CRITERIA AND MEASUREMENT OF INDOOR AIR QUALITY IN SUSTAINABLE BUILDINGS

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Modern building design often specifies airtight structures with minimum fresh air ventilation in order to optimise energy consumption. However at the same time there has been an increase in the sources of indoor air pollution and consequently reduction in indoor air quality (IAQ), resulting in a proliferation of sick building syndrome and other building related illnesses. This paper presents some preliminary findings of an ongoing research programme at the University of Brighton and highlights the importance of providing healthy indoor environments and its significance to sustainable buildings where efficient use of energy and other resources are fundamental. The wide ranges of pollutants are identified and suitable indicators are evaluated together with appropriate methods of measurement. The paper includes analysis of computer simulations performed to assess the IAQ provided by domestic heating systems. The initial results suggested that a mechanical ventilation system with heat recovery can provide acceptable IAQ with the best use of energy, thus demonstrating its potential for use in sustainable buildings.

Keywords: air quality indicators, energy, indoor air quality, measurement methods.

INTRODUCTION

It has been estimated that in general people spend approximately 90% of their time indoors. Since the oil embargoes and energy crises of the 1970s, the drive to reduce energy consumption in buildings has led to the development of alleged energy efficient designs that have produced tighter building envelopes with less outdoor air infiltration. This kind of air tight design, along with an increase in the number of indoor pollutant sources, e.g. photocopier machines and office furnishing materials, and the change to a more office based working practice, has subsequently led to the proliferation and increase in building related illnesses or sick building syndromes. Much work regarding air quality has been concerned with outdoor air pollution, as the indoor environment has traditionally been perceived as being “safe” from air contaminants. Consequently the quality of the air indoors, and its impact on health has been overlooked (Colls, 2002). The initial impetus to conserve energy in buildings that affected indoor air quality (IAQ) arose from the oil crises of the 1970s. A further drive to develop energy efficient designs for buildings has come from sustainability issues, and the need to use existing resources in a responsible manner as highlighted by international conferences such as the Brundtland Commission in 1987, and the Rio Earth Summit in 1992. Sustainability in buildings is now being considered in the design, management, and construction stages of building, and it is

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also considered in the materials used, the energy requirement and the healthy indoor environment of the whole life cycle of the building. Indoor air quality (IAQ) is an intricate subject because it relates to many parameters, and not solely to one environmental factor. Over nine hundred pollutants have been identified indoors, depending on the activities taking place in the environment (Hays *et al.*, 1995). The majority of people in developed countries spend approximately 90% of their time in an indoor environment; whether it is at work or at home (Colls, 2002). In either environment the occupants need to feel comfortable in terms of temperature, humidity and ambient air quality. The increase in the amount and type of equipment in commercial buildings and residences has increased the amount of pollutant sources found in the indoor space, e.g. photocopiers and printers. Additional pollutant sources include new building materials e.g. MDF, soft furnishings, floor coverings, and decorative coatings, which can emit various chemical compounds into the indoor environment. The occupants of a building are themselves a contributing factor to the IAQ, as they all exhale carbon dioxide, emit metabolic body odours such as perspiration, some smoke, and many use personal hygiene products such as perfume or aftershave. All of which add to the composition of the indoor air. In many work places, energy conservation has been accomplished by reducing the infiltration of outdoor air, and by recirculating air in ventilation systems. Air conditioning or ventilation systems are normally designed to provide the required thermal comfort and the IAQ is often compromised due to the associated energy demand. In many cases the “build tight” principle has created unforeseen issues such as Sick Building Syndrome and Building Related Illness. The aim of the current research at the University of Brighton is to review the main IAQ pollutants, identify and evaluate suitable IAQ indicators, and to propose IAQ criteria for a sustainable building. The measurement methods associated with the identified IAQ indicators are also reviewed and assessed. Taking a three bedroom domestic house as a case study, a computer simulation program was used to optimise the best sustainable option in terms of IAQ and its associated energy requirement. The simulation modelled three heating options: a conventional, low pressure hot water and radiators, central heating system; a mechanical ventilation system without heat recovery and a mechanical ventilation with heat recovery. The results highlighted the need to change the current ventilation design criteria and the advantages of adopting a ventilation system with heat recovery as a more sustainable design.

