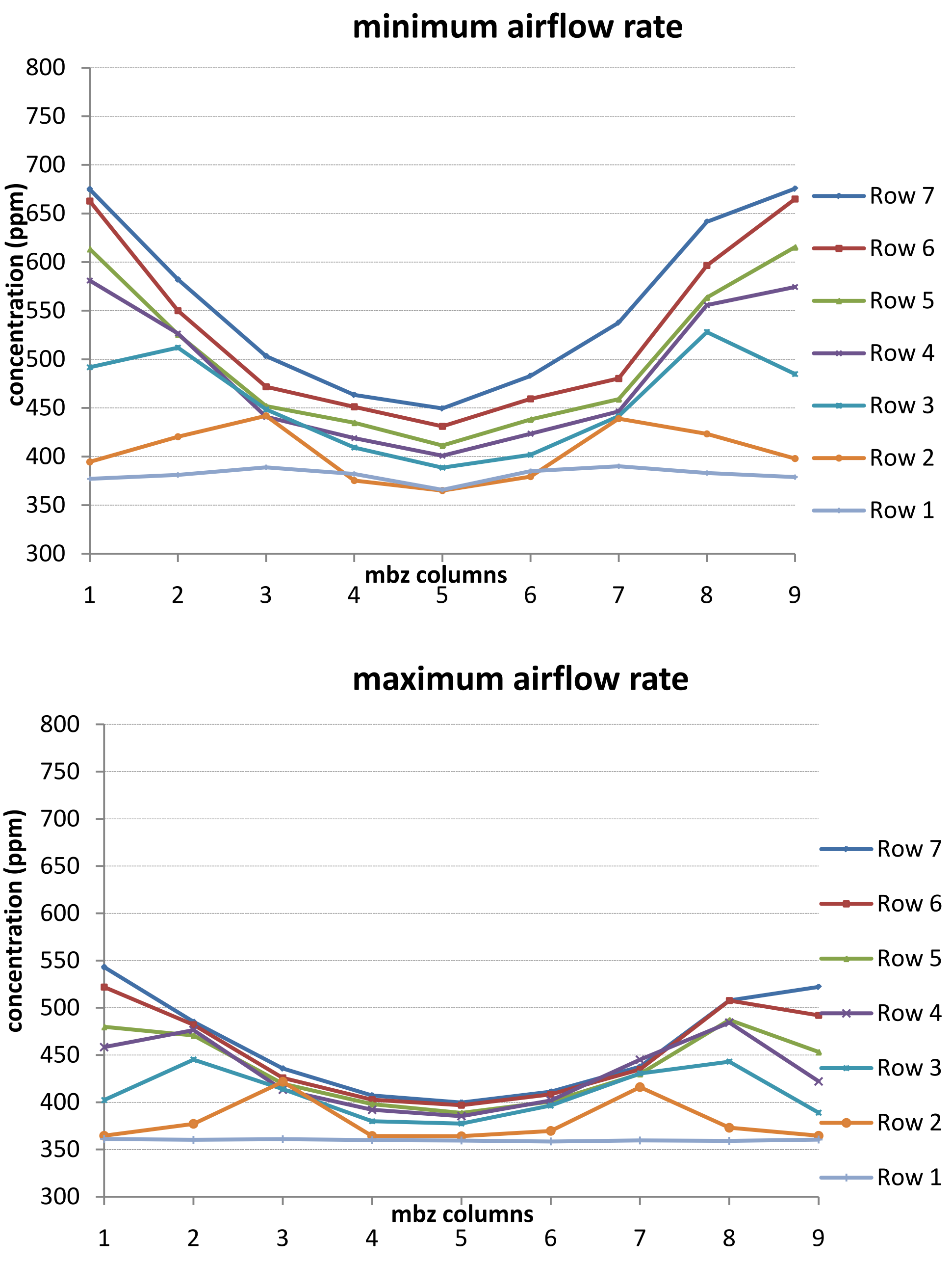


Figure 7.17 Front view vertical profile of CO_2 concentrations of mbzs

The minimum airflow rate simulation had the greatest spread of CO_2 concentration distribution of all the airflow rates. The maximum airflow rate however had the smallest range of concentrations, which gave a flatter distribution of CO_2 concentration as shown by the compression of the lines in Figure 7.17. The effect of increasing the airflow rate reduced the CO_2 concentration for each of the seating rows. Furthermore, the airflow pattern in the vertical plane was not altered by increasing the airflow rate, as it only reduced the CO_2 concentrations in the rows of seats. Therefore, the effect of increasing the airflow rate would only be beneficial to the occupants sitting towards the back of the lecture theatre.

The next two subsections describe the local mean age of air distribution in two different aspects, a three-dimensional view and in a vertical profile.

1. Planar Local Mean Age of air distribution

In order to consider the airflow pattern resulting from the increase in airflow rate values, the local mean age of air was simulated (Figure 7.18). The three-dimensional surface plots of the LMA (Figure 7.18) show that the minimum ventilation rate of three a changes per hour (ACH) has the greatest variation in age of air values which is reflected by the uneven peaks and troughs of LMA values.

The maximum airflow rate (6 ACH) produced a relatively uniform distribution of age of air with the lowest simulated LMA values. Increasing the ventilation rate had the effect of evening out the LMA distribution. Regions of higher values were still present at the back and side of the breathing zone indicating regions of less air movement. Increasing the airflow rate did not make a difference to occupants sitting in the front row, but it did to occupants sitting at the back of the lecture theatre.

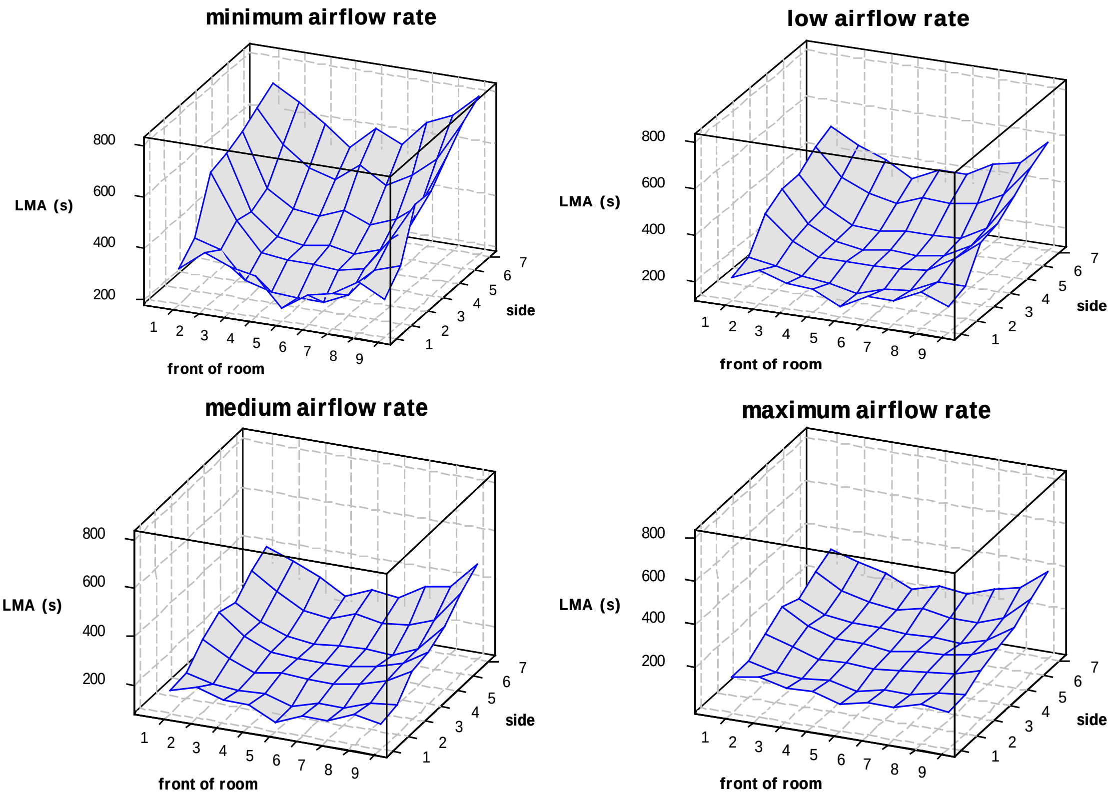
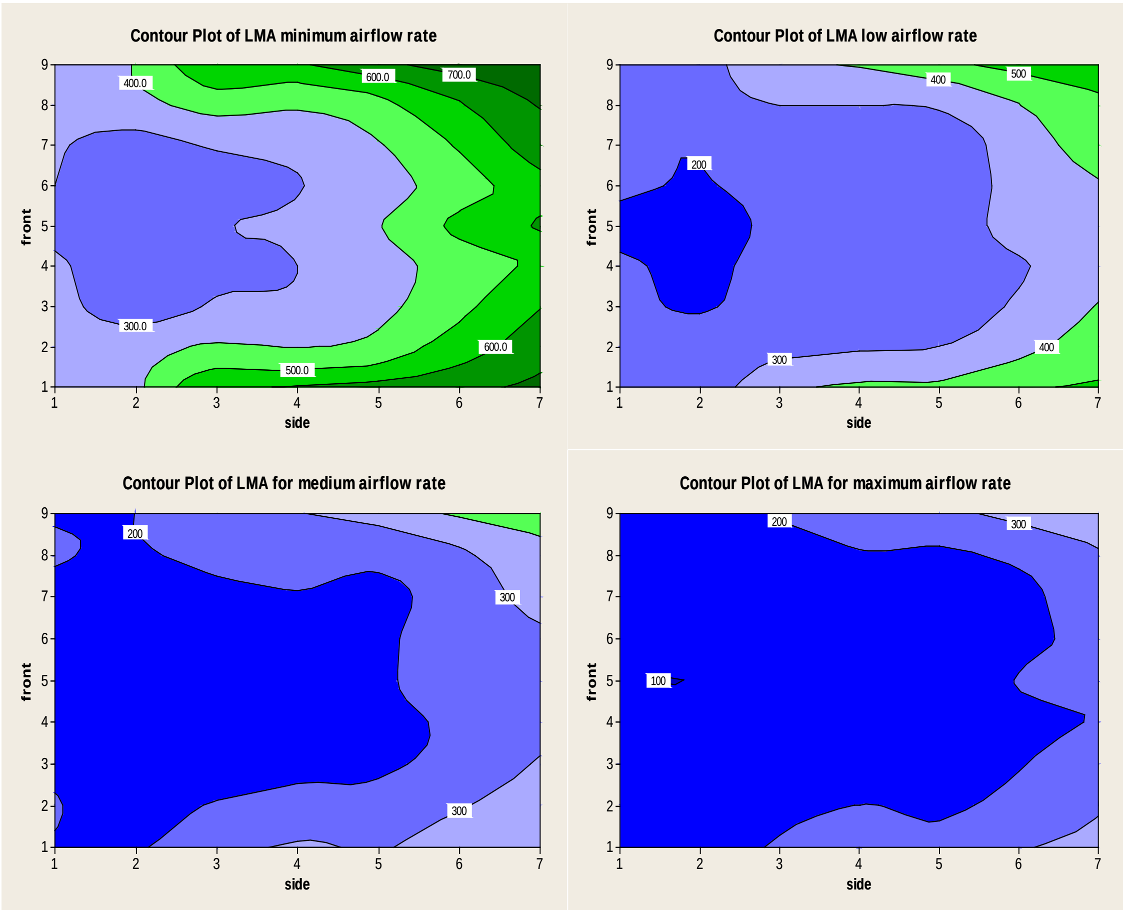
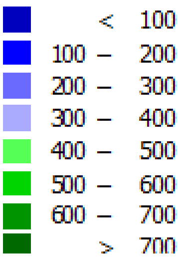


Figure 7.18 LMA surface plots of the ventilation rates simulated

The contour plots illustrate the effect on LMA values due to increasing the ventilation rate (Figure 7.19). As the ventilation rate increases, lower LMA values are demonstrated by a smoothing of the contour lines. In the AQSM of the minimum airflow rate, the LMA distribution shows corresponding higher LMA values. The regions at the side and back of the lecture theatre have contours that are in close proximity. These areas correspond to the surface plots of the LMA, and additionally to regions of high CO_2 concentrations in the results from the previous section.

The maximum airflow rate delivered similar LMA levels for the entire breathing zone. This is displayed in the contour plot (Figure 7.19) as a large contour area with LMA values less than 300 seconds, which indicated the freshest air. The planar LMA plots reflect the regions in the lecture theatre where less fresh air is delivered. However, increasing the airflow rate only moves the dead zones further towards the back of the lecture theatre and does not eliminate the regions of relatively still air. Therefore, the planar plots of LMA confirm that increasing the airflow rate does not result in an even distribution of IAQ in the breathing zone.



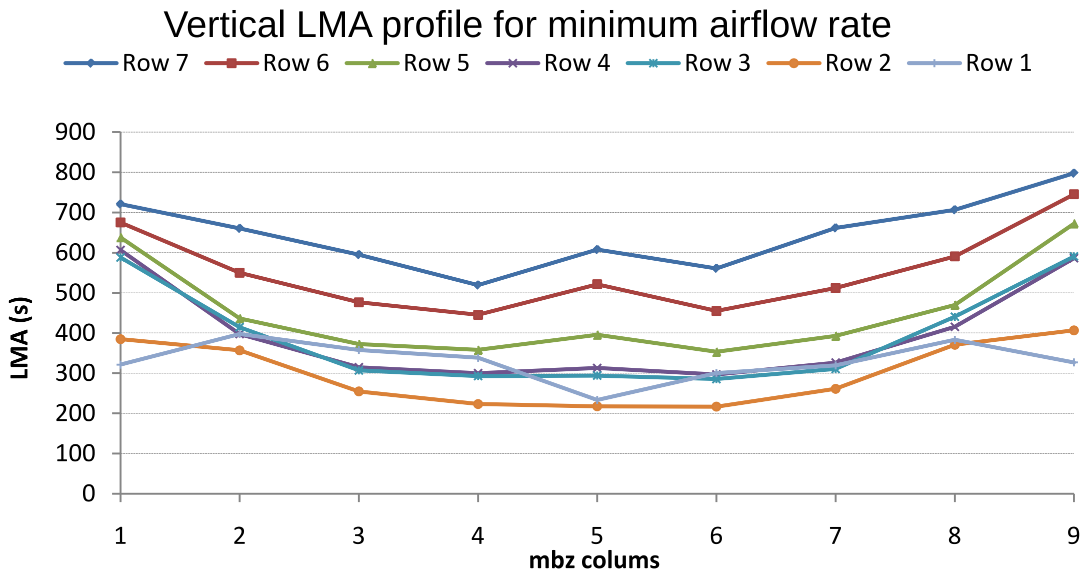


Contour colour key

Figure 7.19 Contour plots of LMA for the different ventilation rates

2. Vertical LMA profile

The difference in vertical LMA distribution (Figure 7.20) for AQSM of the minimum and maximum airflow rates illustrates that the two vertical profiles had a similar shape. The back row of seating (Level 7) experiences the oldest LMA. However, this is probably due to the lack of supply air grilles in the back row of seats.



