The Development of a Methodology for a Tool for Rapid Assessment of Indoor Environment Quality in Office Buildings in the UK

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Thesis submitted to the University of Nottingham for the degree of Doctor of Philosophy

March 2012

Preface

“Diamonds resist blows to such an extent that an iron hammer may be split in two and even the anvil itself may be displaced. This invincible force, which defies Nature's two most violent forces, iron and fire, can be broken by ram's blood. But it must be steeped in blood that is fresh and warm and, even so, many blows are needed." - PLINY THE ELDER

Abstract

This thesis describes a methodology for the development of a novel tool for rapid assessment of Indoor Environment Quality (IEQ) in office buildings in the UK. The tool uses design, measured, calculated and surveyed data as input for IEQ calculations. The development of such a tool has become a necessity especially in the developed world where legally binding targets for Green House Gas (GHG) emissions have been agreed and where buildings are required by law to display energy performance certification. The novelty of this tool is that it addresses the need to present an indoor environment performance rating that can be presented alongside energy performance certification since the energy performance of office buildings depends significantly on the criteria used for the indoor environment.

The tool, called the IEQAT (Indoor Environment Quality Assessment Tool), is based on the IEQ model which was developed from literature review. The IEQ model is based on the IEQ index which was derived from contributing factors or sub indices that include Thermal Comfort, Indoor Air quality (IAQ), Acoustic Comfort and Lighting. The model was tested by studying the responses of occupants of three office buildings in the UK. Their subjective responses which were collected via a questionnaire were compared against model simulation results which were calculated using physical measurements of IEQ variables such as air temperature, illuminance (lux), background noise levels (dBA), relative humidity, carbon dioxide concentration (ppm), and air velocity. By fitting a multivariate regression model to questionnaire data, a weighted ranking of parameters affecting IEQ was produced and new provisional weightings for the IEQ model, which is more relevant to the UK situation, were derived.

Acknowledgements

This thesis is dedicated to my daughters Wendy and Lisani and to my parents.

I would like to express my sincere gratitude to the following people for their support and guidance. First, I would like to thank Prof. Xudong Zhao (De Montfort University) for his help, support and guidance during the initial part of the work. I would also like to thank Prof. Cees van der Eijk of the Methods and Data Institute (Nottingham University) for his input during study and questionnaire design. Many thanks also go to Dr. Nelson Chilengwe and Nick Cullen of Hoare Lea and Partners for their continued support during the entire duration of the project.

To my main supervisor, Prof. Saffa Riffat I would like to say Thank you for your support, guidance and project supervision. I would like to thank the EPSRC and Hoare Lea & Partners for their financial support. Thank you also to Hoare Lea - Leeds Office, Marsh Growchoski & Associates and Hestia Managed Services for giving me the opportunity to use their offices for data collection purposes. Many thanks go to my family especially my partner for their patience, understanding and encouragement. Thank you especially to my University for giving me the opportunity.

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Nomenclature

A_i	Area ratio of a floor space
A_{total}	Total floor area under investigation (m^2)
B_i	Weighting coefficients from regression
C	Heat exchange by convection (W/m^2)
C'	2* background noise design value (*dBA*)
'C'	Assignment by cut-off
*C**	Comfort
C_{CO2}	Concentration of Carbon dioxide (*ppm*)
C_i	Perceived air quality (*decipol*)
C_I	Is the pollutant concentration in the inhaled air
$C_{I,O}$	Is the pollutant concentration in inhaled air without PVS
C_{PV}	Is the pollutant concentration in the personalized air
Decipol	perceived air quality in a space with a pollution source strength of one *olf*, ventilated by 10 *1/s* of clean air, i.e. *1 decipol = 0.1 olf/(l/s)*
DR	Draught Rating
E	Heat loss by evaporation (W/m^2)
F	Floor temperature (°*C*)
f_{cl}	The ratio of the surface area of the clothed body to the surface area of a nude body
GH	Granby House
h_c	Convective heat transfer coefficient ($W/m^2/K$)
IAQ	Indoor Air Quality
I_{cl}	Thermal resistance of clothing, clo ($1\ clo = 0.155 m^2 K/W$)
K	Heat exchange by conduction (W/m^2)

L_{index}	Lighting comfort Index
LTCH	Leeds Town Centre House
M	Metabolism, W/m^2 (*1 met = 58.15W/m^2*)
MGA	Marsh Grochowski & Associates
'N'	Non equivalent groups
O	Observations or Measures
olf	Number of standard persons required to make the air as annoying (causing equally many dissatisfied) as the actual pollution source
*P**	Performance
p_a	Water vapour pressure (*Pa*)
PD	Percentage Dissatisfied
PD_{Acc}	Percentage Dissatisfied with acoustic environment
PD_{IAQ}	Percentage Dissatisfied with Indoor Air Quality
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PPD_{TC}	Predicted Percentage Dissatisfied with thermal comfort
q	Ventilation rates *l/s* standard person*
R	Heat exchange by radiation (*W/m^2*)
'R'	Random assignment
R_a	Colour rendering index – lower limit
RES	Heat exchange by respiration (*W/m^2*)
RH	Relative Humidity (%)
*S**	Satisfaction
S_i	IEQ Score
SBS	Sick Building Syndrome
SI_i	Sub index – Contributors to perceived IEQ
t_a	Air temperature (°*C*)

TC_{index}	Thermal Comfort Index
t_{cl}	Surface temperature of clothing (°*C*)
t_{dp}	Dew point temperature (°*C*)
t_f	Temperature of floor (°*C*)
t_{mrt}	Mean radiant temperature (°*C*)
T_{opt}	Neutrality temperature or the optimum temperature (°*C*)
T_{oave}	Average monthly outdoor temperatures - is simply an arithmetic average of the mean monthly minimum and maximum daily air temperatures for the month in question (°*C*)
T_o	Operative Temperature (°*C*)
t_u	Is the turbulence intensity expressed as a percent (*%*)
UGR	Unified Glare Rating
v_{ar}	Relative air velocity (*m/s*)
VAS	Visual Analogue Scale
W	External Work, met = 0 for most metabolisms (*W*)
X_i	IEQ variables
'X'	Treatments or program

1. Introduction

1.1 BACKGROUND

"Fossil fuels are part of the 'natural capital' which we treat as expendable….If we squander fossil fuels, we threaten civilisation" (Schumacher, 1973)

Buildings that score high in energy and environmental performance have now become flagships of sustainability within the built environment as global efforts are made to reduce carbon emissions. The rapidly increasing demand for energy in offices and other buildings has raised concerns over the accelerated depletion of already dwindling natural resources and the negative impacts of Greenhouse Gas (GHG) emissions on the environment. Offices demand energy in the form of electrical and thermal for equipment, lighting, ventilation, heating and cooling purposes. Most of this energy is predominantly supplied from fossil fuels that release Greenhouse Gases into the atmosphere causing global warming.

The ozone layer is depleting and global warming is taking place as we speak. There is now enough evidence to suggest this, for example, some of the evidence can be found in data gathered worldwide by the National Aeronautics and Space Administration's **(**NASA) Goddard Institute for Space Studies (GISS). The data which is presented in a paper by Hansen et al (2010) shows the difference between surface temperature in a given month and the average temperature for the same period during 1951 to 1980 as summarised in Figure 1.1.

A new analysis from the Goddard Institute for Space Studies also showed that 2010 tied with 2005 as the warmest year on record, and was part of the warmest decade on record.

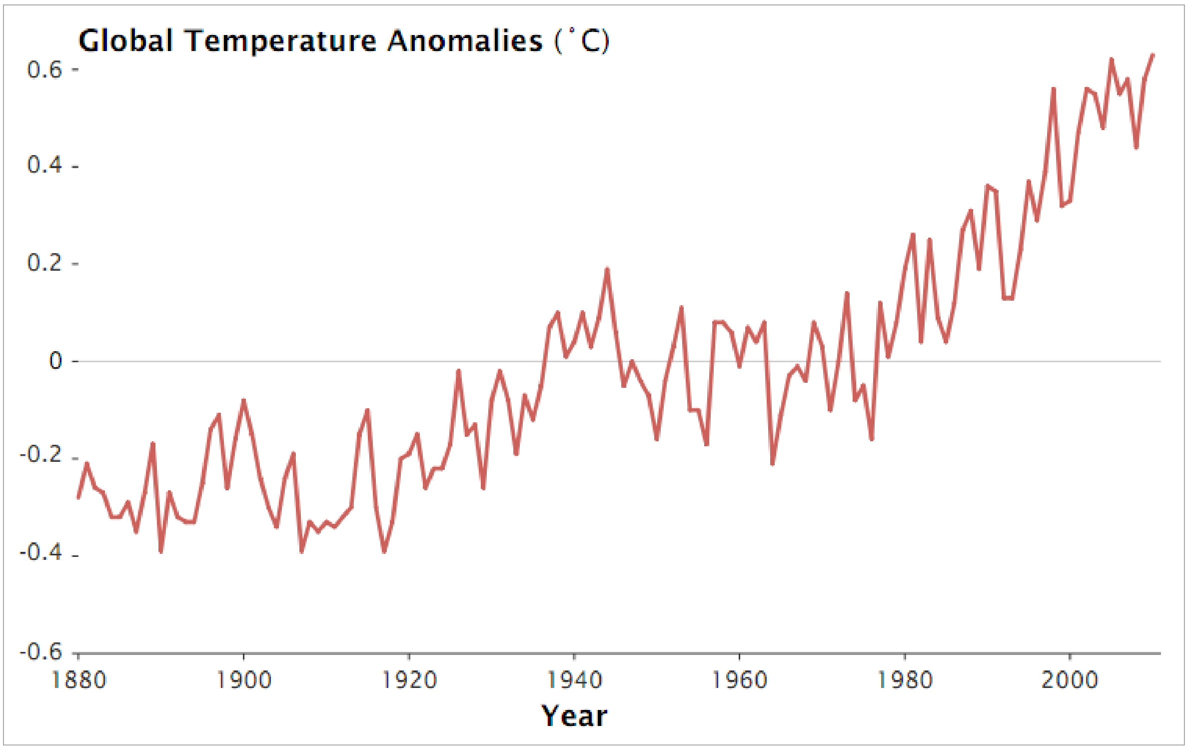

Figure 1.1 Global Temperature Change Estimated at the Surface, Over the Period 1880 to 2010, Source: (Hansen et al, 2010)**.**

The demand for primary energy has been increasing in the UK and worldwide raising concerns over the security of supply in the future. According to the International Energy Agency (International Energy Agency, 2011), the global primary energy demand is expected to rise in the next 25 years, although broad policy commitments have already been announced by countries around the world to address climate change and growing energy insecurity.