IAQ CRITERIA

Indoor Pollutants

A pollutant can be defined as a substance that has the potential to contaminate or cause adverse health effects in living systems. The indoor pollutants and their sources are multiple and varied. Air that enters a building can itself import atmospheric pollutants from outdoors e.g. buildings situated close to busy main roads in urban areas or in city centres. Meteorological factors and ventilation characteristics can influence levels of indoor contaminants by affecting the air change in the building (Yocum and McCarthy, 1991). The concentrations of some outdoor pollutants are normally lower indoors, due to deposition on internal surfaces or chemical reaction throughout the circulation time in the building. However, there are additional sources which can be generated indoors, e.g. mainstream 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). Indoor air pollutants can be divided into inorganic and organic gases, airbourne particles, and biological air contaminants. A selection of typical pollutants is summarised in Table 1 along with some associated health effects.

Table 1: Indoor air pollutants

Pollutant	**Possible Health Effect**	**Emission Source**
Gases		
Nitrogen oxides	Respiratory irritant	Fuel combustion.
Sulphur oxides	Respiratory irritant	Fuel combustion.
Radon	Carcinogen	Diffusion from soil, construction material, cigarettes.
Ozone	Respiratory irritant	Photocopiers, laser printers.
Ammonia	Respiratory irritant	Metabolic activity, cleaning products.
Carbon dioxide	Simple asphixiant	Metabolic activity, combustion, tobacco smoke.
Carbon monoxide	Toxic	Fuel combustion, tobacco smoke.
Formaldehyde	Irritant	Insulation materials, furnishings, tobacco smoke.
Volatile Organic Carbons	Compound specific	Solvents, paints, adhesives, furnishings, building materials, tobacco smoke.
Airbourne particles		
Asbestos	Carcinogen	Insulation, fire retardant material.
PM_{10} & $PM_{2.5}$	Respiratory	Smoke (tobacco, combustion)
Dusts	Respiratory	Household, heavy metals, skin cells.
Biological		
Allergens	Allergic reactions	Animal dander, plant pollens, insects.
Bacteria and viruses	Morbidity	Occupants, animals, plants, air conditioners.
Spores (fungi and moulds)	Allergic reactions, irritants	Soil, plants, foodstuffs, surfaces.

The majority of gases are present as a result of combustion processes. The oxides of nitrogen and sulphur dissolve readily in water to produce corrosive acids, which have a potential for lung damage. There have been indoor studies that have examined a possible link with nitrogen dioxide levels from gas cooking, to impaired respiratory function, especially in vulnerable individuals like asthmatics and young children. One study by Samet and Spengler (1987) found that cooking with gas under normal house ventilation adds 25 ppb to the background nitrogen dioxide level. The background levels vary greatly due to seasonal variations and the traffic density of the area; e.g. levels at a busy kerbside can range from 50 – 60 ppb (Elsom, 1996). However there has been no definite proof of the health risk of nitrogen dioxide exposure from cooking mainly due to the difficulty in measuring direct personal exposure, confounding factors and biases (Samet and Spengler, 1991). An important category of gaseous indoor pollutants are volatile organic compounds (VOCs). VOCs are organic compounds with a boiling point at a lower limit of 50 to 100 °C and an upper limit of 240 to 260 °C (WHO, 1989). Their low boiling point means that they will readily evaporate into the surrounding air. There are several sources of VOCs indoors including the outdoor air, building materials, furnishings, decorative coatings and adhesives, cleaning agents, microbial sources and building occupants. The concentrations of VOCs vary according to the building characteristics e.g. age, use, refurbishment and urban location. Several hundred VOCs have been recorded in indoor air, of which a relatively small number may have carcinogenic or mutagenic effects, (e.g. benzene found in tobacco smoke) that pose a chronic health risk (Wallace, 1991). However, it must be noted that exposure to high concentrations have produced cancers in laboratory animals and that the human threshold limit value for benzene is only 25 ppm. The acute health effects from exposure to VOCs are suspected to be associated with Sick Building Syndrome (SBS). This is mainly due to the similarity in SBS symptoms and exposure to high VOC concentrations, i.e. headaches, skin, respiratory tract and eye irritation (Jones, 1999).