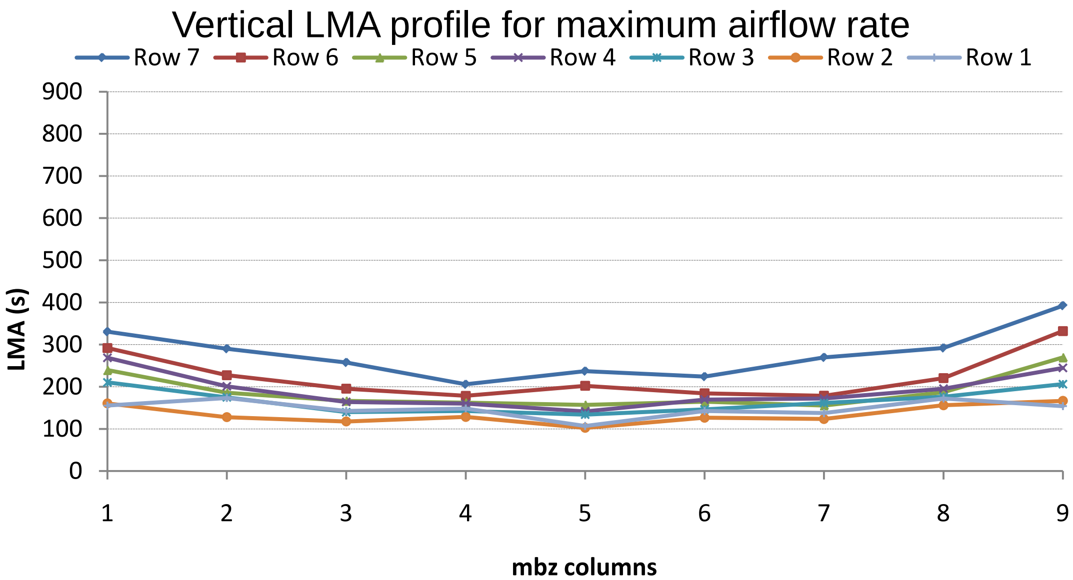


Figure 7.20 Vertical LMA profile in the lecture theatre for the maximum and minimum airflow rates simulated.

The vertical profile of the maximum airflow rate AQSM has a smaller difference between the seating rows, which is also shown in the LMA contour plot. The vertical LMA distribution illustrates that increasing the air supply to the breathing zone gives an increasingly equal distribution of fresh air. However, although the maximum airflow rate delivers the freshest air to the breathing zone there will be an associated energy penalty (higher fuel demand) when using this airflow rate.

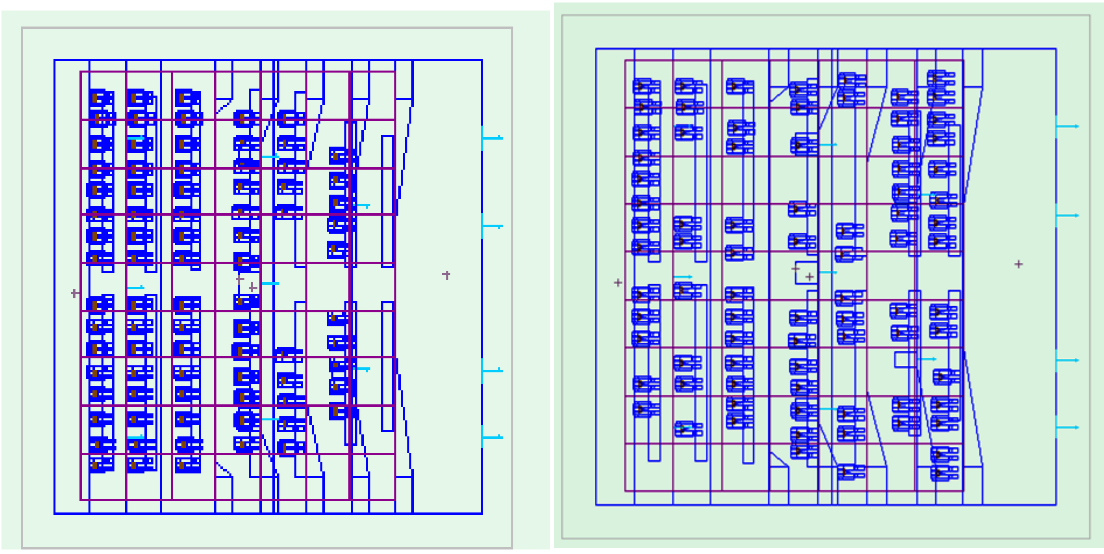
7.3.5 Discussion of the effect on IAQ from ventilation rates

A ventilation system that effectively delivers the correct amount of fresh air to where it is needed in a lecture theatre is an important factor for the energy efficiency of the ventilation system. Over ventilation of a lecture theatre is unnecessary and will increase the operational energy demand from the ventilation system. Under ventilation of the room will mean that the occupants receive inadequate amounts of fresh air and this will cause them discomfort. The application of the IAQ assessment methodology has the potential to predict the effect on IAQ from using the lowest possible ACH (and hence fan speed) in order to assess whether low airflow rates can deliver acceptable IAQ, and to save energy.

This simulation was performed to predict how the lowest recommended ventilation rate compared with the other rates within the recommended range. The expected effect of altering the ventilation rate was that an increase in ACH would produce an improvement in IAQ level; a lower concentration of air pollutants, carbon dioxide - with more fresh air. This behaviour is shown in the simulation results. Nevertheless, the difference in median CO_2 concentrations was 40 ppm and it did not follow the general guidance that the pollutant concentration was reduced by approximately 50% by doubling of the ventilation rate (ASHRAE, 1989). However, this study used the average occupancy number; if the lecture theatre was full, it may be possible that greater differences would found. This could be investigated in future simulations.

7.4 Simulations of IAQ with differing occupancy profiles

This investigation was performed to establish what effect the important parameter of occupant-seating pattern had on the level and distribution of IAQ. The effects on IAQ of two different seating profiles were simulated. One of these seating profiles was a symmetrical occupancy profile (OP). The second was an asymmetrical occupancy profile (Figure 7.21). In both occupancy profiles, the lecture theatre seating capacity was 60% occupied with 82 students sitting different patterns.



Symmetrical   Asymmetrical

Figure 7.21 Plan view of the occupancy profiles simulated

7.4.1 Occupancy profiles

Two AQSM were constructed for each occupancy profile. The air distribution method in the model lecture theatre was a displacement ventilation system. The minimum airflow rate recommended for this ventilation arrangement (three ACH) was used to simulate a worst-case IAQ scenario. Thus, both the AQSMs used the same method of air distribution, the same number of students and the same airflow rate; the only difference between the two AQSMs was the occupancy profile.

7.4.2 Data Analysis

For both sets of CO_2 concentrations the shape of the data was firstly plotted (Figure 7.22) to compare of the CO_2 distributions, and to suggest which measure of central tendency that was most appropriate to describe the overall spatial CO_2 average. The simulation outcome consisted of two data sets from the 63 mini breathing zones (mbz). The AQSM of the asymmetrical occupancy profile had a relatively more symmetrical data pattern than the AQSM of the symmetrical occupancy profile. The symmetrical AQSM had data that was positively skewed with the majority of observations towards the lower CO_2 concentrations and a smaller number of data with greater CO_2 concentrations in the tail of the distribution. However, in order to establish what effect on the IAQ altering the occupancy profile had, the data needed to be further tested.

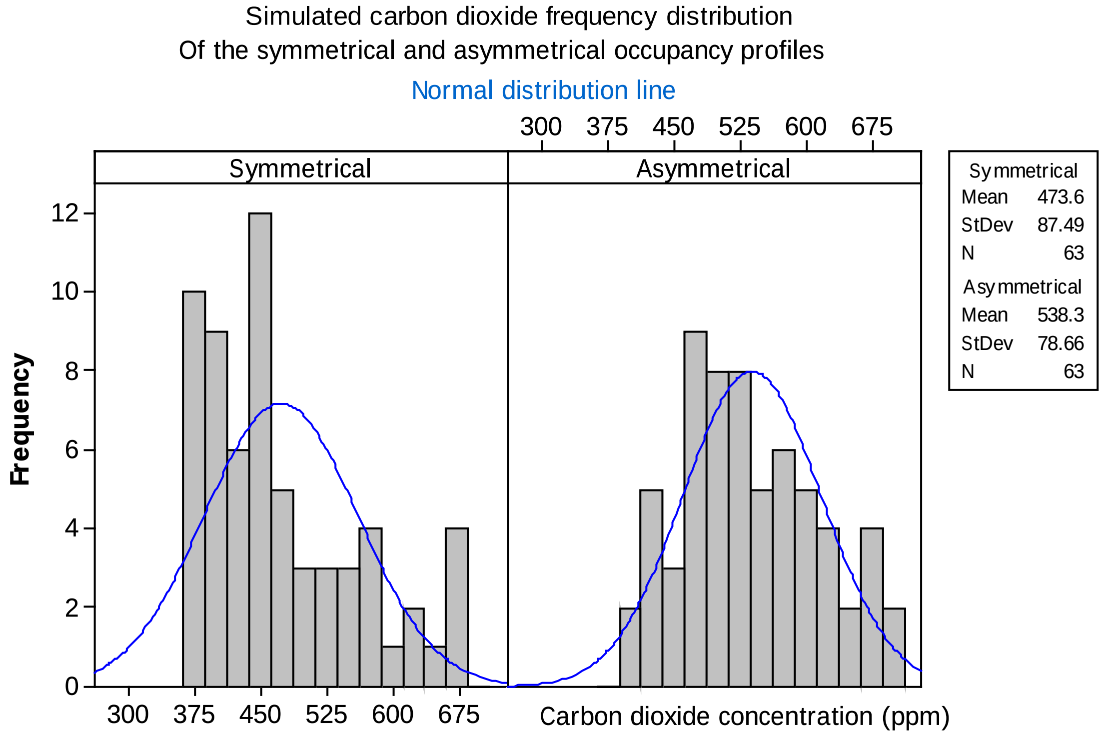


Figure 7.22 Simulated CO_2 frequency distributions of the symmetrical and asymmetrical occupancy profiles

7.4.3 Statistical testing and results of simulation outcomes

A normality test was performed to establish which statistical descriptor to use as the average measure of CO_2 in the breathing zone. An Anderson - Darling test for normality (Figure 7.23) indicated at a 95% confidence level that the AQSM of the symmetrical occupancy profile had a nonparametric distribution ($p<0.05$), but the AQSM of the asymmetrical occupancy profile was normally distributed ($p>0.05$). This indicated that the CO_2 distributions from simulation models of the occupancy profiles were different and that the IAQ in the lecture theatre breathing zone was significantly influenced by the occupants' seating position.

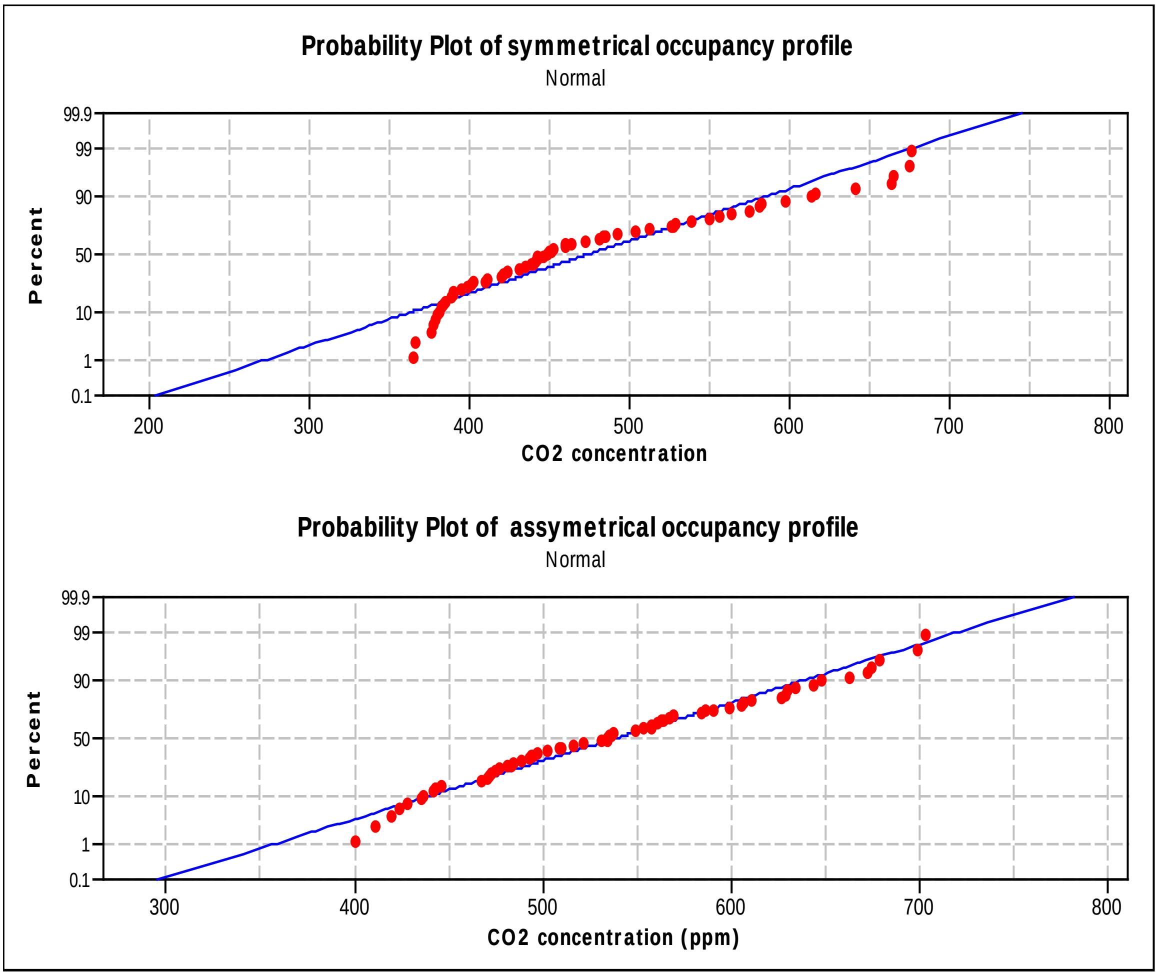


Figure 7.23 Anderson-Darling test for normality on the occupancy profiles

Case	Mean	s.d	Minimum	Q1	Median	Q3	Maximum
Symmetrical	473.6	87.5	365.0	400.8	448.6	528.1	675.5
Asymmetrical	538.3	78.7	400.1	477.0	534.0	599.2	703.2

Table 7.7 Carbon dioxide concentration summary of the two occupancy profiles

The summary data for the AQSMs of the two occupancy profiles are shown in Table 7.7. The AQSM of the asymmetrical occupancy profile had a greater overall CO_2 concentration in the breathing zone, than that of the symmetrical occupancy profile. The highest CO_2 concentrations occurred in the AQSM of the asymmetrical occupancy profile.

The mean and medians of the two models were compared using parametric and nonparametric analysis of variance tests. The outcome from these tests indicated at a 95% confidence level ($p < 0.05$) that the difference in occupancy profile produced a difference in the CO_2 concentration distributions. Changing the seating positions of the occupants significantly influenced the level of CO_2 that the occupants would experience in the lecture theatre breathing zone. Thus the comfort, as measured by IAQ, of the occupants depends upon where they are seated.

The following subsections describe the CO_2 and LMA results separately.

1. Carbon dioxide distribution

The difference in CO_2 due to the change in the occupancy profile was further studied by examining the spatial distribution (Figure 7.24). The difference between the two occupancy profiles is best illustrated by the raised levels of CO_2 concentrations in the simulation of asymmetrical occupancy profile, as this front row was fully occupied compared with this row being empty in the symmetrical AQSM occupancy profile. The shape of both surface plots however indicated that the back and side regions of the lecture theatre consistently experience higher CO_2 concentrations. Consequently, the CO_2 concentration distributions for both occupancy profiles indicate that there was a ventilation problem at the back and side of the lecture theatre.

The simulation results contour plots (Figure 7.25) reiterate that the back and the sides of the lecture theatre show a greater degree of variation in CO_2 concentrations, as indicated by the closeness of the contours in both plots. Both AQSMs with different occupancy profiles produce different CO_2 distribution patterns related to the seating position of the occupants. Occupancy profiles therefore have an important influence on the IAQ delivered by the ventilation system.