Global installed power generation capacity and additional energy by technology in the current policy scenario are illustrated in Figure 1.2. The graph shows that renewable energy sources are expected to claim a greater proportion of installed power generation in the future and global installed power generation capacity is expected to reach 9,000 GW by the year 2035 unless future policy changes are made.

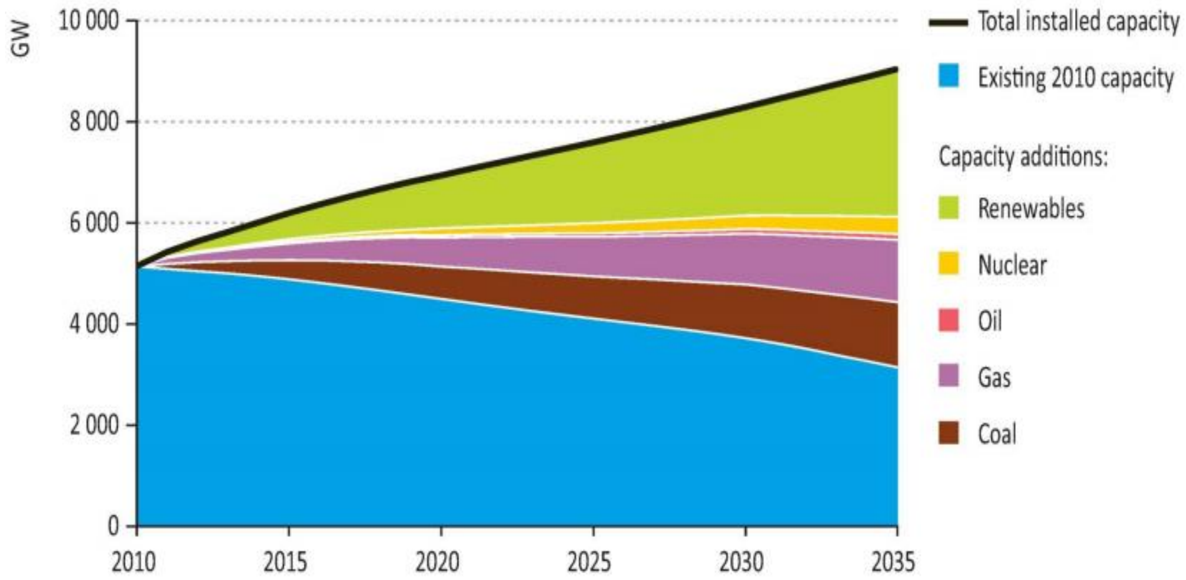

Figure 1.2 Global Installed Power Generation Capacity and Additions by Technology, Source: (International Energy Agency, 2011)

As a result global CO_2 emissions are projected to rise at an even higher rate in future reaching 45 billion metric tonnes in 2030 as shown by the graph in Figure 1.3.

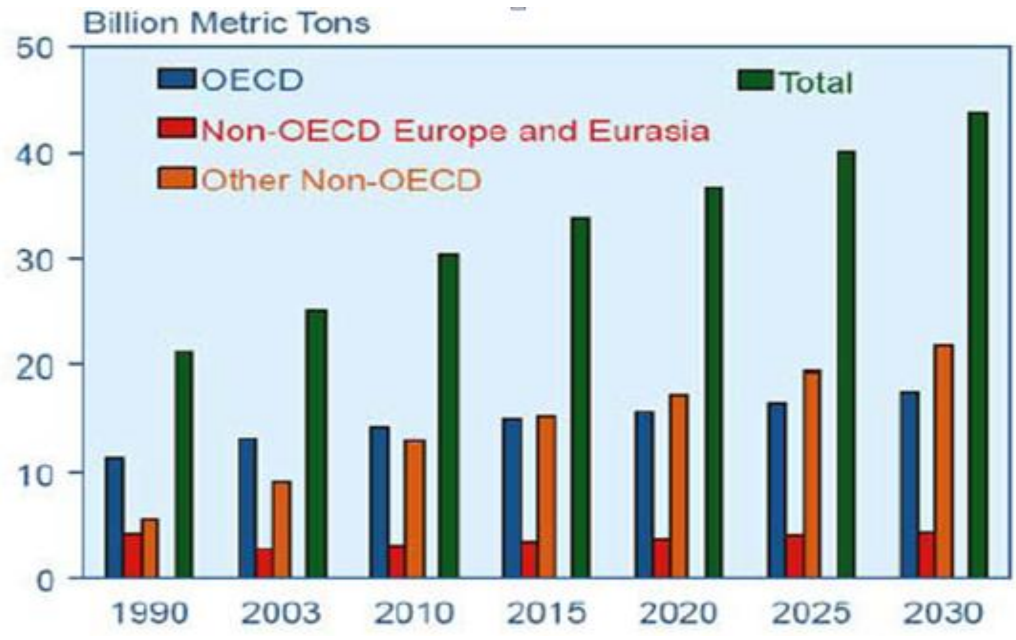

Figure 1.3 Actual and Predicted Carbon Dioxide Emissions by Region, 1990 – 2030,

Sources: (Energy Information & Administration, 2006).

As the world population grows more pressure is likely to be put on primary energy production and consumption. China's energy consumption for example has more than doubled in the past two decades to cater for growth in various sectors the economy. This growth is a direct result of the growth in population in that country (International Energy Agency, 2006).

In 2006 the Energy Information & Administration (EIA), published in its "International Energy Outlook" document a more comprehensive breakdown of global energy use and carbon emissions by region, including energy use forecasts into the future up to the year 2030 (Energy Information & Administration, 2006). World marketed energy consumption is expected to reach 212 Quadrillion Giga Watt-hours by the year 2030 as shown in the graph in Figure 1.4.

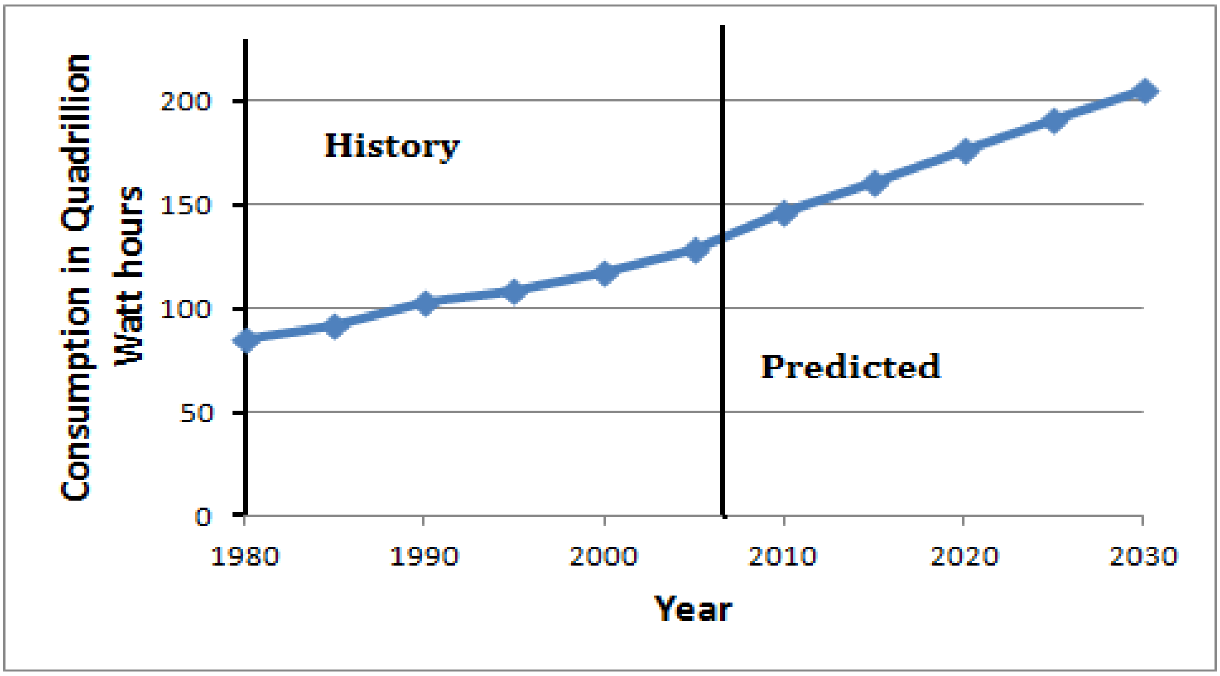

Figure 1.4 World Marketed Energy Consumption, 1980 – 2030, Adapted from: (Energy Information & Administration, 2006)

There is a general consensus among energy producers and researchers that the current situation cannot be allowed to persist and in order to tackle the problem alternative sources of energy need to replace fossil fuels. Another way to tackle this problem is to reduce energy use within rapidly growing sectors. In the UK alone overall energy consumption increased by from 213 million tonnes of equivalent oil to 237 million tonnes equivalent oil between the year 1990 and 2001, an equivalent of 0.5 percent increase per year. This increase has been attributed mainly to growth in the domestic and service sectors. Energy consumption by sector during the past five decades is illustrated in Figure 1.5.