Current Standards

In the UK there are several standards and guidelines relating to potential human exposure to pollutants that are contained in the Health and Safety Executive Occupational Exposure Limits and the control of Substances Hazardous to Health Regulations. Both of which set maximum time weighted exposure concentrations within the industrial work place. At present in the UK there are no Government standards that explicitly define the levels of pollutants found indoors, but the Department of Health are considering producing guidelines in the future (COMEAP, 2001). The closest guidelines the UK has are those of the Chartered Institute of Building Service Engineers Guide A (CIBSE, 1999) which define acceptable IAQ on a percentage basis depending on occupant perceptions. This has a similar approach to the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE,) Standard 62 –1989. The European Union (EU) has several Directives, but none are directly concerned with IAQ. The World Health Organization have published guideline concentrations for common indoor pollutants, and are currently in the process of compiling a document relating building occupants to IAQ (Molhave, 2000).

IAQ MEASUREMENT

IAQ Indicators

An ideal IAQ indicator should be able to show acceptable levels of thermal comfort, odour and relative health risk to occupants. Also the indicator should be easily, and simply measured. However, there are many factors that can affect IAQ indicators. These factors include:

- Building type and design
- Activities
- Temperature and air movement
- Relative humidity
- Age of building
- Range and probable concentration of pollutants

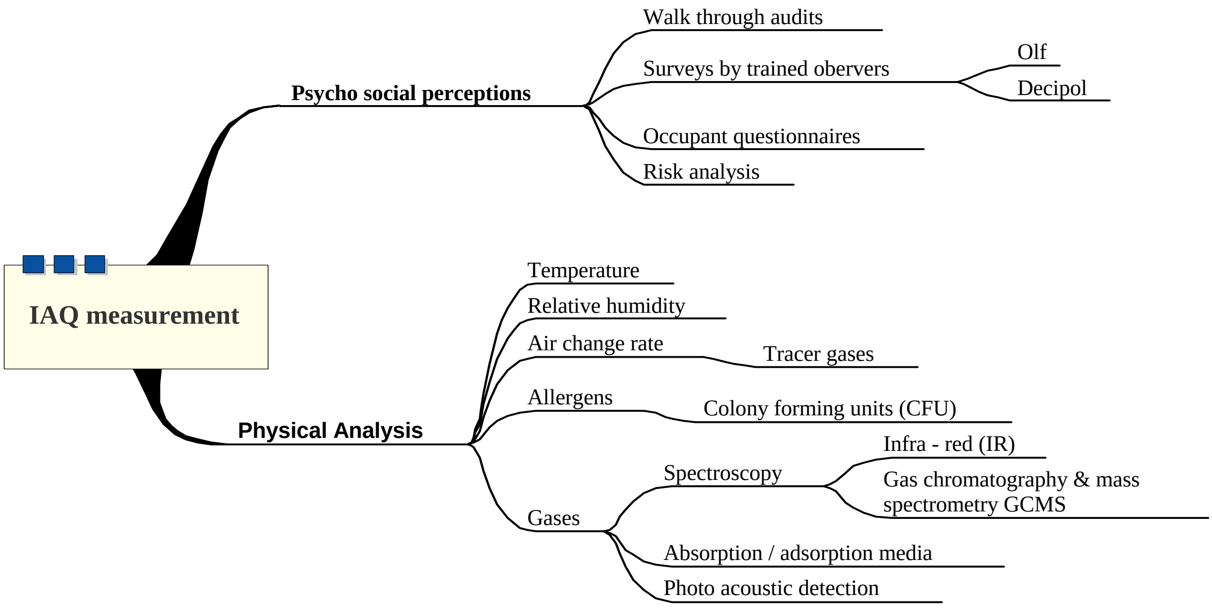
- Health risk associated with each pollutant
- Suitable equipment available to measure pollutants, and the cost