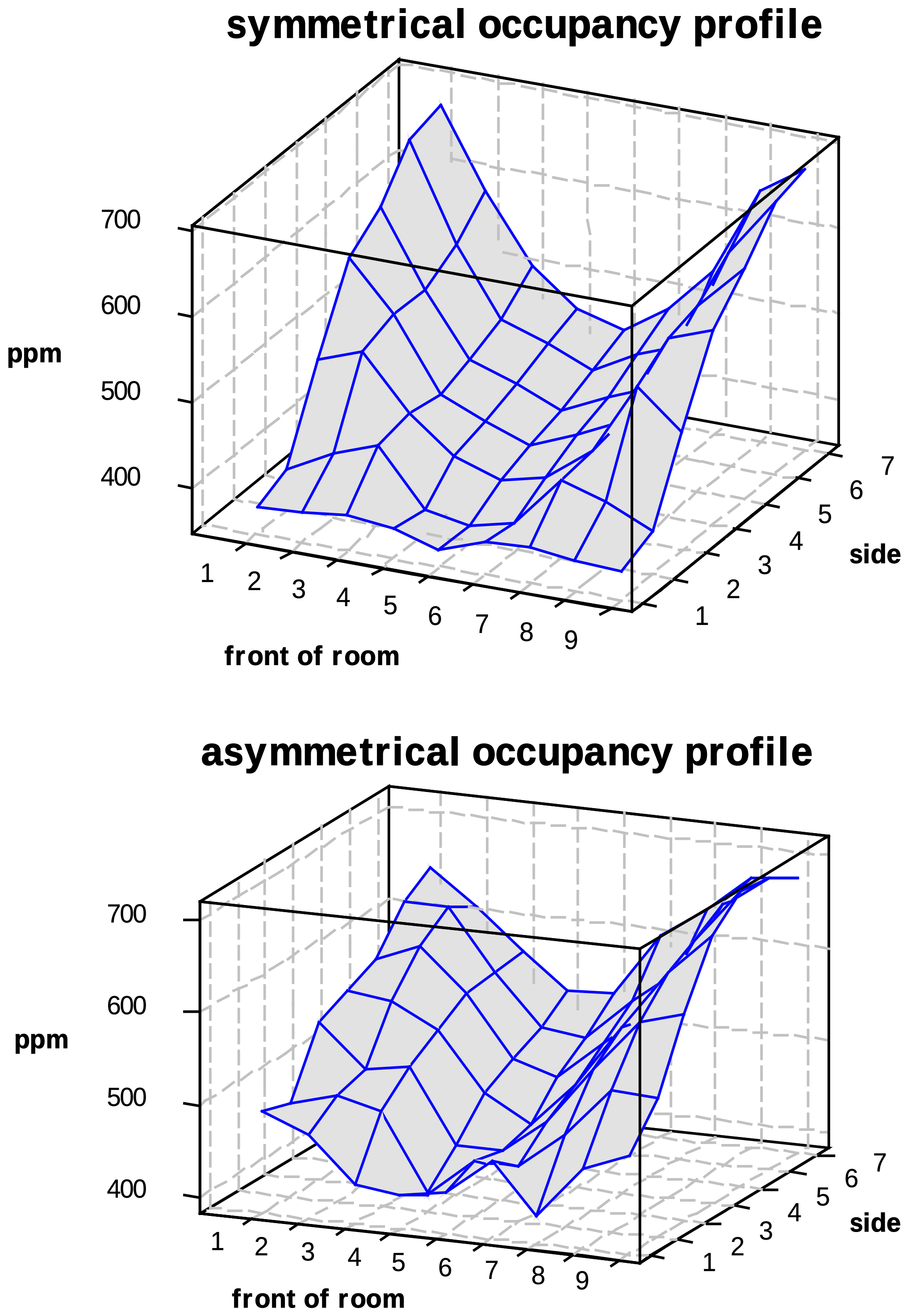


Figure 7.24 CO_2 concentration surface plots of the simulated occupancy profiles

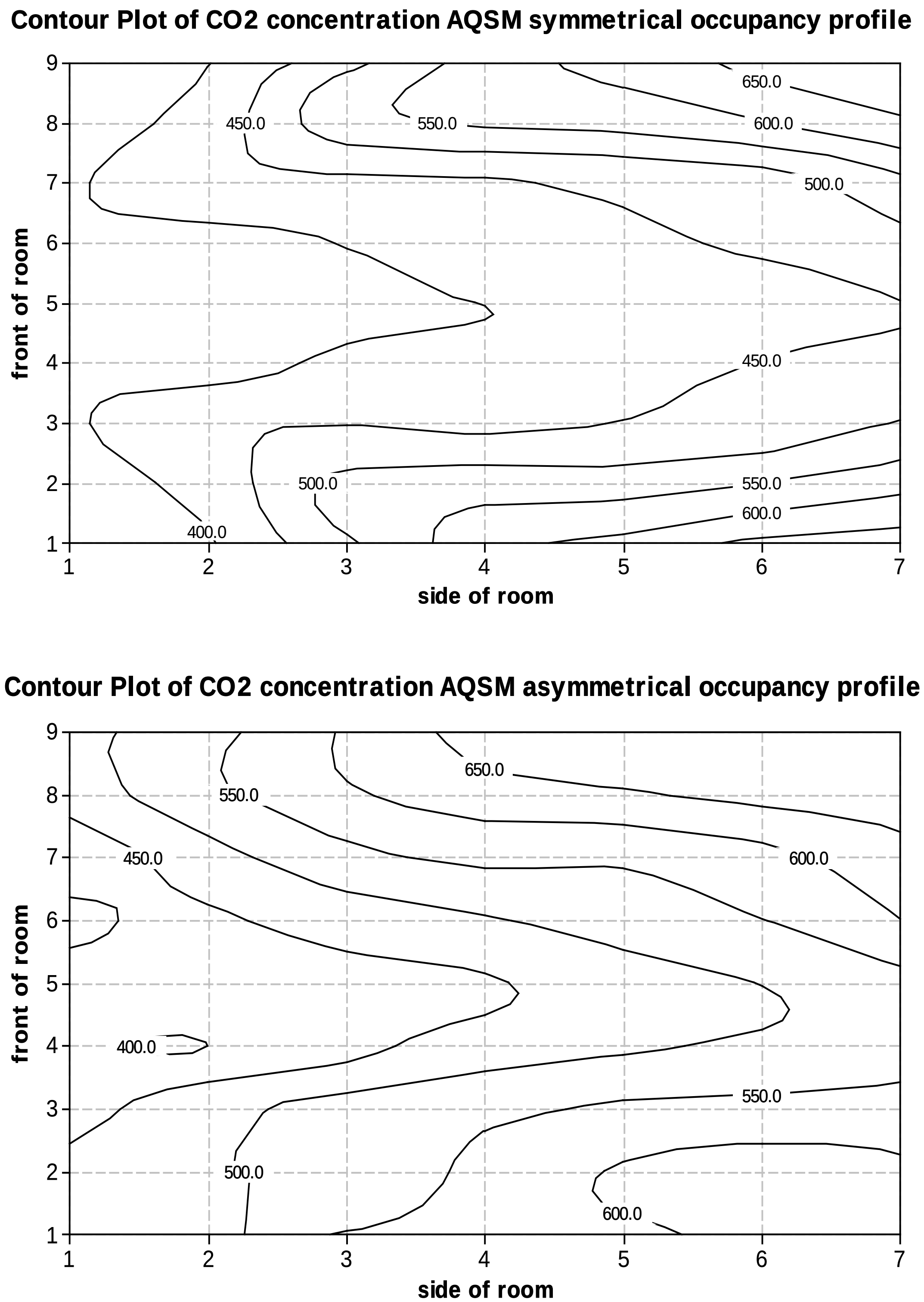


Figure 7.25 Contour plots of CO_2 concentration for the occupancy profiles

2. Local Mean Age of air distribution

The LMA output from the two different occupancy profile AQSMs were compared using standard analysis of variance tests (ANOVA and Kruskal-Wallis), in addition to a Friedman Test to determine whether the occupancy profile influenced the distribution of the LMA. The statistical tests of variance for the LMA values suggested that there was no significant difference on the average LMA when the occupancy profile was changed. However, the three-dimensional surface plots (Figure 7.26) of the LMA show the effect the occupant seating position has on the airflow.

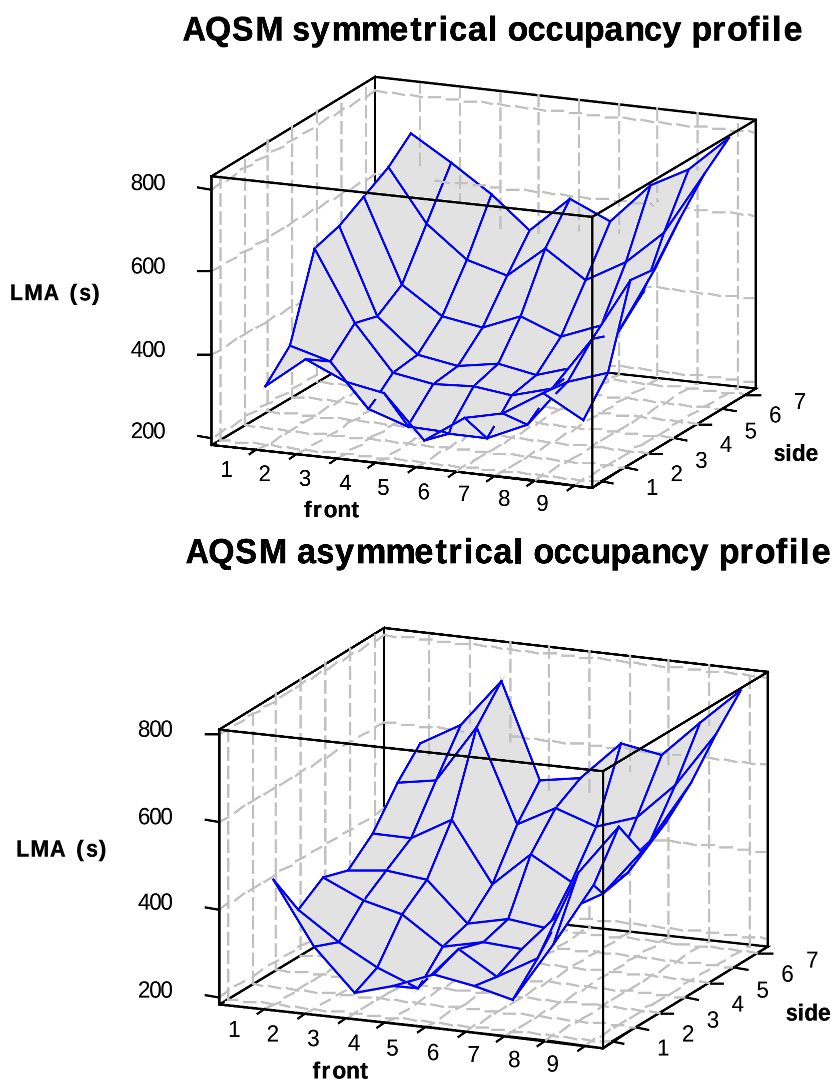


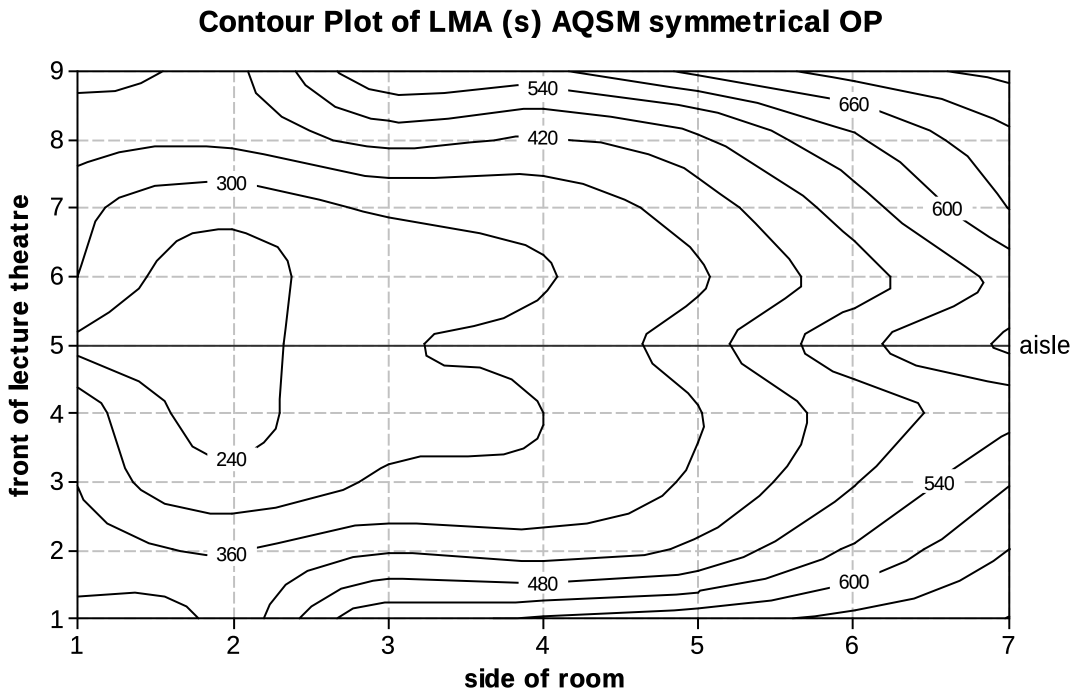
Figure 7.26 3D surface plots of LMA values of the simulated occupancy profiles

The most noticeable difference between the surface plots of the LMA values for the AQSMs, was the location of the peaks of higher LMA values towards the back of the lecture theatre. The symmetrical occupancy profile shows a symmetrical LMA distribution but the asymmetrical occupancy profile has a less symmetrical LMA distribution. As the airflow rate was the same in both AQSMs, the difference in LMA values is probably due to the physical obstruction of the airflow by the occupants.

This obstruction to the airflow pattern that is additionally illustrated in the contour plots (Figure 7.27). The AQSM of the symmetrical occupancy profile had a contour plot that was symmetrical about the aisle region (approximately at mbz 5). The AQSM of the asymmetrical occupancy profile showed a different distribution of LMA values due to the changing seating pattern of the occupants. Changing the location where students were sitting in the lecture theatre influenced the LMA values.

7.4.4 Discussion

Acceptable air quality in the breathing zone of the lecture theatre benefits the occupants. The outcome from the CO_2 simulation analysis was that the concentration of CO_2 in the breathing zones differed according to occupancy profile. This was not however the case for the LMA, where the change in spatial distribution was due to the obstruction of the airflow by the occupants. The results from the CO_2 assessment are important, as they confirm that there is a difference in spatial IAQ when the seating positions of the occupants changes. This influence needs to be considered in the assessment of IAQ in a lecture theatre, as the location where people sit cannot completely be accounted for by design, as individuals will have their own preferences.



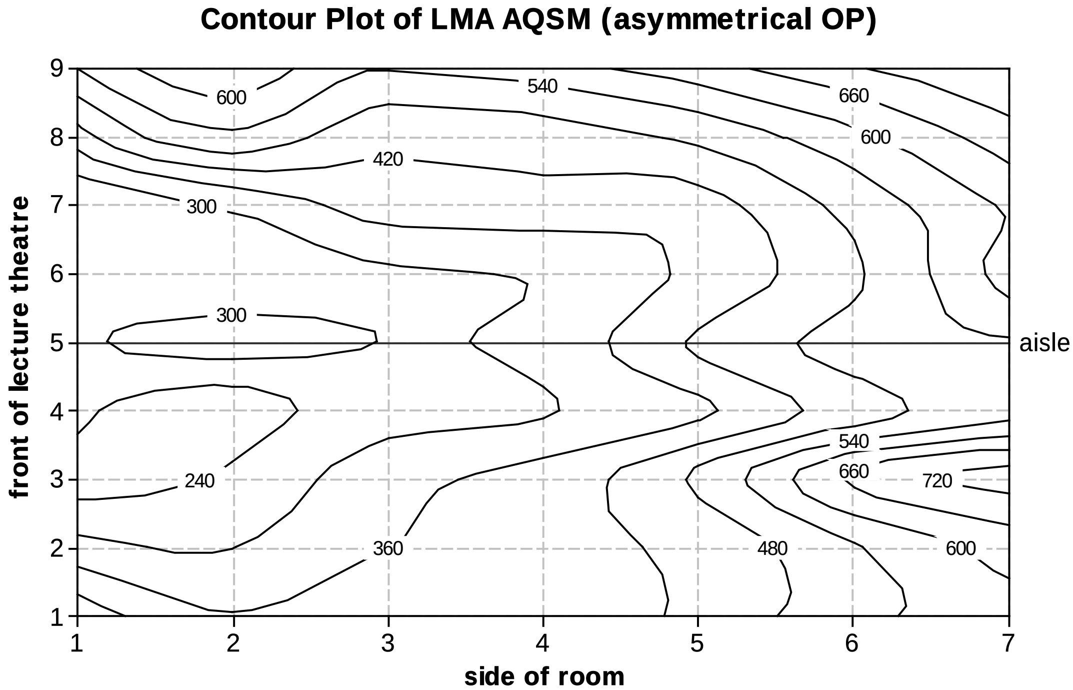


Figure 7.27 Contour plots of LMA values for the occupancy profiles

7.5 Simulation of IAQ using different supply grille arrangements

A simulation was carried out to investigate the effect of moving the supply grilles towards the rear of the lecture theatre (Figure 7.28 and Figure 7.29). Four supply grilles were moved to regions in the lecture theatre which had high concentrations of CO_2 and LMA values that were established from earlier simulations. This produced a new simulation that was compared with the results of the previous AQSM. The ventilation rate used in both AQSMs was the minimum airflow rate (three ACH) and had 82 students sitting in a symmetrical occupancy profile.