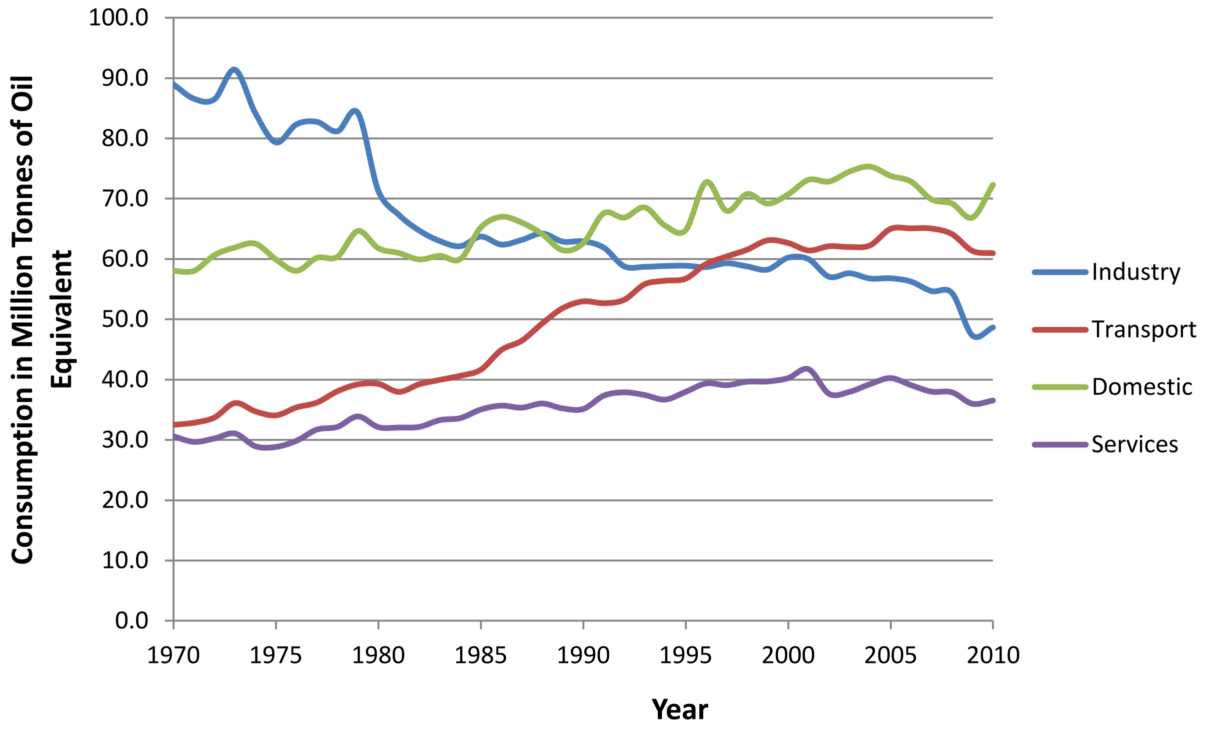

Figure 1.5 Energy consumption by sector in primary energy equivalents 1970 to 2010, UK, Source: adapted from (DECC, 2011)

The service sector which consists of all commercial and public buildings such as hotels, supermarkets, hospitals, schools, museums, universities and offices has experienced growth in the past few decades mainly due to the expansion of the built environment and this came with recent demands for higher comfort levels within buildings, as shown in Figure 1.5 (DECC, 2011).

The service sector now consumes nearly 17% of total energy used in the UK. Buildings now constitute about 20 percent of global energy consumption and in the UK that proportion is as high as 39 percent.

In view of these facts, the European Parliament and Council approved in December 2002 a directive on the energy performance of buildings (EPBD) (European Parliament and Council, 2003). The directive requires among other things the need to develop methodologies for calculation of energy performance of buildings, set minimum requirements for energy performance, apply the minimum requirements in new and existing buildings and develop energy certification standards for buildings. The amount of energy consumed in buildings depends significantly on the standards set for the indoor environment and the design and operation of building systems. Setting criteria for the indoor environment involves setting design standards for systems that control indoor temperature, relative humidity, ventilation rates, lighting and acoustics. National and international standards and guidelines which specify criteria for thermal comfort and indoor air quality have been developed. The standards are cited as references throughout the body of this thesis.

The quality of the indoor environment affects health, productivity and comfort of the occupants (Bjarne and Olesen, 2007; EN15251, 2006). Recent studies by Chiang et al (Chiang and Lai, 2002) on the comprehensive indicator of indoor environment assessment and others by Muhic et al (2004) have shown that the indoor environment has an effect on the health comfort and productivity of occupants. Poor indoor environment quality can negatively affect the profits of any organisation as the costs of absenteeism and low productivity are most often higher than the costs of energy used in the building (Wong et al, 2007, CIBSE, 1986). On the other hand good indoor environment quality can improve overall work performance by minimising the effects of building related illnesses and reducing absenteeism (BRECSU, 2000).

Ratcliffe et al reviewed the effects of increasing energy efficiency on productivity in commercial offices in the UK and acknowledged that although there is little incentive in exceeding minimum standards set by building regulations, there are aspects of the indoor environment such as the increasing use of daylighting and natural ventilation that show significant positive correlations with productivity (Ratcliffe and Day, 2003). For example there is a tendency among office occupants to have preferences for working areas near windows.

In most cases occupants feeling uncomfortable tend to take action to improve the situation, for example, by opening or closing windows, using fans to cool the space, adjusting the levels of clothing or connecting an electric heater. Most of these rash actions are usually energy intensive techniques that may increase both the bill and carbon emissions at the end of the year. In the UK buildings are now required by law to display energy performance certification (Building and Buildings - England and Wales, 2007).

However making energy performance declarations without declarations of the indoor environment does not make sense since the criteria used for the indoor environment significantly affects energy use. Methodologies for calculating energy performance of office buildings have been developed in the UK. The challenge now is to develop IEQ assessment methodologies that are comparable to energy use and which can be used to determine by how much energy efficiency imperatives sacrifice human comfort. This thesis attempts to address this specific problem area.

1.2 AIMS AND OBJECTIVES OF THE STUDY

The primary aim of this study is to provide a methodology for the development of a single index based IEQAT (Indoor Environment Quality Assessment Tool) that can be used for rating offices according to the quality of their indoor environment. The specific objectives of this research are:

- To develop a mathematical model for the IEQAT tool from extensive literature review. This includes developing or adopting indices for thermal comfort, IAQ, lighting and acoustic comfort with particular emphasis on variables that affect energy use and occupant comfort;

- To test the model by studying the responses of occupants of selected office buildings in the United Kingdom. The responses which are collected via questionnaires will be compared against model performance using physical measurements of parameters such as air temperature, illuminance (lux), background noise levels (dBA), relative humidity, carbon dioxide concentration (ppm), and air velocity as input;

- To use the AHP to provide a provisional estimation of IEQ in selected offices; and

- To use multiple regression modelling to determine a weighted ranking of contributing parameters, based on the type of office building and hence develop single indices that can be used to different rank different types of offices according to the quality of their indoor environment.

The novelty and originality of the IEQAT is that it includes the following new aspects in IEQ assessment:

- It represents the first attempt at addressing the need to estimate IEQ in offices using variables that have an impact on the energy performance of office buildings, hence it allows tests on how much of occupant comfort is sacrificed by the choice of particular energy efficiency imperatives to be made;

- The new tool can also be used to determine IEQ of typical office spaces in the UK context using calculated, measured, design and survey data. The tool can be used at any stage of the building's lifecycle i.e. it can be used during the design, construction and operation of the building;

- The methodology also includes new methods for estimating Acoustic and Lighting Indices that reflect the opinion of the occupant. These indices combined with more established thermal comfort and IAQ indices constitute the new index; and

- The use of weightings derived from subjective evaluation of indoor environments to develop a methodology for a computer tool for assessment of IEQ in office spaces in the UK is new. It represents the need to explore new areas of research in an attempt to develop a lasting solution to the problem of IEQ assessment using single index based tools.

1.3 OUTLINE OF THE THESIS

A general outline of the thesis is illustrated in the flow chart in Figure 1.**6**.

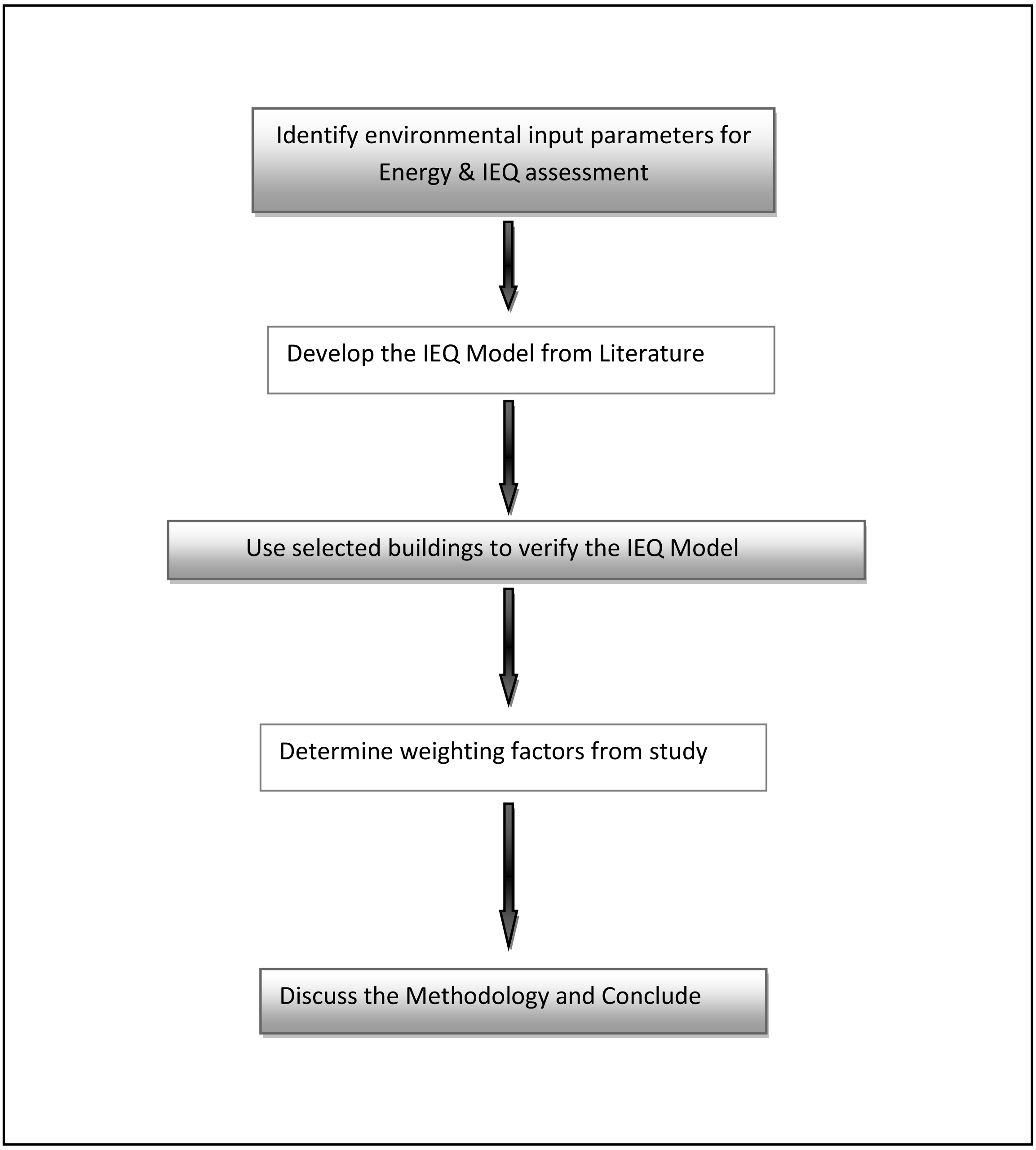

Figure 1.6 Flowchart: The development of a methodology for assessment of IEQ in office buildings.