Due to the large number of IAQ pollutants, in practice it is not feasible to measure and monitor them all. A compromise that takes into account the factors mentioned above has to be made. For instance as carbon dioxide (CO_2) is a respiratory by product its indoor concentration is often used to evaluate IAQ. The recommended concentration of CO_2 not to be exceed indoors is 1000 ppm, based on human body odour, and not on adverse health or comfort effects (ASHRAE, 1989). However, concentrations of CO_2 do not necessarily indicate acceptable air quality, but can indicate the occupancy of the building, the supply rate of outside air required for each individual and the adequacy of the ventilation system. 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, 2000). At present however, there are no agreed pollutants or contaminants that can be described as definite indicators of IAQ; thus reflecting the complexity of the issue. Compounds (or groups of pollutants) that can be considered as key IAQ indicators are gases and volatile substances. Of which, the majority of research in commercial buildings has focused on carbon dioxide, VOCs or a combination of both. Studies in residential buildings additionally have included formaldehyde, nitrogen dioxide, house dust mites, bacteria and fungi as key IAQ indicators (Berry *et al.*, 1996). It is more rational to identify the key parameters that can be sensibly, and readily monitored with equipment and technology that is presently available. The equipment currently available can contain several sensors e.g. temperature, relative humidity, carbon dioxide, and multi-gas monitors for VOCs, and carbon monoxide etc. Mixed gas sensors or IAQ sensors vary in the way they detect the gases. Many commercially available IAQ sensors are based on tin oxide gas sensors, which detect the gas due to a change in electrical conductivity in the sensor surface. There are expensive multi-gas sensors that use a photo-acoustic method to measure the gas. There is a range of IAQ sensors available, many of which can take readings in real time and can be linked to a computer. The cost of the equipment can range from hundreds to thousands of pounds. The more representative IAQ indicator ideally should sense comfort parameters in addition to multi-gas concentrations. The readings measured should be logged continuously to obtain a range of measurements, the output should be easy to interpret, and without excessive cost.

IAQ Measurement

The main objective in measuring IAQ is to assess any actual or suspected risk to occupant health. The measurement itself encompasses the sampling of the pollutant and the subsequent analytical or monitoring method. Air quality can be described quantitatively by measuring the concentrations of substances in the air, or qualitatively by the perceived view of the individuals inhaling the air (Yocum and McCarthy, 1991).There are numerous analytical procedures for physically measuring IAQ parameters, and several subjective techniques as shown in Figure 1.

Figure 1: Outline of measurement methods



Some physical IAQ parameters such as temperature and relative humidity are recorded fairly simply. The detection of gases involves sampling the gas and its ensuing measurement. This can be done by sampling and chemically analysing what has been collected, or by monitoring, where a sample is collected and analysed electronically. Several of the IAQ pollutants can be recorded either way, e.g. VOCs can be sampled using active adsorbents (such as Tenax), thermally desorbed and analysed by a chromatographic or spectroscopic methods (Hollender *et al.*., 2002). A more dynamic real time analysis of VOCs can be performed using photoacoustic techniques (Rey and Velasco, 2000). IAQ audits and surveys can be useful as a scoping tool in initial IAQ investigations where there has been a complaint or problem. The technique using trained observers has been pioneered by Fanger (1988) allows air pollution and sources to be quantified by the olf and decipol units. One olf is the emission rate of bioeffluent air pollutants from a standard person, and a decipol is the pollution caused by one olf, with a ventilation of 10 l/s (Fanger, 1988). However, due to the subjective nature of such methods, it may be more meaningful in IAQ investigations to additionally measure physical parameters (Bluyssen *et al.*, 1996).

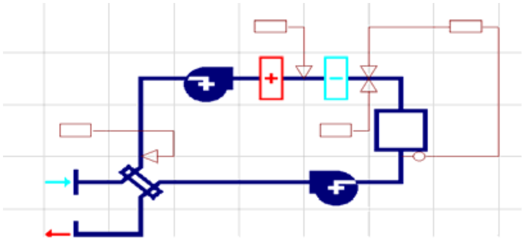
Practicality of measurement

The practicality of the measurement techniques needs to be taken into account. For example, in the case of the measurement of VOCs, the majority of methods require some type of spectroscopic analysis away from the monitor site. The time taken to measure the pollutant concentration is important. In situ measurements in real time are a more useful representation of the indoor air quality in order to detect if any action is required. This is opposed to taking samples that have to be removed from the sensor, and analysed in a laboratory. There are products on the market that are able to measure multiple parameters, e.g. carbon dioxide, carbon monoxide, VOCs, temperature and humidity. The prices for such monitoring equipment range from hundreds to thousands of pounds. Such equipment may be applicable for a commercial building, but will be beyond the budget for most homeowners. Air quality additionally has a perceived aspect which measuring physical parameters does not always indicate, e.g. organic solvents can be detected by the olfactory senses 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 are. This again highlights the difficulty in assessing and measuring IAQ.