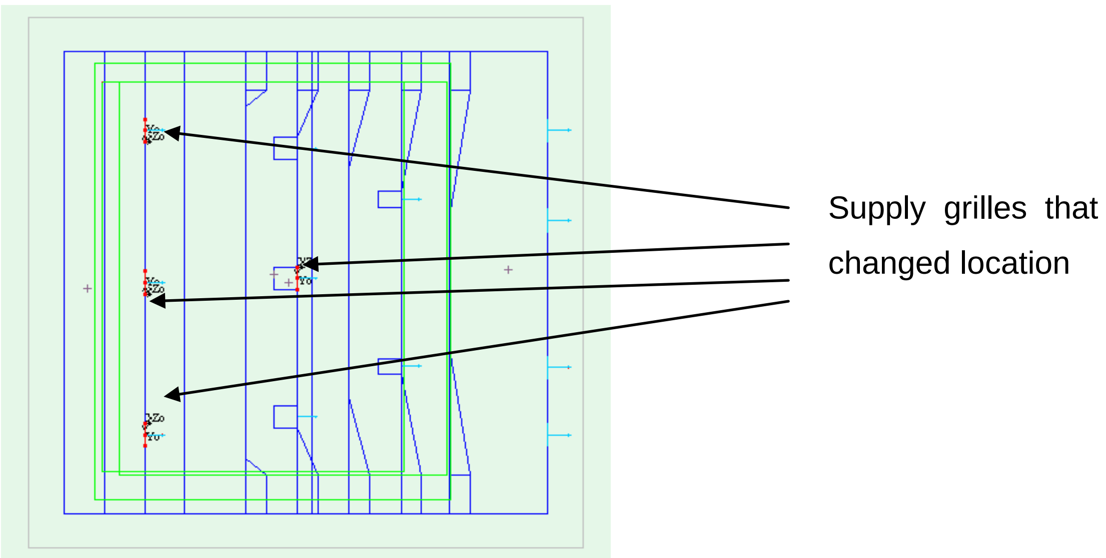


Figure 7.28 AQSM of supply grille position one

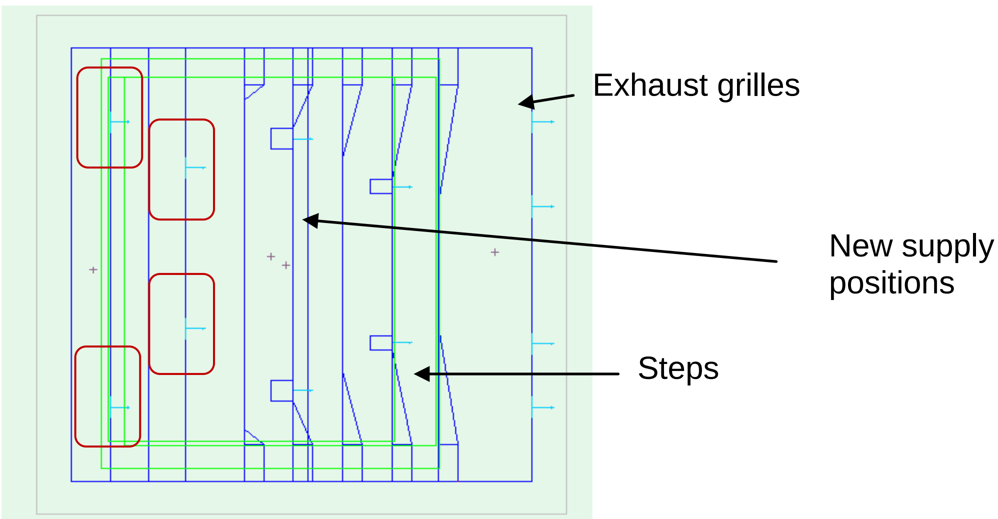


Figure 7.29 AQSM of supply grille position two

7.5.1 Results and analysis

The simulation process resulted in four data sets for each AQSM of the two supply grille positions modelled. The concentration ranges of CO_2 concentrations (Figure 7.30) produced by changing the supply grille positions indicates that there is little difference in concentrations. Both ranges of concentrations are symmetrical and skewed towards lower CO_2 concentrations. Therefore, the median was taken as the spatial average CO_2 concentration in the breathing zone.

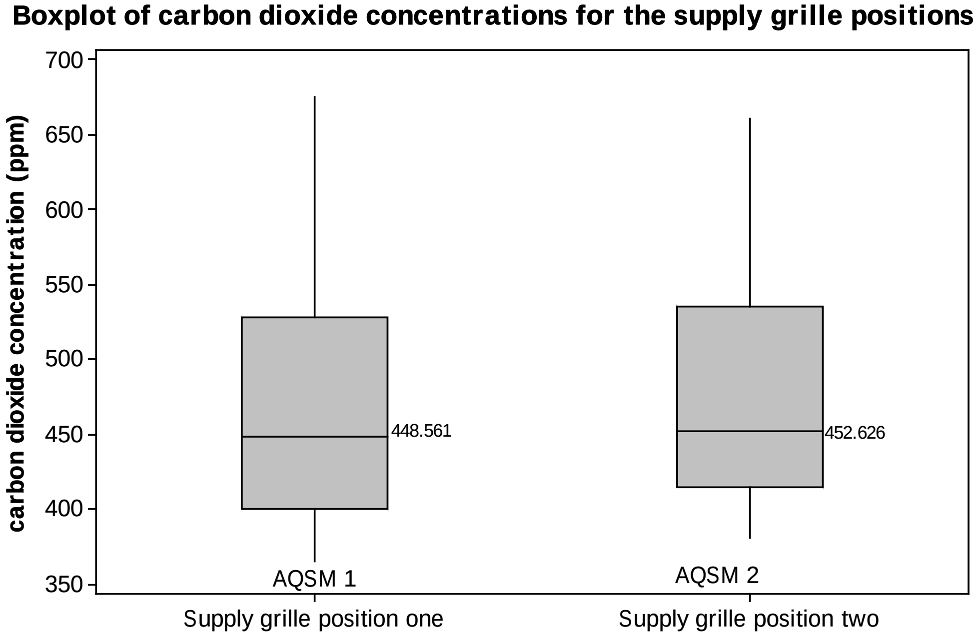


Figure 7.30 Box plot of CO_2 concentrations for the supply grille positions

Nonparametric distribution was confirmed by an Anderson - Darling normality test which showed ($p<0.05$) at the 95% confidence level that the data did not follow a normal distribution. The CO_2 concentration (mean and median) for both cases are close (Table 7.8).

Case	Mean	s.d	Minimum	Q1	Median	Q3	Maximum
AQSM 1: old	473.6	87.5	365.0	400.8	448.6	528.1	675.5
AQSM 2: new	478.7	76.9	381.5	414.7	452.6	535.3	660.9

Table 7.8 Summary of CO_2 concentrations

The similarity of the CO_2 distributions for AQSMs of different supply grille positions are illustrated in the concentration frequency distribution histograms in Figure 7.31. Both CO_2 data are positively skewed towards the lower concentration scale, and the greatest number of observations for both supply grille positions occurs at CO_2 450 ppm. The observations from the simulation results suggest that changing the location of the supply grilles at the back of the lecture theatre does not alter the CO_2 distribution in the breathing zone.

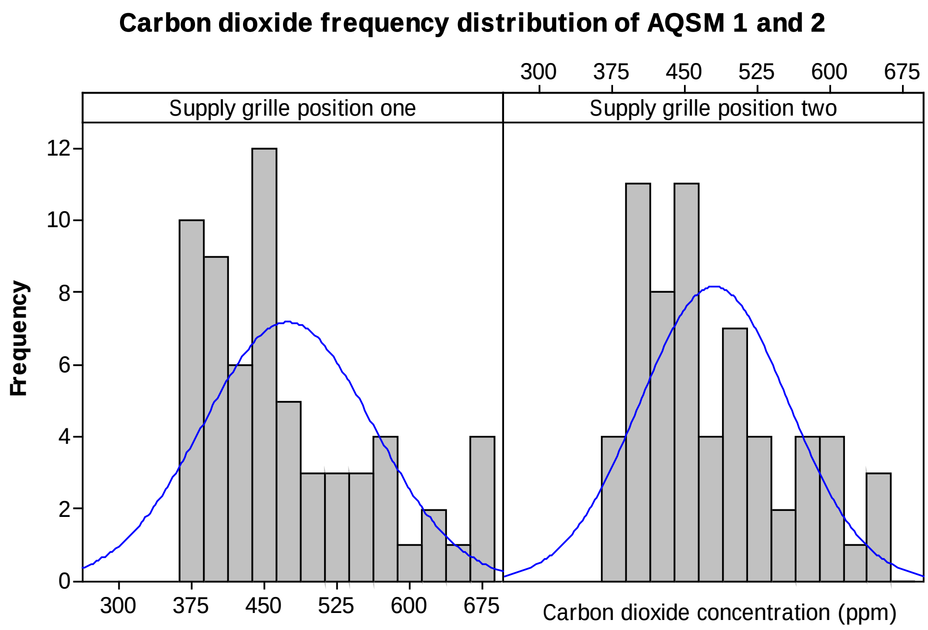


Figure 7.31 CO_2 concentration frequency distribution of AQSM 1 and 2

Supply grille arrangement	N	Median	Ave Rank	Z
Position one	63	448.6	60.9	-0.79
Position two	63	452.6	66.1	0.79
Overall 126	63.5			

H = 0.63 DF = 1 P = 0.428

accept the null hypothesis Ho

Table 7.9 Kruskal-Wallis Test on concentration

A Kruskal-Wallis (Table 7.9) test on the medians suggested that there was sufficient evidence that the two distributions were not significantly different at a 95% confidence level (p=0.428). Therefore, even though the distributions appeared similar, there was no significant effect on the carbon dioxide concentration when changing the supply air grille location. The CO_2 and LMA distributions are examined in the following subsections.

1. Spatial CO_2 distribution

To investigate further the predicted outcomes from the supply grille AQSMs, three-dimensional CO_2 concentration plots for the two AQSMs (Figure 7.32) were drawn. The similarity between the simulation results for the two different supply grille positions is reflected in the plots. Both distributions have roughly the same three-dimensional shape due to the similarity of CO_2 concentrations in the mbzs. The back and sides of the room in both cases had peak concentrations of CO_2. Therefore, moving the supply grilles did not improve the simulated ventilation to these regions in the modelled lecture theatre.

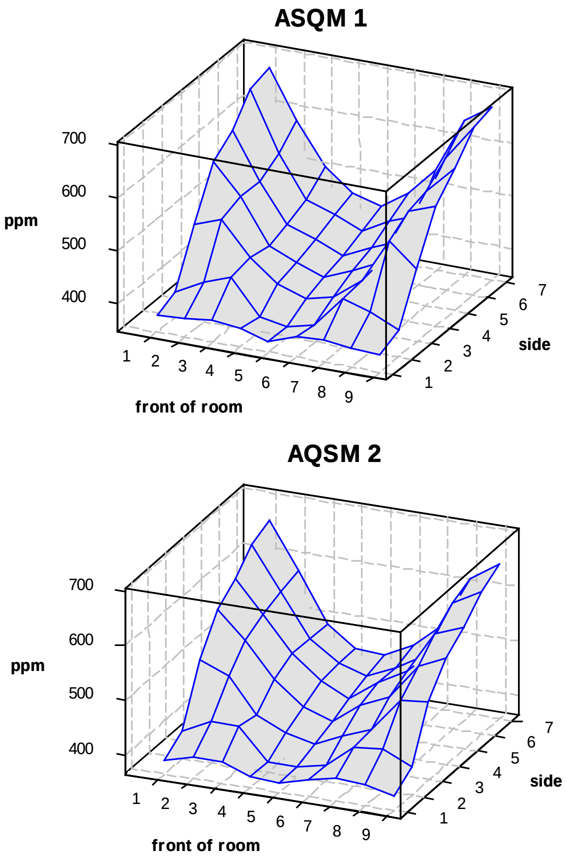
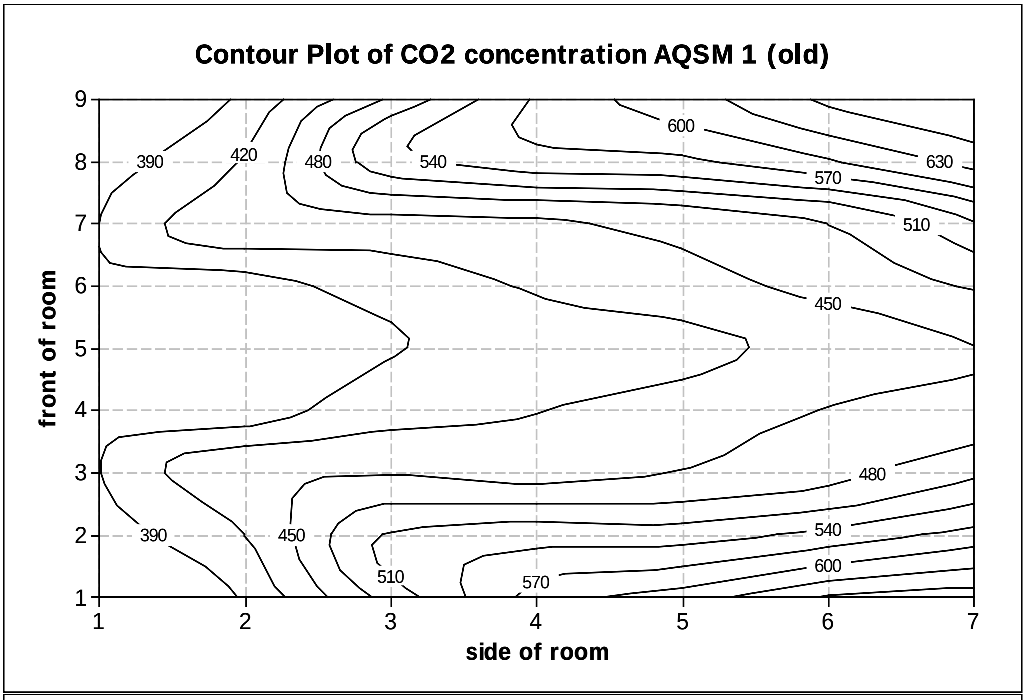


Figure 7.32 3D surface CO_2 concentration plots of supply grille AQSMs

Some differences were observed in the simulation results. The small changes in CO_2 concentrations from altering the supply grille locations are seen in the contour plots (Figure 7.33). The main difference occurs at the front of the room, in row 1. The CO_2 concentration in this row is higher in AQSM 2 (new), although the number and position of the occupants were the same as in the AQSM 1 (old).