This chapter **(Chapter 1)** gives a brief background in energy use, building comfort and global warming concerns in the UK and worldwide. The chapter also contains a brief introduction to the PhD study, its aims and objectives including a brief outline of the thesis and the novelty of the study.

Chapter 2 is a review of energy consumption in office buildings, energy use reduction strategies including current legislation and IEQ analysis methodologies used for office buildings in the UK. The chapter also presents various aspects of the indoor environment that affect the occupant's perception of IEQ. This includes a description of individual components affecting IEQ and a review of previous studies in buildings. Current standards in the operation of office buildings are also discussed in this chapter.

A chapter 3 presents the development of a Mathematical Model for calculating IEQ in office spaces in the UK based on literature review. A formal mathematical specification of the expression for IEQ acceptability is also highlighted in the model. Indices contributing linearly to perceived IEQ and a step by step program on how to predict comfort in offices are presented in this section. Recommended overall evaluation, classification and long term evaluation of the indoor environment are presented based on the new methodology.

Chapter 4 describes the methodology used to determine the relative importance of each of the proposed IEQ variables and methods used to evaluate the IEQ assessment tool developed in Chapter 3. It begins by describing the study design, the buildings and occupant selection procedures, the design of the questionnaire and a brief description of the equipment used to collect measurements. The chapter concludes by looking at typical software used to collect and analyse collected data.

Chapter 5 summarises the results of case studies used to test the IEQ model. Cases include a natural, mixed mode and a mechanically ventilated office in urban settings. Comparisons between calculated and surveyed comfort results are made in this chapter. IEQ results calculated using the AHP are used as provisional IEQ model data throughout the Chapter. Regression analysis of questionnaire data is used to determine relative weightings of each of the five proposed IEQ parameters and hence new models are developed. The chapter also highlights lessons that are learnt by studying each of the case buildings.

Chapter 6 presents the conclusions of the PhD study, the limitations of the IEQ methodology, improvements to the methodology based on case study results and recommendations for further work.

2. Literature Review

2.1 ENERGY USE IN OFFICE BUILDINGS

2.1.1 Major End uses

Offices together with retail, hotels and restaurants are one of the largest consumers of energy within the commercial/service sector (Wade and Ramsey, 2003). Researchers have been keen to understand how much energy these buildings consume relative to others in the same sector. A review of building energy consumption information within the sector by building type was compiled by Pérez-Lombard et al (2008) and the results are summarised in Table 2.1. The table shows that offices are the second largest consumers of energy behind retail despite the fact that they offer the greatest potential for action to achieve significant CO_2 emissions savings (Wade and Ramsey, 2003).

Table 2.1 Energy Use in the Commercial Sector by Building Type, (Pérez-Lombard et al, 2008)

Building Type	Proportion of Energy Used (%)
Retail	22
Offices	17
Hotels & Restaurants	16
Schools	10
Hospitals	6
Leisure	6
Others	23

Pérez-Lombard et al (2008) argued that energy supplied to office buildings is used in two main areas, (1) building services and (2) equipment services. Building services uses include a variety of applications such as HVAC, Domestic Hot Water (DHW), lighting and sanitary facilities. HVAC systems constitute about 55 percent of energy used in offices in the UK and most of this is channelled towards thermal comfort demands such as heating and cooling. Heating and hot water needs of offices are largely catered for by burning fossil fuels such as natural gas and petroleum products such as LPG.

In some cases electric immersion heating may be used in place of gas and oil boilers (BRECSU, 2000, Pérez-Lombard et al, 2008). Electric heating tends to contribute more carbon emissions as most of the electricity supplied to office buildings comes from power stations. Cooling uses significant amounts of electricity although it uses less compared to the pumps and fans which distribute the heat or coolant to various parts of the building. Lighting is yet another high end user of electricity despite efforts being made to increase the contribution of daylighting in new office designs (BRECSU, 2000).

Equipment uses include computers, printers, food preparation equipment, etc and these are mainly powered by grid electricity (Picklum et al, 1999). Electricity is also used in other areas including parking lots, lifts and security systems and the amount used increases with the complexity of the building as a whole. Prestige offices with a large range of services tend to consume more compared to simpler ones. Table 2.2 is a summary of energy use in office buildings by type of end use as prepared by Scras et al (2000). The table shows that by the year 2000 space heating and lighting consumed most of the energy in the UK.

Table 2.2 Energy Use in Offices by End Use in the UK (Scras, 2000)

Building Services Uses	Amount of fuel used (Peta Joules)	Equipment Uses	Amount of fuel used (Peta Joules)
Heating	51	**IT**	8
Hot water	5	**Catering,**	6
Cooling	11	**Other electricity –** lifts, exterior lighting; & special equipment rooms, etc**.**	2
Fans/Pumps/Controls	2		
Lighting	16		
Process	3		

Another breakdown in energy use in offices was compiled by Perez-Lombard in 2008 and the results are summarised in Table 2.3. It is important to note that HVAC systems and lighting consume a total of more than 70 percent of energy used in the buildings therefore targeting these areas is an important step towards reducing energy use in offices.

Table 2.3 Proportion of Energy Consumption in Offices by End Use (Pérez-Lombard et al, 2008)

Energy End Uses	Proportion of Usage
HVAC	55
Lighting	17
Equipment (Appliances)	5
DHW	10
Food Preparation	5
Refrigeration	5
Others	4

According to research carried out by EIA and DTI (Energy Information & Administration, 2006) offices are responsible for CO_2 emissions of well over 2.2 million tonnes per year (D.T.I., 2002). Results of a research funded by DEFRA in 1998 provided a breakdown of energy use and CO_2 emissions by type of occupier, end use and fuel type (Pout et al, 2000). Data for commercial offices was extracted and it is presented in Table 2.4.

Table 2.4 Energy consumption and CO_2 emissions in UK Commercial Offices: source – Wade and Ramsey (2003), Research carried out by Pout et al* (2000).

	Fossil Fuels (PJ)	Electricity (PJ)	CO_2 (kT)
Heating	46	5	3680
Hot Water	5	0	469
Catering	3	3	370
Light	-	16	2238
Cooling	-	11	1319
Small Power	-	2	250
IT	-	12	1031
Other	-	2	184
Process	-	3	7
Unknown	-	0.3	121
Total	**54**	**56**	**9669**

* CO_2 data includes emissions from power stations

The amount of energy used in an office building depends on the type, size and operation of that building. In other words the amount of energy used in an office building depends on the design standards of the building and its services. Offices where a high level of performance is expected are more likely to consume more energy than those with lower levels of expectation. Whether the building is mechanical or naturally ventilated (presence of air conditioning) has a large bearing on the amount of energy used since the use of air-conditioning adds considerably to the energy demand of office buildings (BRECSU, 2000).

The proportion of open plan space also has an effect on the amount of energy used as these tend to use more energy particularly for lighting (BRECSU, 2000). For this reason The Energy Efficiency Best Practice Programme has studied typical and good practice energy consumption in four types of offices and the results are summarised in Table 2.5. The exercise is aimed at encouraging positive management action in order to improve the energy and environmental performance of offices. Good Practice is described in the Energy Consumption Guide 19 (BRECSU, 2000) as a situation in "which significantly lower energy consumption has been achieved using widely available and well-proven energy-efficient features and management practices".

Typical Practice is described as energy consumption patterns, which are consistent with median values of data collected in the mid-1990s for the Department of the Environment, Transport and the Regions (DETR) from a broad range of occupied office buildings". Table 2.5 gives benchmarks against which one can compare the performance of their own office building and highlights that typical high performing offices tend to use more energy that low performing counterparts. For example a typical prestige office consumes 2.8 times more energy per unit of floor area than a typical naturally ventilated cellular building and "Typical" offices in general use 60% to 90% more energy than “good practice” offices (BRECSU, 2000).

Table 2.5 Typical and Good Practice Energy Consumption in Offices in the UK (Wade and Ramsey, 2003)

	kWh / m^2 of treated floor area							
	Naturally ventilated cellular		Naturally ventilated open plan		A/C, standard		A/C prestige	
	Good Practice	Typical	Good Practice	Typical	Good Practice	Typical	Good Practice	Typical
Heating/Hot Water	79	151	79	151	97	178	107	201
Cooling	0	0	1	2	14	31	21	41
Fans/Pumps, etc	2	6	4	8	30	60	36	67
Humidification	0	0	0	0	8	18	12	23
Lighting	14	23	22	38	27	54	29	60
Equipment	12	18	20	27	23	31	23	32
Catering	2	3	3	5	5	6	20	24
Other	3	4	4	5	7	8	13	15
Computer Room	0	0	0	0	14	18	87	105
Total	**112**	**205**	**133**	**236**	**225**	**404**	**348**	**568**

The amount of energy used in buildings has been rising in the past few years in the UK and the rise has been attributed to three reasons (BRECSU, 2000). First**,** there has been a significant growth in the information technology sector and a rise in the use of air conditioning systems to improve comfort in recent years. The demand for electricity for cooling has been increasing and it is expected to rise significantly in the near future since only a small proportion of office space is currently air conditioned. Over half of the offices that were built in the 1990s had air conditioning systems installed and during the last decade the number of chiller units sold to the UK market has more than tripled. Almost 45% of the units were installed in commercial offices reflecting the need for higher performing offices in that area (Giles, 2002).