ACCEPTABLE IAQ IN SUSTAINABLE BUILDINGS

The importance of building ventilation is paramount to IAQ. The aim if the current research is to explore a ventilation strategy that can be adopted for a sustainable building - one that has acceptable IAQ. A computer simulation program was used to compare the IAQ with improved ventilation and its associated energy requirement. The software used was APACHE (Application Program for Air-conditioning and Heating Engineers), which contains a thermal simulation component. The residence studied was a generic three bedroom detached house with living and dinning room. The simulation was run over an entire heating season, October to March to measure the heating energy demands of the model house. The program allows a HVAC system to be constructed from a selection of generic HVAC plant. This was incorporated into the simulation as an optional heating system (see Figure 2).

Figure 2: A schematic of the mechanical ventilation system used



The air change rate in air changes per hour (ACH) was initially varied to demonstrate the expected response of the heating energy requirement. Three cases study models were chosen to compare the energy associated with IAQ. Each of the models represented different ventilation strategies, they are:

Model 1 - Natural ventilation with a conventional central heating system.

Model 2 - Mechanical ventilated without a heat recovery.

Model 3 - Mechanical ventilated with a heat recovery.

The ventilation strategy simulations are summarised in Table 2.

Table 2: Ventilation strategies.

Model	1	2	3
Room Temperature °C	21	21	21
Natural ventilation	✓	X	X
Mechanical ventilation	X	✓	✓
Heat recovery	X	X	✓

RESULTS AND DISCUSSION

The IAQ for each model was based on carbon dioxide as a convenient indicator, and was based an overnight four-person bedroom occupancy.

Figure 3 shows the level of carbon dioxide at different ventilation rates. Taking the ASHRAE recommended maximum carbon dioxide concentration as 1000ppm, an ACH of approximately 1.4 would be necessary for an acceptable level of IAQ.

Figure 3: Carbon dioxide concentration at different ventilation rates

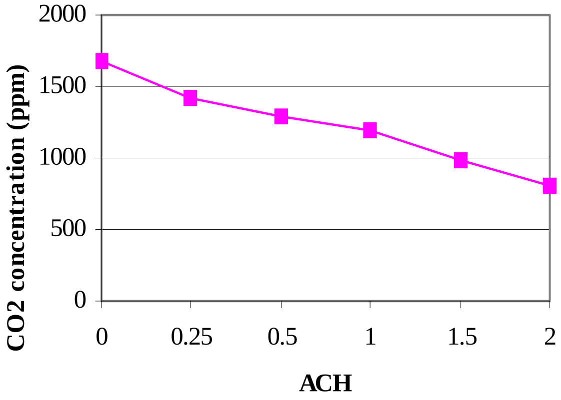


Fig.4: Heating energy variation in the models

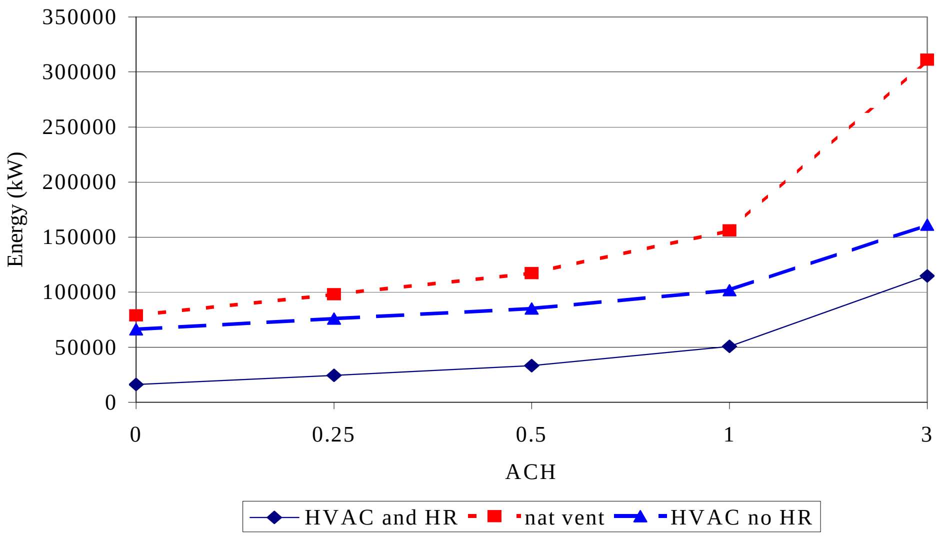
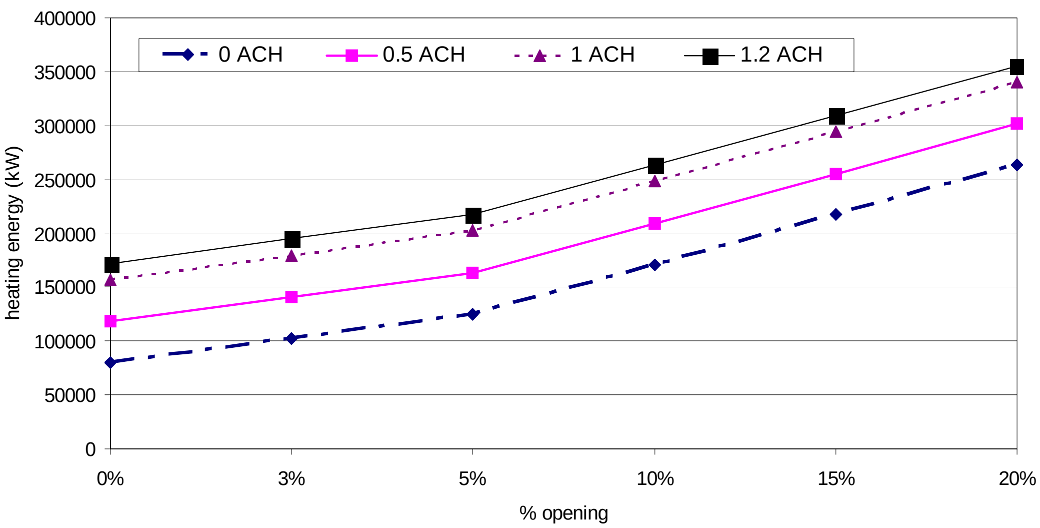