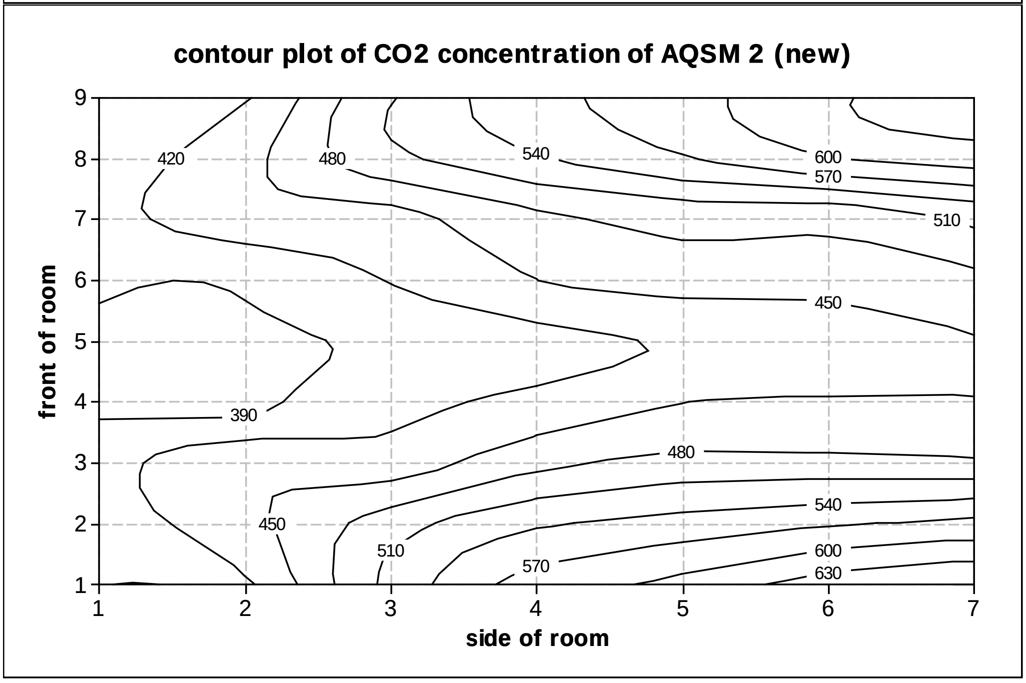


Figure 7.33 Contour plots of CO_2 concentration for the supply grille AQSMs

2. Distribution of LMA

Statistical testing of the LMA for each model found that changing the supply grille locations did not significantly affect the shape of the LMA distribution. However, this did not demonstrate that the two AQSMs had the same spatial LMA distribution. Therefore, to examine further any effect of moving the supply air grilles the LMA was plotted in three-dimensional surface plots (Figure 7.34).

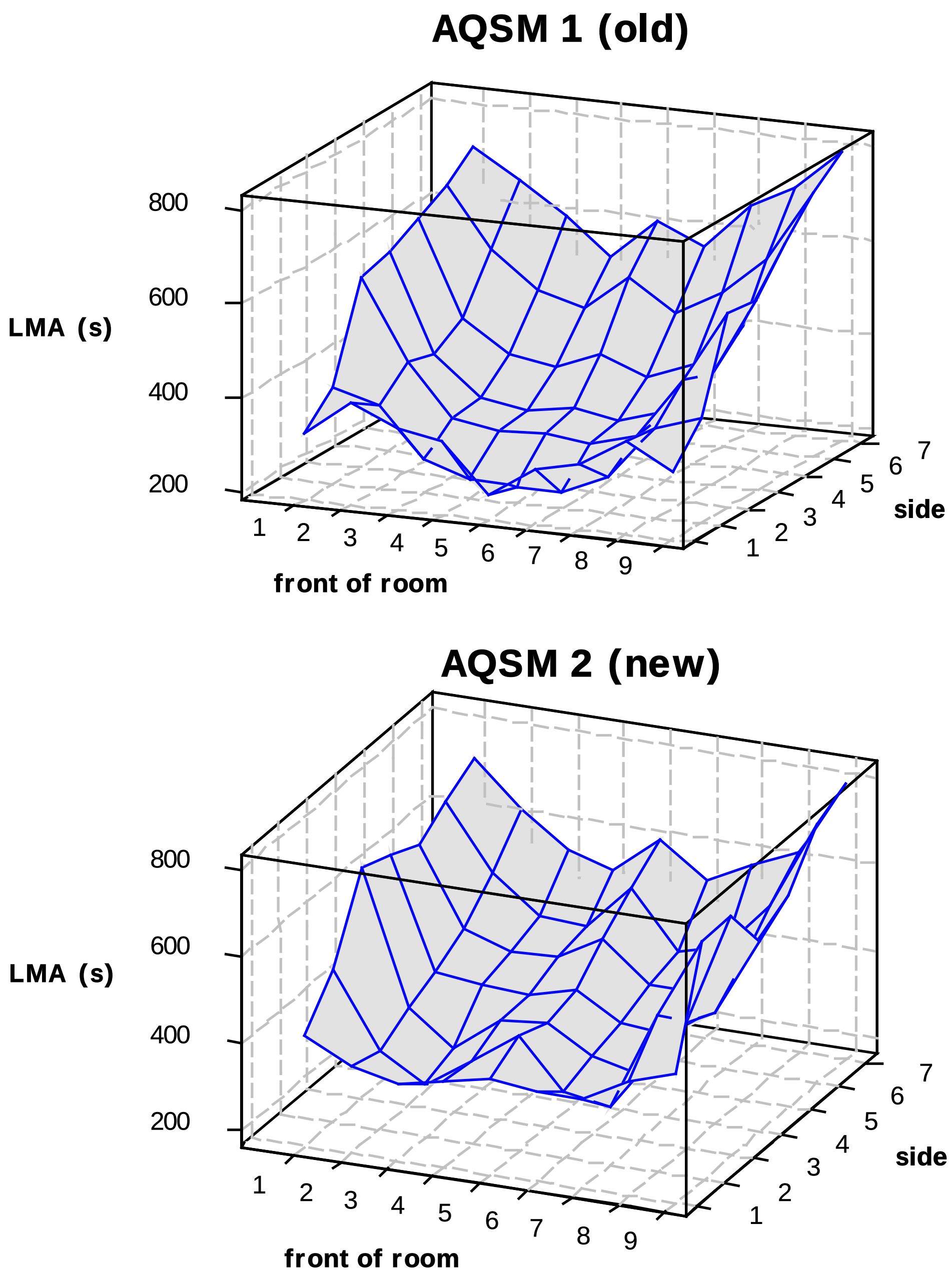


Figure 7.34 LMA D surface plots of supply grille position AQSMs

Small changes are seen in the LMA contour plots of the supply grille position AQSMs (Figure 7.35). The main differences in the contour lines of the models are towards the front of the room between the side rows, one to four. The change at the front of the room is seen in the contour at the front mbz column number 5 in AQSM 2. This had a higher LMA value of 420 seconds, as opposed to the same position in the simulation of supply grille position one of 240 seconds. The contours of LMA values in AQSM supply grille position two on both sides of the room are closer together than in AQSM supply grille position one. Therefore, AQSM 2 showed more pronounced peaks of older age of air at the sides of the breathing zone than in AQSM 1.

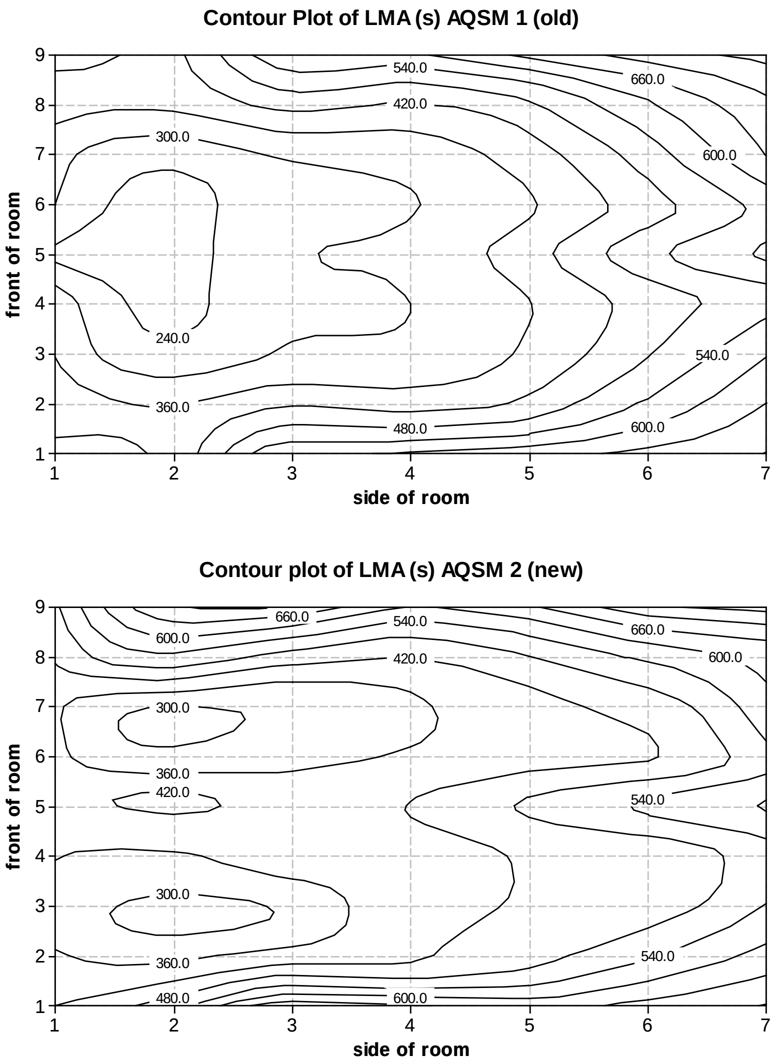


Figure 7.35 Contour plots of LMA for the AQSMs

The change in CO_2 concentration distribution was predominantly due to the change in the pattern of airflow resulting from changes to the supply grille arrangement. This was illustrated in the changes at the front of the room and at the sides of LMA contour patterns. Changing the position of some of the supply grilles however, did not significantly improve the CO_2 distribution in the lecture theatre.

7.5.2 Discussion

The effect of altering the supply inlets was examined by moving a selection of air inlets into previously observed dead zones of air, in the region at the back of the lecture theatre. The distribution of data was both normal and nonparametric, and it was found that there was no significant difference between the medians. Considering the overall IAQ level, (both CO_2 and LMA) these two medians had similar values, and were not statistically different. In this respect, neither arrangement improved the IAQ according to the assessment criteria. However, a further study could investigate the effect on IAQ resulting from increasing the number of supply inlets as compared to changing their position.

7.6 Review of the AQSM

Using the assessment methodology to run the simulations described in this chapter produced several outcomes. Eight variations of the modelled lecture theatre were simulated: three ventilation arrangements; four ventilation rates; two different seating profiles, and two variations in supply grille location. All the simulations attempted to determine which combination delivered the most acceptable IAQ level and distribution.

As discussed previously (Chapter 3) the assessment of IAQ by using a single zone homogenous assumption has limitations when applied to a lecture theatre. The main issue is that it takes a long time taken to attain a complete and instant homogenous state in a lecture theatre and class is unrealistic in normal use.

The AQSM approach described here has several advantages over the single zone homogenous assumption. As Table 7.10 shows, the AQSM can consider additional important variables to produce a more realistic outcome on the timescales of which lecture theatres are occupied.

Approach	Occupant number	Occupant position	VA	Ventilation rate	Breathing zone	Room volume
Homogenous IAQ assessment	✓	×	×	✓	×	✓
AQSM	✓	✓	✓	✓	✓	✓

Table 7.10 Variables assessed by the methodologies

The developed assessment methodology is flexible to the user's requirements. It can be used to assess the IAQ in the breathing zone of both the lecture theatre as a whole or in smaller regions of the lecture theatre for detailed IAQ prediction. This ability to adapt the AQSM to the particular requirements of the user is novel.

The assessment methodology described in this chapter concentrated on the breathing zone in the room, but the process can be extended to the whole room volume if required. This is because a selected volume is divisible into smaller volumes for use in the assessment. The location of the occupants is also accounted for in the developed methodology. This is important as the occupants present physical obstructions to the airflow provided by the ventilation arrangement, and are sources of contaminants (in the case of CO_2)

The developed assessment methodology was developed for a specific example of a large space, a lecture theatre, and as such is aimed at rooms with a similar topography. The primary sources of indoor pollutants simulated were point sources, the occupants, as opposed to area sources such as wall surfaces. The assessment methodology is principally concerned with ventilation by mechanical means and not natural ventilation. This is because natural ventilation is largely unsuitable for lecture theatres and this was accepted when the IAQ assessment methodology formulated in this research was under development.

The developed assessment methodology gave a more refined and detailed assessment of IAQ in a lecture theatre than when using the homogenous assumption. The broader implications of the developed methodology were that it provided detailed IAQ predictions for use in design scenarios. The benefits of the AQSM methodology are summarised as follows:

- Uses predetermined sub-volumes of the breathing zone to predict values of the variables in each of the sub zones to map the spatial distribution of IAQ.
- Takes into consideration the physical plan of the room and the furnishings.
- Considers the airflow pattern produced by the ventilation method and arrangement.
- Uses state of the art software to generate predictive data.
- Enables data output in several formats.
- The 3D output visually portrays the variations in magnitude and the spatial position of the IAQ.
- Additionally predicts the overall and maximum pollutant concentration for use in an evaluation.
- Parameters can be altered in an iterative order to achieve an optimum IAQ.
- Can be adapted to use any known gaseous pollutant.
- Can be used to consider area sources of pollution as well as point sources.

7.7 Conclusions

The AQSM was used to simulate the effect on IAQ of changing four variables: method of air distribution, ventilation rate, occupancy profile and supply air grille location in a lecture theatre. The results illustrated the horizontal and vertical spatial variation in the IAQ (in terms of the LMA and CO_2 distribution) in the four different cases. The differences are summarised in Table 7.11.

The simulations predicted the patterns of IAQ in the breathing zone and the methodology was capable of producing detailed IAQ maps. It thus has the potential to be used at the design stage, for example in analysing whether problems such as poor circulation areas exist within the breathing zone. It presents an opportunity to modify the seating pattern to avoid areas of poor circulation or to address this through improved ventilation arrangements.

It is important when ventilating a lecture theatre that unnecessary high ventilation rates should be avoided as this affects energy use. The assessment methodology can provide important information on the anticipated IAQ resulting from a proposed ventilation arrangement and offer the potential to avoid post occupancy complaints from room users. Thus, time spent at the design stage in order to provide energy-efficient and acceptable IAQ should be considered as an investment.

The most recent Buildings Regulations in 2006 were concerned with reducing energy consumption of buildings whilst providing ample ventilation. The mandatory move to compulsory air tightness testing reinforced the mantra of “build tight ventilate right”. Providing acceptable IAQ is still predominantly considered to be achieved by specifying the correct ventilation rate in the building design. The consideration of IAQ is thus not fully included in the design of lecture theatres. If however, an IAQ assessment was included in the design brief, then the developed approach offers the potential to produce energy efficient ventilation arrangement tuned to the design characteristics of the lecture theatre.

Case	Outcome	Significance
Selection of most appropriate ventilation system capable of delivering required IAQ in the space. AQSM 1, 2, 3.	The displacement ventilation system had the most variation of IAQ in the breathing zone. AQSM one; (high-level mixing method) was the most appropriate method of air distribution according to the example criteria.	The average IAQ level was significantly different between the three methods of air distribution. The difference in the ventilation methods was additionally portrayed in the IAQ maps.
Selection of a ventilation rate that satisfies a design criteria AQSM of minimum to maximum airflow rates.	Slightly lower overall carbon dioxide concentration and LMA with increasing air change rate. Model A the lowest ACH provided acceptable IAQ.	An inverse relationship between the ventilation rate and CO_2 concentration was not observed in the breathing zone. The difference between 3 and 6 ACH in the overall CO_2 was 40 ppm.
Assessment of the effect that varying the occupancy profile has on the IAQ distribution. Occupancy profile AQSMs	A change in IAQ, occurred related to occupant seating arrangements. Symmetrical seating experienced better overall IAQ.	The occupants have an effect on IAQ distribution: this should be considered in the room design.
Alteration of the supply air grille locations.	No difference in IAQ resulted from altering the supply grille locations.	Modify the design by changing other variables.