Upgrading new and existing offices will mean the use of air conditioning technologies to ensure appropriate IEQ will be a common feature in the developed world in the next decades (Adnot, 2003). The electrical air conditioning load is subject to sharp peaks in demand for power during certain times of the day and this causes strain to the utility suppliers. This coupled with the rise in the amount of office equipment used will likely influence the future source of supply of electricity. Office equipment now accounts for about 5 percent of energy used in office buildings as the use of computers, printers, copiers, vending machines and communication equipment such as servers continue to increase (Pérez-Lombard et al, 2008).

Secondly, there has been growth in the number of new buildings erected in the UK. The new build rates within the service sector are typically around 2% and forecasts show that this rate is set to continue increasing (Pérez-Lombard et al, 2008). Figure 2.1 demonstrates a rapid growth in commercial office floor space since the early 1970s in England and Wales. From 1980 to 2000 the total office floor space almost doubled.

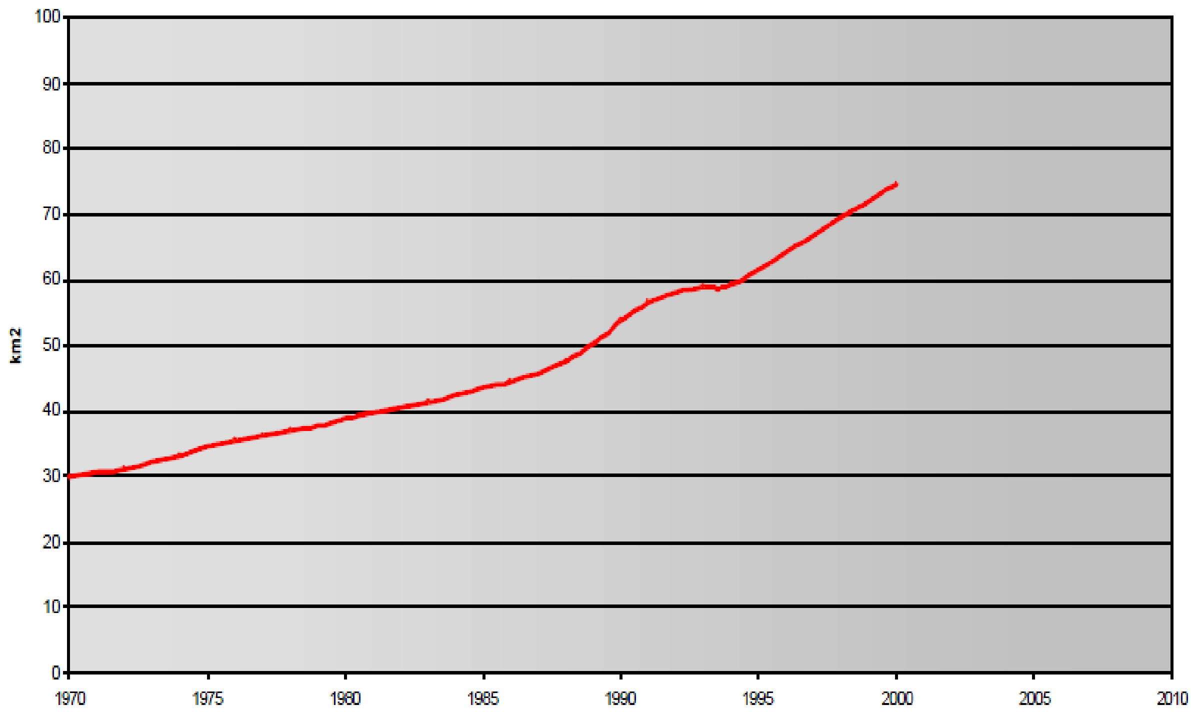

Figure 2.1 Growth in commercial office floor space in England and Wales 1970 to 2000

(DTLR, 2001)

Thirdly and finally, offices have been used more intensively in recent years resulting in longer occupancy hours. People in Europe now spend more than 90 percent of their time indoors (Environment Protection Agency, 1994) and that period includes time spent inside office buildings. The proportion of energy used increases as occupancy time increases.

2.1.2 Strategies to Reduce Energy Use in Office Buildings in the UK

Offices offer the greatest potential for action to achieve significant savings in both energy and carbon emissions. Reducing energy use in office buildings is important if the UK is to achieve its goal of reducing carbon emissions as set in the 2008 UK Climate Change Act (D.E.C.C., 2009). Using readily identifiable energy saving methods could save around 20 percent of energy used in commercial offices alone (Pout et al, 2000).

Every effort needs to be made to implement energy saving measures in new and existing office buildings. For new buildings some of the measures include the use of energy efficient office designs such as those which maximise the use of good building fabric and form to control the internal environment (Carbon Trust, 2000). For example target U values of 0.15W/m^2.K for walls result in buildings that have very good thermal properties (higher end of the spectrum). Lower U values for windows, ceiling, doors, and floors also contribute to reduced energy use in buildings; so does the minimisation of thermal bridges where possible and the improvements in building air tightness.

Other measures that can be applied to new buildings include the use of better architectures such as the use of atria for natural daylighting, passive cooling strategies, advanced glazing and reduced building depths (Carbon Trust, 2000, BRECSU, 2000). Designs which facilitate effective use and control of building services such as the BMS are also encouraged. Another way of improve energy performance of new office buildings is to target HVAC systems by designing passive ventilation systems (stack ventilation).

For existing buildings, management of the building thermal load, general energy efficiency, efficient operation of energy systems and the use of natural energy are of paramount importance. Energy efficiency in the building service system includes improvements in HVAC systems, lighting systems, hot water supplies, office equipment, elevators, etc. Monitoring of occupancy hours, the use of operation and management systems, improved maintenance services and reduced use of unoccupied spaces can help save energy (Picklum et al, 1999).

Sustainable technologies such as Combined Heat and Power (CHP), heat pumps, condensing boilers, wind turbines and solar products are now finding wider applications in commercial buildings and they help significantly reduce carbon emissions. They can be use in both new and existing buildings where opportunities exist. Improved controls of optimisers that help avoid overheating, cooling and unnecessary lighting (occupancy sensors) are becoming increasingly important. The use of energy efficient lighting such as fluorescent lamps and lighting timers is strongly encouraged. Changing consumer behaviour is also critical if the above measures are to be successful (Pérez-Lombard et al, 2008, Picklum et al, 1999).

Finally the Energy Review (PIU, 2002) highlights the need to improve energy efficiency in buildings and recommends "action to deliver a phased transition to low energy commercial buildings through development of the Building Regulations". Legislation can play an important role in driving change towards a low carbon lifestyle. The UK government has put in place legally binding, long term frameworks based on the Kyoto Protocol (UNFCC, 1998). This framework has been put forward in the form of regulations, directives, taxation and incentives.

The Energy Efficiency Commitment (EEC) (OfGEM, 2007) was set to encourage electricity and gas suppliers to make energy savings by working in partnership with project partners such as social housing providers, charities and retailers. The EEC phase 1 started in 2002 and EEC 2 ran from 2005 to 2008, while EEC 3 which began in April 2008 is expected save 293 million lifetime tonnes of carbon. Beyond the Kyoto protocol Part L building regulations (Department for Communities and Local Government, 2006) came into effect in 2006 (revised in 2010) to help enforce energy reduction commitments and some of the requirements for both new and existing non domestic buildings are found in Part L1A, L1B, L2A and L2B. The Energy Performance of Buildings Directive (EPBD) (European

Parliament and Council, 2003) which was issued by the European parliament in 2002 is embodied in the UK Buildings regulations (Department for Communities and Local Government, 2006).

The directive requires among other things that member countries develop methodologies for the calculation of integrated energy performance of buildings, set minimum standards for energy performance of new buildings, apply requirements to existing buildings and develop certification systems for energy use in all buildings (European Parliament and Council, 2003, Department for Communities and Local Government, 2006). It also suggests that cost effective measures should be included where major renovations of buildings are carried out in order to improve energy efficiency (European Parliament and Council, 2003). The directive provides a general framework for calculation of energy performance of buildings based on the following:

- Thermal characteristics of the building, heating and hot water installations;
- Air conditioning;
- Ventilation;
- Built in Lighting;
- Building position, orientation, effect of outdoor conditions and passive solar systems;
- Natural ventilation; and
- Indoor Environment Quality (IEQ).

In this thesis more focus is on the IEQ aspects of commercial office buildings.

2.2 THE INDOOR ENVIRONMENT

2.2.1. Introduction

Providing and maintaining the required indoor environment quality is an energy demanding exercise that requires designers, owners and energy users of buildings to make a balance between energy saving imperatives and providing comfort (Bjarne and Olesen, 2007). The quality of the indoor environment is described in the EN15251 standard (EN15251, 2006) as depending on the design and operation of building systems that control temperature, humidity, ventilation rates and illuminance. It also depends on the interaction between the occupant and the building envelope and its acceptability depends on how occupants accept the thermal environment, indoor air quality, acoustics and lighting comfort. These aspects and many other little understood factors such as vibrations, workplace design, electromagnetic effects, etc constitute what is perceived as IEQ by occupants and they will be highlighted in the subsequent sections in this Chapter. Some researchers have found that factors such as individual physiological state, health, social relations, financial state, state of adaptation to the climate and other person specific factors contribute to subjectively perceived IEQ (ASHRAE, 1993).

2.2.2 Overview of IEQ Assessment in Office Buildings

The way IEQ is perceived is viewed by many scholars (Jokl, 2003, Bjarne and Olesen, 2007) as a complex phenomenon that requires some knowledge of how the human body system functions. Jokl (2003) highlighted the different types of stimuli that affect our perception of the indoor microclimate as shown in Figure 2.2. The diagram also highlights the importance of four main aspects of the indoor environment namely, thermal, aural, acoustic and visual environment.