Figure 4 shows the results of the thermal simulations in the variation of heating energy requirements of each of the models at different ventilation rates.Analysis shows, model 3 with heat recovery proved to be the least energy intensive heating system, with model 1 having the highest energy demand. This suggests that using mechanical

Figure 5: Energy vs ventilation rates and percentage window openings



ventilation with heat recovery system instead of a conventional heating system or a combination of both is a more sustainable design option. To illustrate the effect of natural ventilation has on the energy demand, simulations were run varying the ventilation with different percentage window openings and ACH (see Figure 5). This also showed an expected increase in heating energy with greater window openings and a greater air change rate due to an increase in heat energy required to compensate for the influx of cold outside air. A window opening at around 10% is enough to approximately double the energy. The simulations with closed windows, and zero air change rate demonstrated the baseline-heating requirement due to natural infiltration. The simulations depicted the relationship between incoming air and energy. The relationship between IAQ and energy follows that; the greater amount of incoming fresh air provides the higher IAQ. This is a simplification as there are several factors that contribute to IAQ, such as the concentration and variation of internal pollutant sources, room temperature and relative humidity. However it was shown that using 1.4 ACH as a benchmark an acceptable level of IAQ could be maintained. Natural ventilation, relying on window opening, although capable of providing good IAQ is not the best strategy in terms of cost in comparison to a mechanically ventilated system. The most sustainable ventilation strategy was a mechanical ventilated system with heat recovery, as it required the less that half of the energy demand of a naturally ventilated system with comparable IAQ.

CONCLUSIONS AND FUTURE WORK

This research sets out to establish representative IAQ indicators and to review and identify IAQ criteria for the design of buildings. Currently there are no clear IAQ standards suitable for buildings in the UK. Carbon dioxide is a general IAQ indicator of building occupancy, but it cannot indicate if there is a problem with less benign IAQ contaminants such as VOC emissions, which are related to several building conditions. The review of IAQ measurement showed that the measurement techniques and equipment are inadequate and more integration of indicator parameters, in addition to thermal and humidity sensors, is necessary to reflect the IAQ that has to reflect the type and usage of the building being monitored. The equipment also needs to be affordable to the majority of would be users. The ideal scenario for good quality indoor air is to have a ventilation system that is able to provide thermally treated fresh air, but has a low energy demand. Preliminary investigations have showed that the use of typical design of one air change per hour is inadequate. The use of mechanical ventilation with heat recovery for higher ventilation rate is a most sustainable of the options considered. In order to assess the IAQ at different locations of the building the development of computer simulation is necessary. Further investigation can then be undertaken to represent the dynamic ventilation behaviour of the building. The current research represents the preliminary study of an The on-going research to evaluate the relationship between IAQ and energy use of buildings will include the development of this simulation and further investigation can then be undertaken

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