Table 7.11 Assessment outcomes

IAQ design expertise using CFD exists but is largely employed in the aeronautics and automotive industries. This approach to IAQ is not routinely employed in the built environment, other than in specific designs for air quality in clean rooms, for example, operating theatres. The simulations described in this chapter justify the use of CFD in the assessment of IAQ. This research has shown that the CFD methodology can be used in the detailed prediction IAQ in lecture theatres and can stimulate alternatives thus leading to design optimisation.

CHAPTER EIGHT

Discussion

8.0 Summary

The purpose of the study was to understand more about the indoor air quality (IAQ) comfort of lecture theatres. Thermal comfort in lecture theatres is included in published industry design standards, whereas IAQ is not subject to the same level of guidance. However, in addition to appropriate thermal comfort, occupants also need to be provided with an environment that has acceptable IAQ.

The aim of this research was focused on the development of a methodology capable of assessing IAQ in lecture theatres using non-homogenous conditions. This concluding chapter reports the key findings of the research, including how IAQ is commonly assessed. The pilot study outcomes are summarised as this information informed the development of the IAQ assessment methodology that incorporates a predictive IAQ model. The verification of the predictive IAQ model and the capabilities of the assessment methodology in testing four key variables influential to IAQ are additionally described. The chapter outlines how the aim and objectives were met, includes the general conclusions, and closes with recommendations for future work.

8.1 Key findings

IAQ is often overlooked in many indoor environments including lecture theatres, as the emphasis is placed primarily on energy efficiency. Providing acceptable air quality at the lowest possible ventilation rate is beneficial for the operational energy savings as it can influence the building's CO_2 emissions, or "carbon footprint". However, a complex relationship between IAQ and building ventilation exists, with the ideal being an efficient energy ventilation system that delivers acceptable IAQ.

The ventilation of the building is important in terms of removing the heat load, in addition to providing adequate amounts of fresh air but in some cases the ventilation system itself is a source of IAQ concern. Many non-residential buildings rely on some form of mechanical ventilation rather than natural ventilation for the supply of fresh air and the removal of stale air. Nevertheless, mechanical ventilation methods can use significant quantities of energy, which is a significant consideration due to the monetary cost to the building owner (Pennycook, 2009).

The impact upon energy use of providing satisfactory IAQ must be considered. It is generally believed that introducing air quality control in ventilation systems will increase the energy demand in buildings. This may not always be the case, as the design and the operation of ventilation systems primarily influence the energy requirement (Roulet, 2001). The main design requirement for mechanical air distribution methods is to provide the minimum required ventilation rate under the building regulations; as this is the only regulation that needs compliance (Office of the Deputy Prime Minister, 2006).

A common misconception is that a high ventilation rate ensures acceptable IAQ and a way to avoid IAQ problems is to over ventilate the space. Using a high ventilation rate entails a high fuel cost. However if the behaviour of the IAQ within the breathing zone is known, over ventilation could be avoided and therefore conserve the ventilation system's operational energy and reduce its running cost. Thus, there is a need to assess the IAQ delivered by ventilation methods before installation, ideally at the building design stage, to ensure energy efficient operation and the air comfort of the building occupants.

In universities, students spend a great deal of their time in lecture theatres. Any feelings of discomfort in a lecture theatre are significant, as that particular environment should be as comfortable as possible to provide a conducive learning experience (Daisey *et al.,* 2003). The literature review in Chapter 2 showed that a majority of studies in lecture theatres were concerned with the thermal comfort of the room and not directly with IAQ. As a result, the theme of this research focused on investigating air quality in lecture theatres in order to increase the understanding of the occupant comfort in this indoor environment.

8.1.1 Current IAQ assessment

A review of existing literature highlighted the difficulty of the measurement of IAQ in lecture theatres. The large room size required the use of many monitoring sites to obtain a representative understanding of IAQ in the space. Due to the complexity of the problem, it was commonly assumed that well mixed (homogenous) conditions occur within the occupied space, as this simplified the IAQ assessment. Thus, a homogenous assumption is widely used in assessing IAQ.

It is feasible that a single zone homogeneous state might be attained in all spaces, given enough time. Whether homogenisation actually occurs in lecture theatres in a reasonable amount of time during the occupation of the building is debatable. Other authors (Gadgil *et al.,* 2003;Richmond-Bryant *et al.,* 2006;Sekhar and Willem, 2004) share this view. This, therefore, indicated shortcomings with assuming homogenous indoor air conditions in lecture theatres.

The limitations of using a homogenous approach to assess IAQ in lecture theatres were considered in Chapter 3. The important constraining factor in applying this assessment methodology to lecture theatres is that it cannot simulate variations in IAQ, in particular, differences in airflow pattern resulting from different ventilation arrangements and obstructions to airflow (Sekhar and Willem, 2004). It was concluded that using a homogenous assumption to assess IAQ in lecture theatres was an oversimplification and a methodology using a non-homogenous assumption would deliver a more representative assessment of occupant comfort with IAQ in lecture theatres. This research therefore focused upon the investigation of non-homogenous conditions in lecture theatres. The specific IAQ assessment methodology for a lecture theatre should reflect any IAQ variation and give an indication of the spatial IAQ distribution in the breathing zone in order to assess the IAQ comfort of the occupants.

8.1.2 Experimental findings

In order to examine the extent of homogenous conditions in a lecture theatre a pilot study was conducted (Chapter 4). The pilot study was carried out in a newly built lecture theatre (Mayfield House) at the University's Falmer campus. Carbon dioxide was selected as an IAQ indicator in the lecture theatre. This indicator was chosen as it is produced by occupation of the room and its concentration can be used to indicate the performance of the ventilation system in removing contaminants and stale air. Hence, CO_2 measurements were regarded as a surrogate indicator of inadequate IAQ (discomfort) in lecture theatres.

Lecture theatres are designed by appreciating that they are not always fully occupied. The pilot study was performed using two different lectures. Carbon dioxide concentrations were continuously monitored at three different locations in the room. The results of the study indicated that there was spatial variation of CO_2 concentrations in the lecture theatre. This indicated that indoor air conditions inside the lecture theatre were not well-mixed. Therefore, a homogenous approach is an unwarranted assumption in such rooms because of their particular spatial and temporal patterns of occupation.

This research concluded that a homogenous approach was inappropriate to assess the IAQ comfort experienced by occupants in a lecture theatre. Hence, there was an opportunity to develop a novel IAQ assessment methodology for lecture theatres and similar types of rooms such as cinemas and auditoria which was based on not assuming homogenous conditions. Thus, the proposed IAQ assessment methodology required a means of representing non-homogenous indoor air conditions.

The pilot study additionally found that empirical IAQ measurement in lecture theatres had limitations with the number of monitoring points required to assess the IAQ. This was because experimental data collection required sufficient measurement points to represent IAQ variations in the lecture theatre breathing zone. This important finding led to the rationale for using computer simulation.

8.1.3 Air quality simulation model

In the design of specific room types where IAQ is considered vital, such as hospital clean rooms, software is routinely used. However, IAQ is not usually a specific design consideration for other types of rooms in the built environment. A review of the literature on IAQ assessment methods showed that the use of software in the study of IAQ is becoming more prevalent. This is especially the case for computational fluid dynamics programs, which are capable of simulating airflow and pollutant concentrations by processing complex equations (Alamdari, 1994).

The use of computer modelling is advantageous because of its potential for investigating different design scenarios which would not be feasible in an experimental setting. For instance, using many monitoring points in a field study would require increased amounts of equipment, longer set up time and potentially more interference with the occupants' use of the room. Also the large amount of data produced would require lengthy analysis on the part of the assessor. Therefore, it was concluded that CFD was an appropriate tool to simulate IAQ in an assessment of lecture theatres.

In addition to removing the need for physical sampling equipment, software can allow the investigation of different designs and scenarios to simulate the effect from different variables on the occupant IAQ comfort in a lecture theatre. To represent the non-homogeneity in lecture theatres, parameters that were capable of portraying spatial IAQ variation were reviewed. The outcome was that carbon dioxide concentrations and local mean age of air values were selected as the most appropriate measures of IAQ for use to describe the spatial IAQ distribution. Therefore, the developed IAQ assessment methodology used computer fluid dynamic software to produce an air quality simulation model (AQSM) for predicting the IAQ in lecture theatres.

8.1.4 Verification of the predictive IAQ model

The computer model resulting from applying the IAQ assessment methodology was tested in two ways using a longer duration survey of a lecture theatre.

Firstly, the non-homogenous premise of the developed methodology was validated by collecting a larger amount of empirical data than that acquired in the pilot study. Secondly, the AQSM output was examined by its application to several lectures and comparison with measured data. These two exercises were therefore key in exploring the developed IAQ assessment methodology, in order to determine its validity and practicality.

The carbon dioxide concentrations were measured in a different lecture theatre (Lecture Theatre 1) for three weeks at six different measurement locations, for a range of lectures with varying occupancy numbers. During extended empty periods (overnight, and at weekends) the measurements illustrated that the CO_2 decreased to concentrations close to ambient levels. The conclusion from large-scale data collection was that CO_2 concentrations varied significantly between sampling locations at the same time point. This outcome supported the finding from the pilot study and reiterated that well mixed conditions did not occur during the occupancy of the lecture theatre, thus validating the non-homogeneity premise of the IAQ assessment methodology.

The performance of the AQSM was examined by applying the developed methodology to two different lectures in LT1. The results from applying the assessment methodology from each modelled lecture were compared to the CO_2 measured during the corresponding lectures. The IAQ assessment using the methodology gave comparable results to the monitored CO_2 concentration. This result illustrated that the assessment methodology was applicable to the assessment of occupant IAQ comfort in a lecture theatre.

8.1.5 Capabilities of the IAQ assessment methodology

The premise that IAQ in a lecture theatre varied throughout the space led to the deduction that four key variables affect IAQ. These variables are the method of air distribution, the ventilation rate, the occupancy profile, and the position of air grilles. The developed IAQ assessment methodology was applied to these four variables and described in Chapter 7. The significance of the simulations are described as follows.

To assess the method of air distribution, three types of ventilation methods were used. These were mixing ventilation, displacement ventilation, and piston flow. Displacement ventilation arrangements directly supply fresh air in the proximity to the occupants and would be expected to deliver acceptable IAQ at an energy efficient ventilation rate. However, the AQSM predicted the difference between the distributions was statistically different, as all three methods of air distribution delivered different IAQ levels.

For the displacement ventilation simulated, approximately 12% of the occupants received higher CO_2 concentrations than 4% of occupants that were supplied by mixing ventilation. Even though the mixing ventilation system had a slightly higher average CO_2 concentration, it still performed better in delivering a comfortable IAQ when compared to a displacement ventilation system. Importantly, a displacement ventilation system is widely recommended for lecture theatres due to the room height (Schild, 2004). However, the application of the assessment methodology to the ventilation system types, found that a mixing ventilation method of air distribution delivered a better IAQ distribution than the displacement ventilation system normally recommended for lecture theatres.

A displacement ventilation system was modelled in the second simulation to examine the effect of changing the ventilation rate on IAQ. The AQSM of the displacement ventilation system predicted that although increasing the ventilation rate lowered the CO_2 concentrations, as expected, but it did not improve the delivery of fresh air to the occupants in the lecture theatre. In the lecture theatre design that was simulated, using a higher ventilation rate than the recommended minimum of three air changes per hour was unnecessary. The assessment methodology predicted that the occupants could still receive acceptable IAQ, without the need for using high ventilation rates. This would lower energy costs.

As the displacement system is typically recommended for lecture theatres, such a system was again used to simulate the effects of occupancy profile on CO_2 concentration and LMA. In the model lecture theatre, it was found that changing the occupancy seating profile significantly influenced the spatial average IAQ level and its distribution, with a symmetrical seating profile experiencing improved IAQ. This highlighted the significance of the occupants seating pattern on the IAQ in the lecture theatre which should be appreciated when considering the delivery of acceptable IAQ to the occupants.

In order to simulate the effect on IAQ from two supply grille arrangements, four supply inlets were moved to previously identified zones with less fresh air but for this AQSM there was no significant change. Overall, the use of the assessment methodology predicted that changing the method of air distribution in the lecture theatre produced the most significant change in relation to the delivery of comfortable IAQ to the occupants.

8.2 Conclusions

Students spend a great deal of time in lecture theatres and this environment should provide a conducive learning experience, not only in terms of thermal comfort; but also in terms of the IAQ. For this reason, the IAQ in a lecture theatre should be considered alongside thermal comfort. Lecture theatres have distinctive design and occupancy characteristics and the IAQ assessment methodology used should be able to deal with these. The absence of such a methodology was identified as a gap in the current knowledge that this research would fill.

Carbon dioxide represents a useful surrogate measure for ventilation and IAQ. Levels of CO_2 can indicate the ventilation characteristics of a room, and provide an indication of how effectively contaminants, such as volatile organic compounds found in the indoor air, may be removed. Raised levels of CO_2 can indicate that the room is inadequately ventilated, which can lead to occupant discomfort. This research considered CO_2 a surrogate indicator for IAQ in that, if the indoor air has low concentrations of CO_2 then the room showed be well ventilated, free from indoor contaminants, and less likely to produce occupant discomfort.

A common IAQ assessment method considers the room occupants as a mass of people together with an unwarranted assessment approach of homogeneity of air in large spaces. It was found that this approach has limitation when applied to lecture theatres. A novel IAQ assessment methodology using computer software has been developed and verified. The zoning procedure in the AQSM allowed the portrayal of IAQ at the local level. The identification of an appropriate sub zone volume (1.95 m^3) was a key stage in the research model as it allowed IAQ to be displayed at the occupant scale.

From this research, the new method rejects the homogenous assumption and allows the designer to consider the comfort of individuals compared with the comfort of the mass as a whole. This allows the personalisation of air quality for the individual and therefore allows the building designers to design for good air quality for particular places in large spaces.

The experimental validation of the AQSM predictions has illustrated that the assessment methodology provides useful results. The research aim to develop a methodology for the assessment of IAQ in lecture theatres using non-homogenous conditions was therefore met. Furthermore, the application process of the IAQ assessment methodology to hypothetical lecture theatre design scenarios showed that although the methodology employs computer simulation it is user friendly.

Applying the developed IAQ assessment methodology in the various theoretical design situations illustrated its potential for assessing the design of a lecture theatre. It was shown that it was possible to use the assessment methodology to produce a room design or ventilation configuration which could provide acceptable IAQ whilst using minimum ventilation rates. As the methodology considers the breathing zone and not the whole space, such over ventilation can be avoided and consequently have an environmental benefit in saving energy.

Modelling a spatial IAQ distribution highlights regions of acceptable (comfortable) and unacceptable IAQ in order to address any poor IAQ issues and enables design alterations to provide acceptable IAQ, and deliver energy efficiency. Importantly, the assessment criteria in the developed methodology, is left open to the user to decide on the maximum and overall level of pollutant concentration. Therefore, this is a key advantage of the assessment methodology, as the assessor can create or apply whatever judgement criteria are required for the particular lecture theatre design.

This developed IAQ assessment methodology has great promise for use in the design of lecture theatres and similar large spaces. The use of this assessment methodology can predict acceptable and comfortable IAQ to the occupants of lecture theatres and auditoria. In addition, it can be used to explore energy efficient designs and ventilation strategies.

8.3 Recommendations for future work

The methodology was modelled on a lecture theatre as an example of a large space. The application of the assessment process for application to other types of large spaces needs further exploration. It is probable that the methodology can be applied relatively easily to other types of large spaces or occupied indoor areas, particularly those such as cinemas and auditoria using tiered seating.