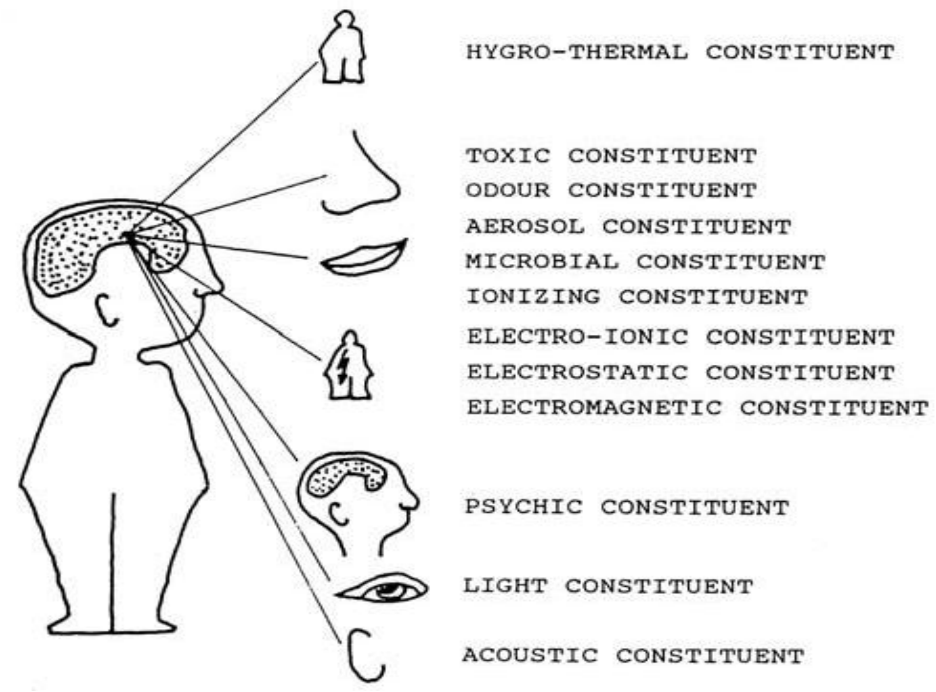

Figure 2.2 Main constituents of stimulus in indoor microclimate (Jokl, 2003)

Several attempts have been made by researchers to develop methodologies for assessment of IEQ in offices and similar environments globally. One such attempt was carried out by Chiang et al (2000) in aged care buildings in Taiwan. The researchers graded IEQ parameters such as carbon dioxide and carbon monoxide concentrations, dust particles, air velocity, air temperature, mean radiant temperature, relative humidity, noise level and illuminance into categories based on comparisons with recommended (health related) values in those buildings. The results of the model (field measurements) clearly showed close congruence with subjective assessments. The study highlighted the fact that comprehensive assessments of various integrated factors of the physical environment are still developing and in this case the point scoring system was based less on occupant perception the indoor environment. It should be expected that more credibility should be given to systems that reflect the opinions of the occupants (Lai et al, 2009).

Mui and Chan (2005) developed the so called Building Environmental Performance Model (BEPM) which compared building energy use with satisfaction with the indoor environment. The BEPM tool incorporated the adaptive comfort temperature control approach and a CO_2 demand control module which made it possible for the building management system to maintain thermal satisfaction whilst maintaining optimum energy consumption. However two other important parameters namely lighting acceptance and acoustic comfort were not incorporated into the system. The adaptive thermal comfort model also made the BEPM only suitable for naturally ventilated office buildings.

Most current standards cover separate aspects of the indoor environment, for example the EN15251 (2006) covers thermal comfort, Air Quality, Acoustics and lighting. The standards also show a strong focus on the development of recommendations for acceptable indoor environments making allowances for national differences in the requirements as well as for designing buildings for different quality levels (Olesen, 2004). However, satisfaction or lack of with each aspect is considered separately suggesting that there is a general lack of evidence that interactions between them exist, although it is common knowledge that all of the aspects play a part in the way occupants rate the indoor environment.

A study carried out by Toftum and King (2002) on the way humans respond to combined indoor environment exposures concluded that there was little evidence of significant interactions between different aspects of the indoor environment suggesting that these aspects acted exclusively on occupants. Only the effects of air temperature and relative humidity were found to be linked to perceived air quality suggesting that the combined effects of the parameters could be additive to some extent. How the parameters combine to influence IEQ has proved to be the most elusive part of the conundrum.

Bjarne and Olesen (2007) has attributed this to lack of knowledge of how various aspects can be added together to form a single representative index since their relative weightings are not known. Lai et al (2009) examined the quality of the indoor environment from the prospect of an occupant's acceptance in four aspects: thermal comfort, indoor air quality, noise level and illumination level. This provided some basis on which models that predict the quality of the indoor environment given a set of conditions could be developed.

Lai used the operative temperature as a basis for thermal acceptance of the indoor environment and gave occupants the freedom to adjust their clothing based the prevailing conditions. This study follows an earlier study conducted by Wong et al (2007) in which a logistic model was used to determine the overall acceptance of the IEQ based on weighting factors derived from subjective evaluations. This approach is more practical in naturally ventilated office environments and improvements need to be made before it can be accepted in a variety of environments.

Perhaps the most compelling study was carried out by Chiang and Lai (2002) who developed a comprehensive indicator of the indoor environment in office buildings using a consultative process involving building services experts in Taiwan. The researchers used the Analytical Hierarchy Process to derive weightings of each of the four main contributors to overall IEQ. This process will be described further in Chapter 3, Section 3.35.

2.2.3 Current IEQ Assessment Tools

The building sector has witnessed several criteria based tools for the assessment of environmental performance (including IEQ) of office buildings. Most of the tools are considered as comprehensive since they assess a variety of parameters such as energy use, indoor environment, water usage, materials usage, recycling, etc. The analysis tools have varying levels of accuracy hence they have been applied at different stages of design and operation of office buildings. Some of the most recognised tools include the BUS occupant survey developed by the Usable Buildings Trust (Boarders, 1981). This tool can be used for quickly assessing building IEQ performance (among other aspects of building performance) primarily from the feedback of occupants hence it is more applicable during post occupancy evaluation of office buildings.

The most predominantly used tool is the BREEAM tool which was developed by the Building Research Establishment (BRE, 1990). This voluntary assessment tool is used for environmental assessment of building performance using recognised measures of performance which are set against established benchmarks. The tool has a health and well being aspect which is of interest to this research. Its French counterpart, the "*Haute Qualité Environnementale"* (High Quality Environment, HQE) was developed by the Paris based Association for High Quality Environment (ASSOHQE) (2002) and contains advice on how to create pleasant indoor environments and tips on how to manage the impacts of the outdoor environment on conditions inside buildings. Both the BRE and the HQE have made efforts to develop a Europe wide building environmental assessment methodology and in 2009 they signed a memorandum of understanding to work together towards this goal.

Other international tools include the Green Star Scheme developed by the Green Building Council of Australia (GBCAUS, 2003) to assess the environmental performance of buildings in specific sectors, e.g. in offices, retails, education, and at a distinct phases of the development cycle. The tool also assesses IEQ among other aspects of building performance and like most assessment tools the point scoring criteria aspects of the indoor environment could be improved to reflect the view of the occupant. The LEED Post Occupancy Evaluation Methodology for Offices (POEM-O) is one of the tools and it was developed by the U.S. Green Building Council (USGBC, 1998) as part of a whole-building approach to sustainability. Its main disadvantage is that it can only be used at post occupancy stage of a building's life cycle.

The Australian NABERS rating system (Nabers, 2010) is a comprehensive performance-based rating system for existing buildings which also assesses IEQ. It is used as a voluntary tool which is used mainly for assessment of homes, offices, hotels, retail, transport, hospitals and offices across Australia and New Zealand. However, this rating system ignores the importance of lighting to occupant perception of IEQ in office buildings. The method can only be used for existing buildings hence it cannot be used as a design tool. Finally the Sustainable Building Consortium of Japan developed the CASBEE assessment tools (IBEC, 2008) for use in a wide range of buildings (offices, schools, apartments, etc.).

The main advantage of most tools is that each of them is developed to assess building performance at a specific stage of its lifecycle, i.e. tools have been developed for pre-design, new construction, existing buildings and renovations. The major disadvantages of the indoor environment assessment components is that it is difficult to compare the scoring of indoor environmental parameters to the health and well being of occupants. This has prompted a call for novel approaches, other than questionnaires, that reflect the perceptions of the occupant.

New tools need to generate predictions that correlate well with subjective assessments. Another common feature in most tools is that they treat IEQ indices such thermal comfort, IAQ, acoustics and lighting as separate entities hence it is difficult to use them for comparison with energy use.

2.3 THE THERMAL ENVIRONMENT

2.3.1 Overview of Thermal Comfort Assessment in Office Buildings

One of the primary objectives of buildings is to provide a comfortable thermal environment for occupants. The creation of comfortable thermal conditions is an energy demanding exercise that requires designers and building users to strike a balance between energy saving and occupant comfort (Bjarne and Olesen, 2007). Fanger (1973) identified six main factors affecting perceived thermal comfort as air temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation and activity levels. How these factors combine to influence thermal comfort (ISO 7730, 2005) will be explained in Chapter 3.

Thermal comfort is defined in the ASHRAE Standard 55 (ASHRAE, 2005) and in ISO 7726 (1988) as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE, 2005). That state of mind is a complex link between the physiology and psychology of an individual; between the building occupant and the heating ventilation and air conditioning system (HVAC) or the building’s architecture (ASHRAE, 1993; Wolkoff, 2003; Humphreys, 2007). This complex link is illustrated in the Cylindrical Model of Thermal Interaction of Human Body and the Environment shown in Figure 2.3.

The Cylindrical Model is one of the models that have been successfully used in practice and it shows that the regulation of human bodily functions and activities depends on the generation, storage and dissipation of heat (ASHRAE, 1993, CIBSE, 1986). Principles of thermoregulation are widely found in various texts (Ganong, 2003; Hensen, 1991) and they will not be described further in this thesis. The cylindrical model, which is incorporated in many thermal comfort standards and thermal comfort assessment systems, is explained below (ISO-7730, 2005; ASHRAE, 2005).