Two working lecture theatres in the university were used in the study. One lecture theatre was used as a model template to derive the dimensions of the sub volume of the breathing zone in the room, but both lecture theatres were used as air-monitoring sites to investigate the non-homogenous premise of the assessment methodology. The process of obtaining the dimensions of the sub volumes could repeated for other types of large spaces without tiered geometry such as sports halls, to produce corresponding mini breathing zone volumes for specific types of large spaces.

In the application of the AQSM described here, the occupants are the point sources of contaminants (carbon dioxide). The assessment methodology is not however limited to point sources, as it can be adapted to examine area sources of pollution indoors. The assessment methodology can also assess contaminants other than carbon dioxide, for example ozone from photocopiers. Thus, the assessment methodology process of creating a predictive AQSM is not limited to CO_2 as an IAQ contaminant.

Most of the modelling of the four variables described here used a displacement ventilation method of air distribution. Future work could investigate other methods of air distribution, especially methods that are not generally recommended for delivering acceptable IAQ at the lowest possible ventilation rate. Such ventilation methods and ventilation rates could be assessed using the methodology in order to confirm whether such methods really are unsuitable for providing comfortable IAQ in lecture theatres.

This research set out to investigate the air quality in a lecture theatre as an example of a large space. The study identified that there was a gap in knowledge in the IAQ assessment of lecture theatres. Consequently, to contribute to this gap, this research developed a predictive model for assessing the occupant comfort with IAQ in a lecture theatre.

GLOSSARY OF TERMS

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Acronym	Term	Definition
ACH	Air Change per Hour	The number of complete volumetric air changes of a space that occur in an hour.
ADPI	Air Diffusion Performance Index	Used to measure the uniformity of the indoor environment.
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers.	American cognisant authority
BRI	Building Related Illness	An illness with known aetiology caused by an agent in the indoor environment
CIBSE	Chartered Institute of Building Services Engineers	UK cognisant authority
CFD	Computational Fluid Dynamics	A computer simulation program that involves the examination of systems, by analysing, fluid flow, heat transfer, and related phenomena.
CRE	Contaminant Removal Effectiveness	A measure of the how effective the ventilation system exhausts pollutants from a space.
κ-ε	κ-ε	Two equation model in CFD using kinetic energy κ and the rate of dissipation ε.
HVAC	Heating, ventilation and air-conditioning	Mechanical ventilation that delivers air according to a set temperature and humidity.

LACI(ε_p)	Local Air Change Index	The age of the air at a point p, relative to the supply air inlet.
LMA	Local Mean Age of air	The average time taken for air to move from the supply inlet to any point in a space.
MBZ	Mini breathing zones	Sub divided volume of the room breathing zone.
MVOC	Microbial Volatile Organic Compounds	Classification of gaseous organic compounds specifically from species of mould.
Olf	Olf Unit	The emission rate of air pollutants arising from one standard person. (Fanger 1988)
PMV	Predicted Mean Vote	According to Fanger the PMV index predicts the mean response of a large group of people according to a thermal sensation scale +3 to -3. PMV = 3.155[0.303exp(– 0.114M)+ 0.028]L
PPD	Predicted Percentage Dissatisfied	Predicts the number of dissatisfied people. PPD = 100 – 95exp[–(0.03353PMV^4 + 0.2179PMV^2)]
ppm	Parts per million	A measure of concentration.
Ra	Rayleigh Number	A dimensionless number associated with heat transfer in a fluid.
SBS	Sick Building Syndrome	A building with an unusual number of occupants (≥20%) having a physical problem for more than 2 weeks (Schild, 2004).
VOC	Volatile organic compound	Classification of gaseous organic compounds.

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APPENDICES

Appendix A The decay equation

The decay equation for the pollutant concentration is for steady state conditions only and cannot account for the dynamic distribution of the airflow. The equation is derived in terms of the rate at which a pollutant decays in a ventilated room under the influence of dilution from a pollutant free supply air ventilation rate, it accounts for variations of the pollutant concentration according to hourly periods as n which is the number of complete air changes per hour (ACH).

This model assumes that air entering the space is completely and immediately mixed with all the air already in the space i.e. the concentration of the contaminant, air temperature and relative humidity are the same thorough the space. The pollutant considered in the decay equation is carbon dioxide (CO_2), which has an ambient concentration in outdoor air and is a respiratory by product from the room occupants. The steady state decay equation for the pollutant concentration is used, but this equation cannot account for the dynamic distribution of the airflow.

The equation is derived in terms of the rate at which a pollutant decays in a ventilated room under the influence of dilution from a fixed supply air ventilation rate; it represents the variations of the pollutant concentration according to the number of complete air changes per hour (ACH).

The rate of change of the concentration of CO_2 is

$$\frac{\mathrm{D}c}{\mathrm{D}t} = -\frac{\mathrm{cQ}}{\mathrm{V}}$$

where
Q is the ventilating airflow rate (m^3/s)
V is the room volume (m^3)

This integrates to

$$c = Ae^{-\frac{Qt}{V}}$$

Where t is time (s) and A is a constant of integration and is determined by stating a boundary condition. For example when the initial ppm concentration (c_0) in the room is equal to the room concentration (c), at time zero (immediately when the ventilation started) the equation solves to

$$c = c_0 e^{-\frac{Qt}{V}}$$

However, as the ventilating air contains CO_2 and the occupants additional exhale CO_2, variables such as the pollutant generation rate must be considered.

The rate of change of CO_2 in the room can be represented by:

$\Delta c = G\Delta t + Q\Delta t\ ca - Q\Delta t\ c$

Further manipulation of the differential equation for the rate of change of a pollutant concentration thus becomes:

$$\frac{dc}{dt} = \frac{G + Qc_a - Qc}{V}$$

This solves as:

$$c = \left(\frac{10^6 G}{Q} + c_a\right)\left(1 - e^{-\frac{Qt}{V}}\right) + c_0 e^{-\frac{Qt}{V}}$$

(Jones, 2001)

Further versions of this equation exist. If the initial concentration were c_0 with people present and the ventilating air has a concentration of c_a then the relationship is:

$$c = \left[\frac{10^6 V_c}{Q'} + c_a\right]\left(1 - e^{-n}\right) + c_0 e^{-n}$$

If people were present but the room is initially free of gas the relationship is:

$$c = \left[\frac{10^6 V_c}{Q^{'}} + c_a \right] \left(1 - e^{-n} \right)$$

The equations are variations of the homogenous steady state assumption. All of these equations can be used to calculate the pollutant concentrations in a volume of space. Therefore, by applying a simple mass balance approach the IAQ can be calculated for a space. The applicability of this approach for predicting the IAQ in a lecture theatre is however questionable.

Appendix B Computational Fluid Dynamics

B 1.0 Introduction to FloVENT

Computational fluid dynamics is a simulation program that involves the examination of systems, by analysing the fluid flow, heat transfer and related phenomenon. Air or fluid flow has movement (momentum), velocity, temperature, and pressure. Whereas heat transfer, is heat energy transferred due to temperature differences because of conduction – heat flow through a solid or stationary fluid, convection – heat flow from a surface to a moving fluid and radiation – heat flow between two surfaces.

Nevertheless, fluid flow and heat transfer are governed by three conservation equations of mass, momentum and energy. These equations are the Navier-Stokes (after Claude Louis Marie Navier, and Sir George Gabriel Stokes) equations (Figure i), and are partial differential equations, which are solved to produce the output. The equations are the fundamental physical laws of fluid movement. According to Awbi (2001) “there is no mathematical solution for the general (NS) equations”, and recommends that CFD is the only method of solution due to the complexity of solving the equations involved. In this respect, CFD can be considered the “third dimension of fluid dynamics”, however, this is Awbi’s view.

$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \bullet \nabla\right) \vec{u} = - \frac{1}{\rho} \nabla p + \gamma \nabla^2 \vec{u} + \frac{1}{\rho} \vec{F}$$

Figure i. Navier-Stokes equations (University of Colorado at Boulder, no year)

The CFD program solves the complex equations iteratively by using the finite volume approach and uses a Cartesian grid. The number of iterations depends on the complexity of the model, but a normal value of cells is in the order of tens of thousands. The system under investigation is depicted as a 3D grid consisting of grid cells, and for each cell, the program calculates a value for temperature, pressure and other selected parameters at its central point. Additionally on each cell face, a velocity component is calculated. When more cells are assigned, the result is a more defined solution. However, this requires more simulation time (Flomerics, 2003).

During the simulation, the residual errors are calculated for each cell. A measure of total error in the system is given by the sum of the residual errors from all the cells. This is shown graphically during the simulation, to indicate how close to final solution the simulation is. When the iterations versus errors fall to an acceptable value it can be taken that, the model has consequently converged.

B 1.1 Capability and output

The software is specifically capable of solving airflow problems encountered in the built environment. The built environments covered by this software include indoor spaces such as offices, clean rooms, ventilated spaces, and external flow around buildings. An important aspect in relation to IAQ assessment is that turbulence in rooms/spaces can be simulated; in particular, κ-ε turbulence models (currently one of the most widely used) can be solved. However, this requires using more memory, which adds to simulation time.

The main indoor variables that the software can determine are air temperature, pressure, and velocity. Additional variables include the moisture content of air, the flow angle, the air diffusion performance index, Fanger's Indices (PMV and PPD), ventilation effectiveness (LMA, LACI, and CRE), and contaminant concentrations (Flomerics, 2003). For this reason, CFD was considered an appropriate tool for use in the proposed assessment methodology for predicting IAQ in a lecture theatre.

Results of the simulations can be displayed in several formats. The visual output ranges from audio - visual animations, jpeg pictures of planes of results or contour plots, and movement from a defined location or source. The numeric data calculated by the simulation can be exported as a CSV file. Data for all grid cells in the domain can be displayed or for defined regions, and planes. This is very useful as further analysis can consequently be performed using the numeric data worksheet.

Appendix C IAQ and Ventilation effectiveness parameters

C 1.0 Local air change index

The LACI (ε_p) is the age of the air at a point p, relative to the supply air inlet and can be represented as:

$$\varepsilon_p = \frac{\tau_n}{\tau_p}$$

Where τn is the nominal time constant of the room for example in seconds and p is the position of the monitoring point in a space. The index compares the room volume to the volumetric outdoor airflow rate, that is the reciprocal of the air change rate. An LACI = 1 indicates perfect mixing conditions, a value greater than 1 means that the fresh air is reaching the point. However, values less than 1 suggest a poor fresh air supply to the room.

C 1.1 Local Mean Age of air

The LMA (t_p) is the average time taken for air to move from the supply inlet to any point p, in the room and can be written as

$$\tau_p = 0 \infty \int t A_p(t) dt$$

Where Ap (t) stands for the age distribution curve for air arriving at any point p at time t (Flomerics, 2003). The LMA describes the time it takes for air to move from the supply inlet to a point in the room. This can be used to indicate the differences in airflow, as different airflow patterns produce different IAQ distributions. As a result, the LMA illustrates the connexion between IAQ and ventilation.

C 1.2 Contaminant removal effectivness

The CRE can be described as $\mathrm{CRE} = \dfrac{c_e}{\langle c_i \rangle}$

where c_e is the exhaust concentration out of the room and $\langle c_i \rangle$ is the room contaminant mean concentration. If the conditions in the room are perfectly mixed theoretically the CRE equals one. Values less than one however, can indicate that there is some short-circuiting of air and indicate that the ventilation system is defective in its removal of the air contaminants in the room.

C 1.3 Air diffusion performance index

The air diffusion performance index (ADPI) can be used to measure the uniformity of the indoor environment. The ADPI is used as a thermal comfort measure in addition to Fanger's comfort equations for occupants indoors. It is based on measured air velocities ($0.35ms^{-1}$) and draught temperatures in the range -1.7 to 1.1°C (Flomerics, 2003). Specifically the ADPI is the percentage of measurement points that satisfy specified thermal comfort levels that are represented as a percentage of the total number of measurement points. Consequently, the degree of mixing of the ventilating air in a room can be calculated using the ADPI.

Appendix D Development of the IAQ assessment methodology

D 1.0 Zoning

A component of the method consists of splitting the occupied zone into subzones, noting the position of the occupants and other physical parameters that influence the IAQ distribution. The processes in obtaining a volume of the subzone unit are summarised below.

- A scale model of a large space is drawn from a survey of the room;
- The model domain is initially set as one large box to represent the room, and a measure is performed to calculate the IAQ level;
- This initial domain is consecutively bisected into smaller regions, and the level of IAQ measured after each division;
- The IAQ levels are plotted on a graph, which illustrates, that as the dimensions of the subzones becomes smaller; the IAQ levels approach a plateau where further reduction in the subzone volume does not show a variation in IAQ level.
- The dimension of the subzone where the levelling off in IAQ occurs is taken to be the size of the zones appropriate for the assessment process.

D 1.1 Discussion

The methodology considers extra parameters beyond those used in the homogenous approach in order to assess the spatial variation of IAQ levels in a lecture theatre. It is intended that the methodology can be used both in the assessment of existing lecture theatres, and at the design stage of a new build. This should ensure that the most appropriate ventilation system and arrangements deliver the best practicable air quality to the occupants.

The proposed assessment procedure uses a cyclic process of the methodology to attain an optimum IAQ level according to any particular evaluation criterion, for example a concentration of CO_2 or the lowest possible LMA. There is a choice of a variable parameter in the primary tier of the flowchart, secondary to this; there is a selection loop to set the remaining parameters. This is in contrast to the homogenous approach, as the main variables for the volume assessed are the ventilation rate and the number of occupants. However, a way that the proposed assessment methodology can be incorporated into the existing approach is shown as a combination of the two methodology in Figure ii.

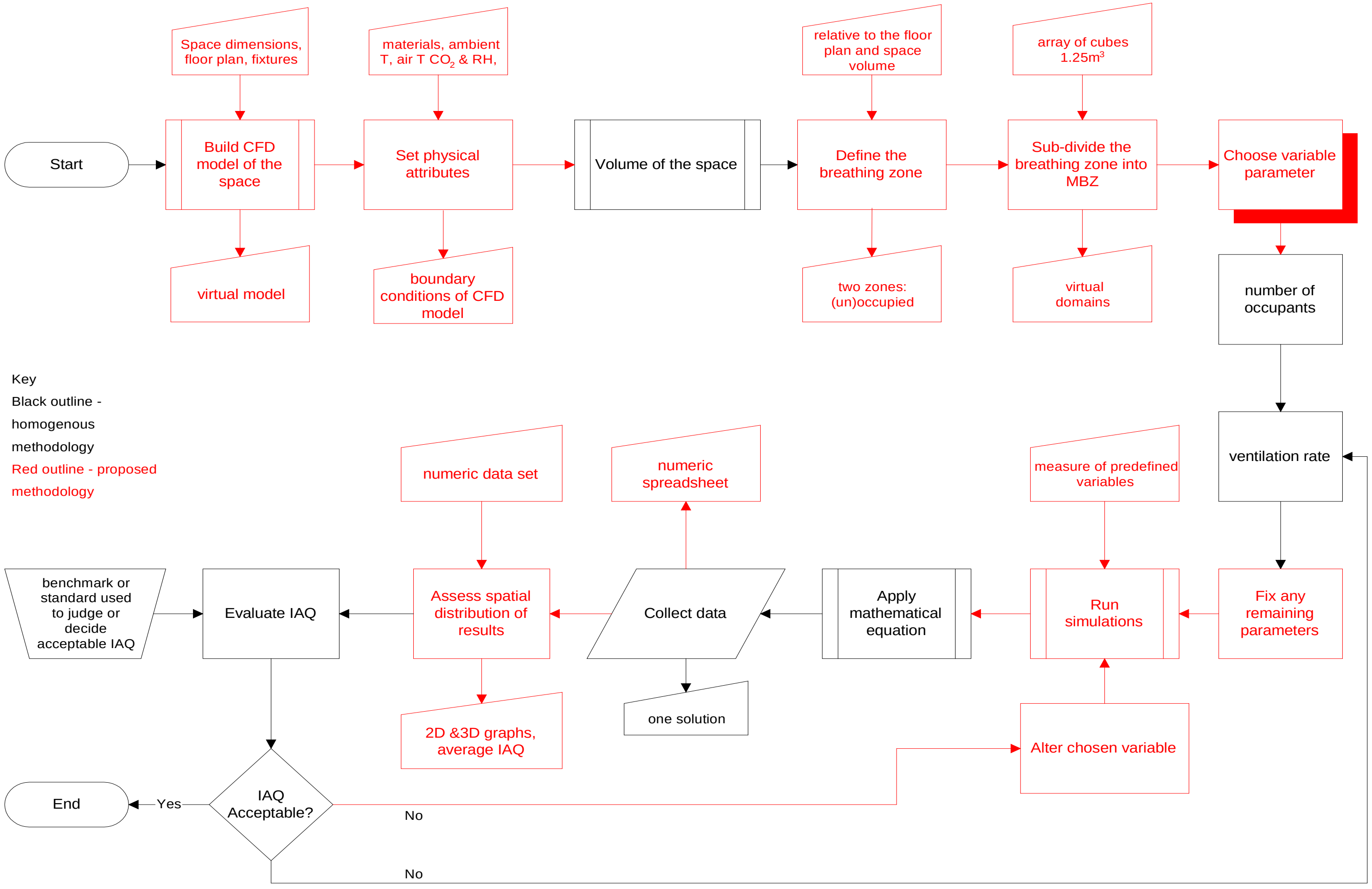
The difference between the two approaches is illustrated with the homogenous procedure drawn in black and the proposed procedure in red. The developed methodology importantly presents a way to assess IAQ not assuming homogenous conditions. Some of the variables considered in both methodology are the same. However, the developed method considers a greater number of variables in a detailed manner in order to portray the spatial variation in IAQ.