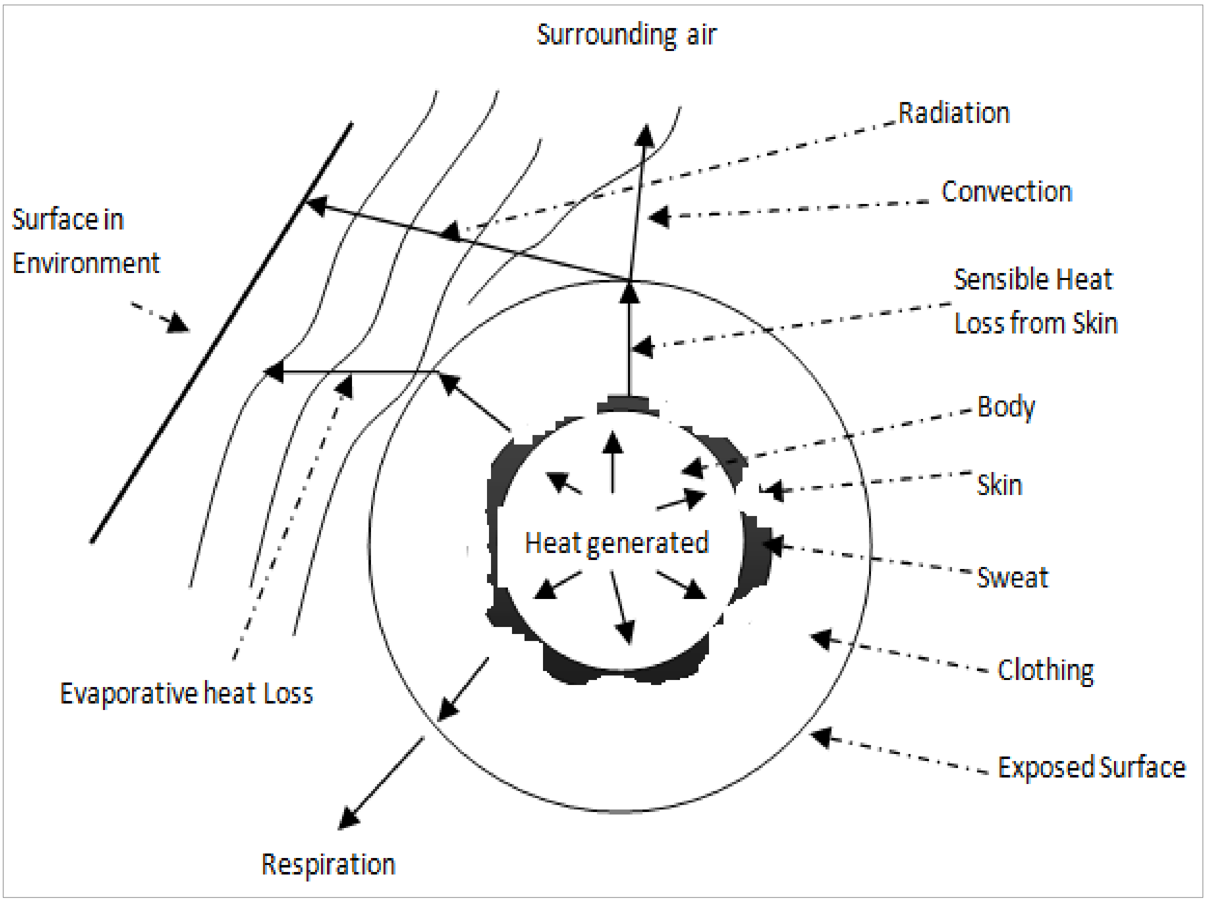

Figure 2.3 The Cylindrical Model of Thermal Interaction of Human Body and the Environment, Adapted from ASHRAE, Page 8.1(1993).

Research has shown that individuals within buildings sense skin temperature rather than air temperature (CIBSE, 1986, Olesen and Parsons, 2002) therefore it is the skin temperatures and other signals received by the receptor organs from the surrounding environment that constitute what is perceived as hot, cold, warm, cool, etc. The perceptual responses are of greatest significance in determining personal thermal comfort and they are measured by subjective evaluation on a widely accepted 7- point ASHRAE thermal sensation scale (Fanger, 2002; ASHRAE, 2005).

The ASHRAE thermal sensation scale was developed by Rohles and Nevins in 1971 and modified by Rohles in 1973 (Olesen and Parsons, 2002). Their studies on college students led to the discovery of correlations between perceived comfort and temperature, humidity and exposure times among other variables. The asymmetrical scale has two extreme ends of comfort i.e. the hot and the cold ends (a state of permissible thermal conditions called discomfort and a state of non-permissible conditions generally referred to as unacceptable) with the neutral (a state of balance in heat production and heat loss is often judged by people as optimal) as the most ideal situation. Table 2.6 shows the seven point ASHRAE thermal sensation scale.

Table 2.6 Seven Point ASHRAE Thermal Sensation Scale (CIBSE, 1986)

SCORE	ASHRAE SCALE & DESCRIPTION
-3	COLD
-2	COOL
-1	SLIGHTLY COOL
0	NEUTRAL
+1	SLIGHTLY WARM
+2	WARM
+3	HOT

Thermal comfort evaluation indices are the most researched of all IEQ indices and a number of thermal comfort equations as proposed in some widely used design guides and standards. Over the past 60 years much research effort has been devoted to their development and only a few will be considered here. More information on thermal comfort indices can be found in the CIBSE and ASHRAE handbooks (CIBSE, 1986, ASHRAE, 1984) or in Fanger's textbook on thermal comfort (Fanger, 1973). One of the first indices to be developed was the Effective Temperature Scale (ET) which was developed in 1923 by Houghten et al and was revised in 1941 by Houghten and Ferderber (1941). In this index researchers proposed that (i) the temperature of the air, (ii) its moisture content, (iii) air movement and (iv) the radiation transfer between the body and surrounding surfaces are the four main parameters affecting thermal comfort. In their research the authors acknowledged that the most important parameter affecting thermal comfort was dry bulb temperature.

The ET scale has however been criticised in various texts because it underestimated the effects of humidity at high temperatures, and overestimated the effects of humidity at lower temperatures (CIBSE, 1982). The Standard Operative Temperature is another early index which has been applied in both the veterinary and human sciences fields. The index which was developed by Gagge in 1940 takes into account the combined effects air temperature, radiant temperature and air movement in calculating Thermal comfort (Gagge, 1940). The scale was modified by Nishi and Gagge in 1941 (Gagge, 1970) to include the effects of humidity. The scale was only applicable in moderate air velocity situations and only when the values of operative temperatures were close to air and mean radiant temperatures. Other models such as the two-node model of human thermoregulation were developed by Gagge and Nevins in 1975 (Nevins et al, 1975).

More recently several methods for evaluating thermal comfort in indoor environments have been put forward by the International Standards Organisation (ISO), ASHRAE and CIBSE. They include the assessment of the influence of the thermal environment on occupants using subjective judgement scales (EN10551, 2010), the application of standards to people with special requirements (BSI-EN, 2005), the evaluation of thermal environments in vehicles (EN14505, 2009), the methods for assessment of human responses to contact with surfaces at moderate temperatures (ISO13732-1, 2006), the analytical determination of thermal comfort using Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices and local thermal comfort criteria such as Draught rating, discomfort due to vertical air temperature difference and radiant temperature asymmetry (EN-ISO7730, 2005). The later models which are mostly applicable in office buildings are explained further in Chapter 3, section 3.3.1.

Even more recently thermal environment assessments involving advanced physiological measurements, computer models, mathematical simulations (differential equations) and thermal manikins have been developed by researchers. Studies involving heated, breathing and sweating manikins have been done by Havenith et al (2008) while Fiala et al (2008), introduced a multi-node model of human physiology to predict dynamic thermal comfort responses to the indoor environment. Fiala et al (2008) measured temperatures of different parts of the body at varying temperatures and found good correlations between core body temperature and thermal sensation.

Earlier Zhang (2004) and his colleagues had performed experiments on occupants under non uniform transient conditions and developed predictive models of local, overall thermal sensation and general comfort (Zhang et al, 2004). The models predicted thermal comfort with reasonable success. However PMV and adaptive models still remain the models of choice in office buildings (Parsons, 2008).

The PMV and PPD models have been tested extensively in air conditioned buildings worldwide. In many thermal comfort studies, researchers have investigated the relationship between actual thermal sensations (observed) to those predicted by the PMV model. Charles (2003) carried out assessments of office buildings located in the North American region (COPE Projects – Canada) using the PMV model and found that the model was a better predictor of thermal comfort in air-conditioned buildings than in naturally ventilated ones. The author attributed this to the influence of adaptation opportunities and outdoor temperatures. The researchers also found differences between predicted and observed PMV values but that the discrepancy between PMV and actual mean vote increased for heavier clothing and higher activity levels (Charles, 2003).

A field study carried out by Melikov et al (2005) in 10 offices equipped with displacement ventilation systems indicated that there was an overlap in those occupants dissatisfied with uncomfortable room temperature, draught and vertical temperature difference. For example the study found that about 49% of the occupants expressed dissatisfaction with air temperature (cold) and 24% expressed dissatisfaction with draught and vertical temperature difference (Melikov et al, 2005). Although the study did not indicate how many of the occupants expressed dissatisfaction with both sets of discomfort factors it highlights the need to approach discomfort estimations cautiously and precisely, that discomfort factors need to be treated as risk factors if they are to be added together.

Different models have been developed for office environments that are naturally ventilated and the most notable include those developed by Humphreys (1994) and earlier models by Auliciems (1981). The latter model is discussed further in Chapter 3, section 3.3.1. Studies carried by Fanger and Toftum (2002) on office occupants in warm climates highlighted that occupants in those climates may sense warmth as being less severe than the PMV model predicts. They attributed this to low expectations of building thermal performance based on conditions outside the building. As a consequence the researchers developed a new extension of the PMV model based on the effects of adaptation to naturally ventilated buildings. Observed thermal sensation votes on the 7 point ASHRAE scale agreed well with new extensions of the PMV model in three continents.