A significant component of the developed methodology is the sub zoning of the room volume, as opposed to considering the entire space in an assessment. The addition of computer modelling to the assessment methodology provides an opportunity to enhance an existing approach. Therefore, the developed IAQ assessment methodology provides an alternative to assuming a homogenous state in order to predict the IAQ in a lecture theatre.

Considering the developed assessment methodology against an existing homogenous approach there are several main distinctions between the two, these are:

- The developed methodology is different to a homogenous approach in that it includes a greater number of variable parameters.
- In a homogenous methodology, the whole room space is assessed, but the developed methodology considers the sub zones of the occupied volume in order to portray spatially the IAQ.
- The developed methodology appreciates the influence the airflow pattern has on IAQ in a large space.
- It uses a detailed model of the space under assessment in terms of the layout and obstacles to airflow, and does not consider the room as a generic volume of space.
- Uses modelling to calculate data resulting from non-homogenous conditions in the large space.
- The outcome of the assessment is in several formats (spatial portrayals, overall level, and range of IAQ) and not a single answer from an equation.

The developed assessment methodology forecasts the overall IAQ in terms of a maximum and a spatial average CO_2 concentration. It is capable of displaying the variation in IAQ in terms of the spatial variation of CO_2 concentrations or age of air (LMA) in various graphical forms. Therefore, the predictive model developed is a novel tool that can be employed in designing an energy efficient, optimum ventilated lecture theatre.



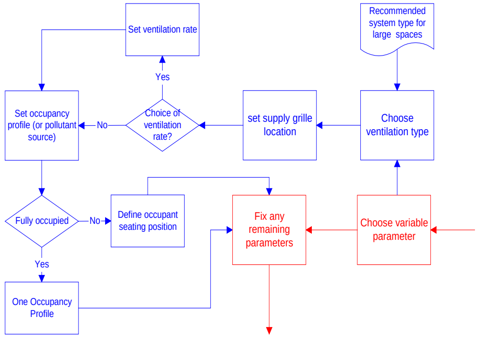


Figure ii) Addition of the proposed methodology to augment the homogenous

Appendix E

Mayfield House Case Study Report:

Indoor air quality of a demand-controlled air-conditioning system 21st November 2005

Appendix F

Chapter 7 Supplementary Results

The carbon dioxide level was assessed in the IAQ methodology by examining the spatial average CO_2 and its maximum level in the breathing zone. A normal distribution is symmetrical about the average value of a data set. Deviations from a normal distribution indicate that the data is less symmetrical about the average value.

If the data distribution is normal then the average of the data is described by the mean. Conversely, in data distributions that are not normal the median describes the average. Therefore, in order to determine which central tendency measure (mean or median) to take as an average level of CO_2 in the breathing zone, the distribution of the simulation data needed to be established. Examining the shape of the data is not sufficient to indicate whether the data is normally distributed or not. Hence, statistical testing of the data was required.

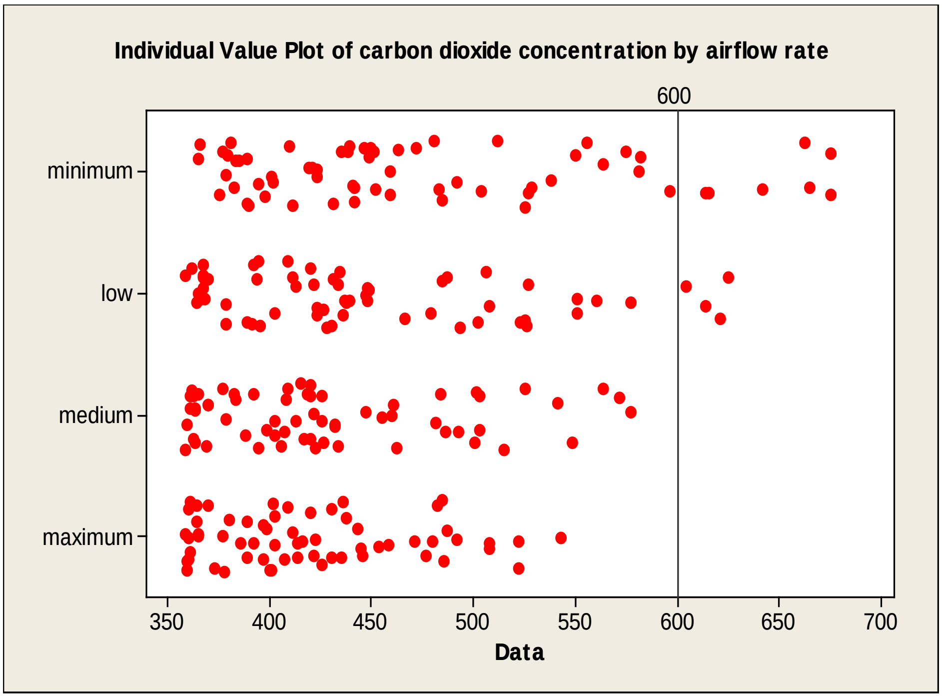


Figure iii) CO_2 concentrations in all mbz for all cases

The AQSM of the minimum airflow rate had 12% of occupants sitting in areas above 600ppm, compared to the AQSM of a low airflow rate with 6% occupants (figure iii). The remaining AQSM of a medium airflow rate and the maximum airflow rate had all occupants sitting in areas below the chosen CO_2 concentration. Therefore, the higher airflow rates satisfied the most the CO_2 concentration criterion, as expected due to more the greater airflow removing the stale room air.

F 1.0 Assessment of different occupancy profiles

```
                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level         N    Mean  StDev  ---------+---------+---------+---------+
Symmetrical   63  473.58  87.49  (------*------)
Asymmetric    63  538.28  78.66                        (-----*------)
                                ---------+---------+---------+---------+
                                       480      ppm  510           540
570
Pooled StDev = 83.19
```

No overlap, thus reject Ho. Therefore, there is sufficient evidence to suggest that the effect of occupancy profile produces differences in median.

F 1.1 Assessment of changing the supply grille configuration

A vertical difference in airflow between the supply grille position one and the supply grille position two is shown in figure iv). The vertical plane is 4.5m from the sidewall and illustrates the airflow pattern of both models. The noticeable differences were above head height in model A that had relatively older age of air towards the ceiling, and at the back of the room. In AQSM supply grille position one , the breathing zone at back of the room had lower age of air than in the model of the supply grille position two due to the corresponded to the change in position of the supply air grilles providing more fresh air. The planar images illustrate the local effect on airflow produced by changing the inlet position.

Further effects can be seen from the lateral plane moving images if required.

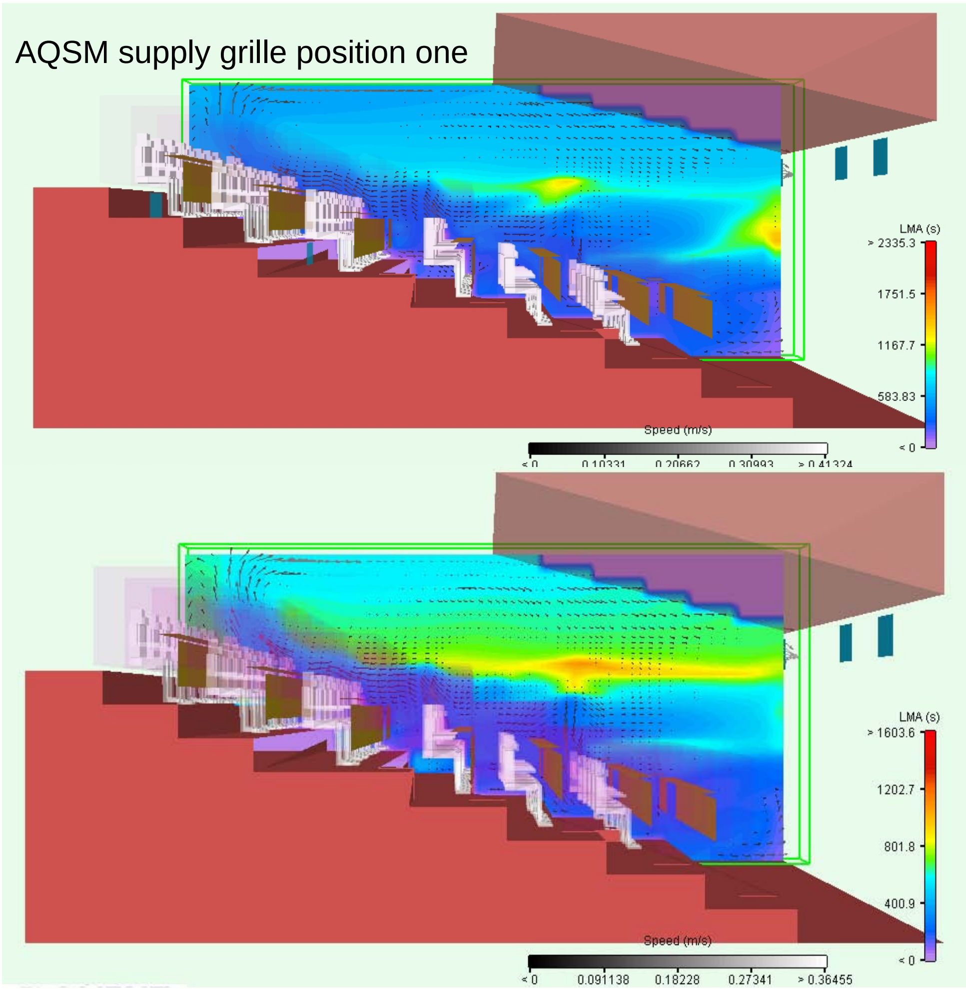


Figure iv) Vertical plane CFD output of LMA from supply grille AQSMs (also shown on p 119)

In the example CFD images, the different colours represent a similar age of air. Such animations can further allow the detailed inspection of expected airflow and CO_2 concentration. Animations on the side-to-side distribution of LMA, air velocity and CO_2 concentrations illustrated the behaviour of airflow in and outside of the assessed breathing zone. The regions in the lecture theatre that had the maximum CO_2 concentrations were outside of the breathing zone and hence corresponded to dead zones with older LMA values.

F 1.2 Vertical profiles of cases modelled

The vertical profile of LMA (Figure v) patterns closely follows the vertical CO_2 concentration profiles for all models. This reflected the important effect the airflow pattern had on the distribution of CO_2. Model 1 with a high-level mixing had a uniform distribution, with close-banding of LMA values, but the values are a higher age. The displacement system in model 2 provided regions with a lower age of air, but did not give an even distribution, as the back and sides of the room had the highest values. Therefore, model one of high-level mixing ventilation satisfied the IAQ assessment methodology as the most appropriate of the systems modelled for a lecture theatre.

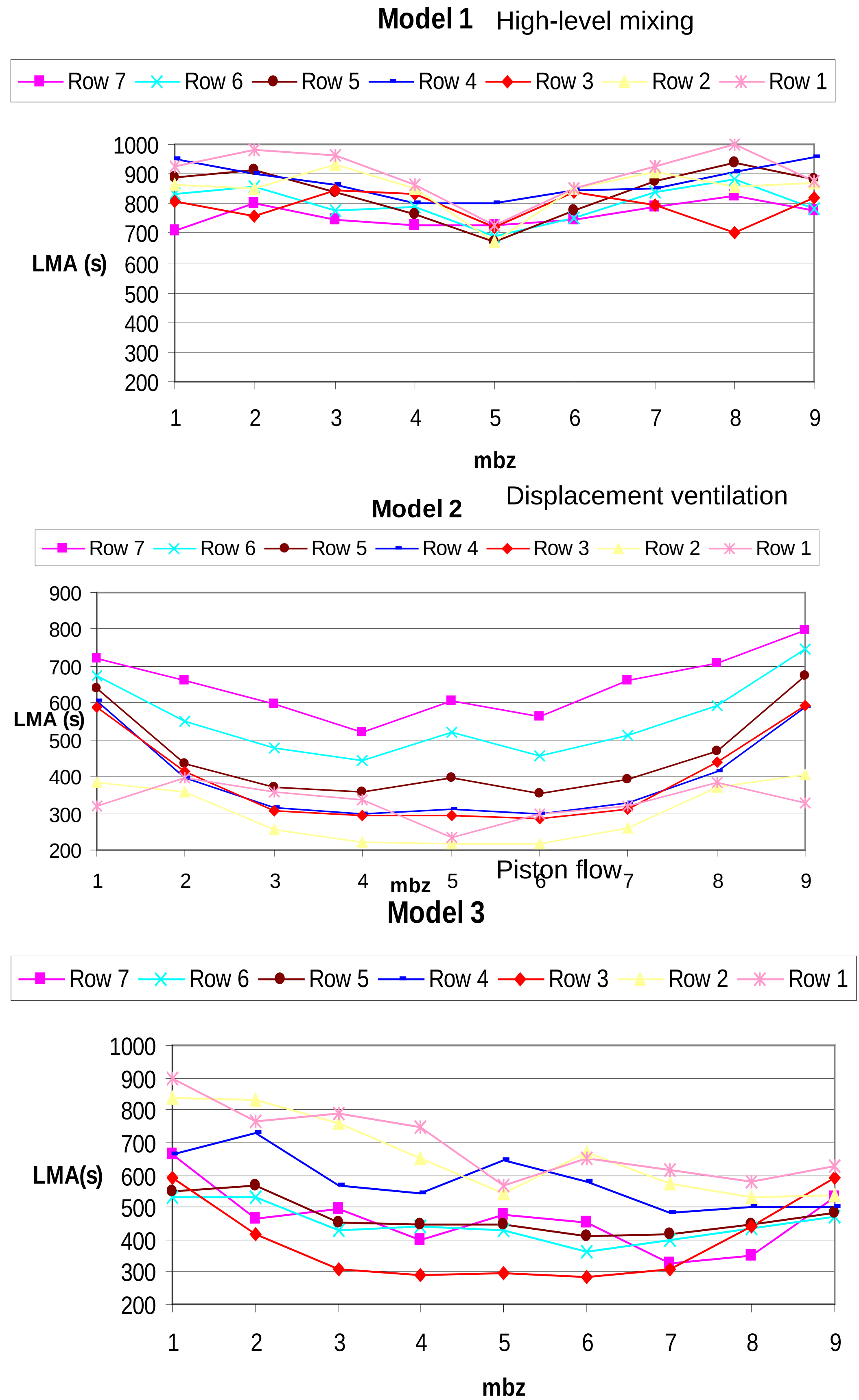


Figure v) Front elevation LMA profiles for AQSM 1, 2 and 3