2.4 INDOOR AIR QUALITY

2.4.1 Air Quality problems in buildings

Air quality is perceived by humans using the combination of the olfactory sense which is situated in the nasal cavity and the general chemical sense which is situated all over the mucous membranes in the nose, eyes and throat (Berglund et al, 1982). The olfactory sense is sensitive to a very large number of odours in the air while the general chemical sense is also sensitive to a large number of air pollutants, (hundreds of thousands of chemicals) (Seppänen et al, 1999; NOHS, 2003).

Literature suggests that a combination of these senses determines whether the air is fresh, stuffy, irritating, pleasant, dry, etc (Commission for European Communities, 1991, European Collaborative Action, 1992). The science of perception is beyond the scope of this thesis and it can be found in various texts, notably in “The Fundamentals of Human Sensation” by Roberts (2002).

Jokl (2003) highlighted that perceived air quality is dependent on the temperature of the air, relative humidity, the concentration of chemical and biological elements in air, static electricity and the number of ionic substances in the air. The impact of each of these factors depends on the magnitude of the stimuli and perception of IAQ is solely based on our sensory evaluation of odour microclimate. Acute and chronic illnesses emanating from poor indoor air quality (IAQ) are very common in the UK (Ganong, 2003).

Studies have shown that buildings are the main route to exposure to air pollutants (Hensen, 1991) because as explained earlier in the thesis, most people in Europe spend most of their time indoors. Research carried out by scientists in the USA suggest that the quality of indoor air in these buildings can have major effects on health, comfort and productivity of occupants (ASHRAE, 2007b). Some studies have highlighted the negative effects of poor IAQ on health and productivity of offices occupants and school children (International Energy Agency, 2006; Berglund et al, 1982; Seppänen et al, 1999; Ratcliffe and Day, 2003).

If good indoor air quality is to be maintained, it is important to identify all important parameters affecting it, develop appropriate assessment criteria and present appropriate technologies that can be used to minimise its adverse impact on human occupants. The scientific committee of the World Health Organisation have warned that pollutants that exist at lower concentrations e.g. Volatile Organic Compounds (parts per million, etc) are still potent enough to cause health problems (WHO, 1984). Pollutant mixtures have been found to have complicated links to negative health outcomes, for example; their combined effects may be or may not be synergistic, addictive, antagonistic or independent.

At present it is difficult to predict the impact of any one or combination of chemicals which usually exist in large numbers at any one particular time as suggested in studies by Hui et al (2008). It is fairly good to assume control of pollution sources by using local ventilation systems, isolation of pollutants, removal of sources of pollution, replacement of faulty equipment, or controlling dominant sources of pollutants as explained earlier. Some researchers suggest (ASHRAE, 1993; European Collaborative Action, 1992; Environment Protection Agency, 1994; Fang et al, 2005; ASHRAE, 1985) identification of the dominant source then calculating the required ventilation rate to remove it as an effective method for minimising air pollution.

Controlling the dominant source is likely to remove all other air pollutants, therefore it is perfect to assume that other chemicals will be sufficiently diluted using this approach. Indoor air quality also varies with time in spaces due to occupant activity, outdoor conditions, building operation and the types of building materials (low or high polluting). Human beings produce bio effluents such as the carbon dioxide gas which pollutes indoor air. Carbon dioxide levels in office buildings can thus be used as an indicator of air pollution.

Studies by Toftum and Fanger (2002) show that in many buildings human requirements of the indoor environment vary throughout the day, with vulnerable individuals being more sensitive to changes while healthy adults are less sensitive. The use of ventilation to improve air quality is an established practice (Olesen and Parsons, 2002) although in most cases ventilation is only set to meet the metabolic requirements of occupants and dilute their bio effluents.

Health aspects of IAQ are discussed by the WHO, UN and in the ECA's 10^{th} and 11^{th} publications (Effects of IAQ pollution on human health) (European Collaborative Action, 1992, Commission for European Communities, 1991). The above sources suggest that in order to minimise the health effects of poor IAQ it is essential to establish a guide that includes an extensive list of known indoor air pollutants of various origins with maximum permissible limits & expose times associated with negative health outcomes. Legally binding IAQ guidelines exist only for industrial spaces but not for non-industrial premises such as offices where concentrations are usually very low (Fang et al, 2004, Daisey, 2003).

2.4.2 Overview of IAQ Assessment in Office Buildings

A number of approaches exist for the evaluation of building ventilation and indoor air quality (IAQ). Indoor air quality standards in industrial buildings are applied widely within the European Union and in the USA. A few IAQ indices have been developed to assess the quality of indoor air in office buildings. The Indoor Air Pollution Index (IAPI) which is described in a study Moschandreas and Sofuoglu, (2003) was developed in consultation with experts who identified each of the pollutants which affect occupant health. The index showed a lot of promise in that it aimed to correlate pollution and an indicator of occupant symptoms. However no recorded study where the index was applied has been found in literature.

The ventilation Efficiency (VE) indices for indoor domains were applied in a study carried out by Bady et al (2008) as part of a tool for evaluating the performance of ventilation systems and the quality of indoor air. Three important indices of the tool included the purging flow rate of pollutants, the number of times a pollutant enters the domain and the time a pollutant takes from once entering or being generated in the domain until its leaving.

The study which was purely simulation provided useful information about pollutant behaviour within the domain and it appears to be a promising tool for coupling with models that try to predict possible health and or comfort outcomes associated with certain pollutants.

The less relevant but informative Master Scale Unit which expresses occupant annoyance with indoor odours is described by Berglund et al et al (1982). The scale has been tried in communities where odour annoyance is expected and complemented by field measurements of concentrations of substances of interest. Some studies have used the concentration of bio effluents such as CO_2 to determine the quality of the indoor environment where main sources of pollution are primarily humans.

A study carried out by Mui and Wong (2007) in air conditioned offices in Hong Kong compared measured CO_2 concentrations with subjective evaluations of the quality of indoor air and a good agreement between the two was observed. The results collaborated observations made earlier by Fanger (1988) where metabolic CO_2 was found to be a good indicator of the presence of other bio effluents that could cause dissatisfaction with indoor air.

Most studies give reasonable estimates of indoor environment quality because the models are derived from subjective measurements validated by physical measurements of IAQ variables, although the Indoor Air Quality (Commission for European Communities, 1991, European Collaborative Action, 1992) suggest methods based only on subjective evaluation. One such study was carried out in more than 15 mechanically ventilated buildings in Slovenia (Muhic and Butala, 2004). The study used concentrations of CO_2 and a selection of VOC as indicators of IAQ, confirming the increasing reliance on CO_2 as a tracker gas for IAQ acceptance in office buildings.

Zeng et al (2005) based the evaluations on the amount and quality of ventilation air supplied to individual workstations within offices spaces. The two approaches to evaluating IAQ in buildings discussed above and the decipol approach (Fanger, 1988) will be discussed further in the next chapter. The main question that remains unanswered however is "*Can co-pollutants be grouped together in such a way that their relative contribution to a specific symptoms are additive?*" (Wolkoff, 2003). In other words if we could find an index that consists of a database of all known major pollutants and their health and comfort outcomes, and if the effects on occupants could be combined (additive) to represent a single index then we could be very close to our answer. Achieving such an aim is a difficult task since at present there is no standard universally accepted index for IAQ assessment in the UK.

2.4.3 Sources of Pollution in Offices

Many types of pollutants exist in ambient air and they range from solid to liquid to gaseous substances (Daisey, 2003; Hui et al, 2008; Janssen, 2003; Office of the Deputy Prime Minister, 2005; Environment Protection Agency, 1994). Solids may be in the form of fine particles or aerosols. Researchers have classified these pollutants on the basis of their origins, composition, chemical properties, physiological effects, physical location and even legislation (Environment Protection Agency, 1994; Fang et al, 2005; Kaczmarczyk et al, 2004). These categories overlap easily meaning that there is no one unique method of categorizing pollutants. In some cases pollutants have been classified into natural and manmade, organic and inorganic, primary and secondary, particulate and gaseous, and major and minor.

2.4.4 The Sick Building Syndrome

A study by Engval et al (2005) pointed to a set of non-specific symptoms related to occupancy in office buildings that are prevalent mostly in Europe & North America and this is supported by information in the ASHRAE standard 55 (2005). These sets of symptoms have been generally referred to as the Sick Building Syndrome. The WHO (1994) defines the Sick Buildings Syndrome as characterised by Ear, Nose and Throat (ENT) irritations, a sensation of dry mucous membranes and skin erythema (skin redness), mental fatigue, headache, high frequency airway infection and cough, hoarseness of voice, itching and non-specific hypersensitivity, nausea and dizziness. The SBS is also characterised by non-specific symptoms such as nasal dryness, nasal congestion (stuffy blocked nose), nasal excretion (running nose) pharyngeal symptoms, difficulty breathing or concentration and tightness of chest .The list is not exhaustive. These symptoms are a result of exposure to indoor air pollutants and affect the health and well being of occupants.

2.5 THE ACOUSTIC ENVIRONMENT

2.5.1 Overview of the Acoustic Comfort Evaluation in Offices

Sound is produced by the vibration of bodies or air molecules and it is transmitted as a longitudinal wave motion. It is a form of mechanical energy therefore SI units have been assigned to its measurement. The amount of sound produced by a source is measured in watts and its intensity is defined as the rate of energy flow per unit area (W/m^2). Sound intensity is usually expressed in decibels (dB) (Wong et al, 2007; Lai et al, 2009; Bies and Hansen, 2003; Bies and Hansen, 2009), which represent a measure on a logarithmic scale of a quantity such as sound pressure, power, or intensity. Loudness generally refers to the perceived magnitude of sound and this is a function of both sound intensity and frequency. Neither the adverse effects of noise on the health and well being of humans nor its interactions with other environmental factors is well known, although several criteria for the indoor acoustic environment has been specified in building services design (Bies and Hansen, 2009).

The processing of sound by the human ear is explained in various texts (Bies and Hansen, 2009; Ganong, 2003; CIBSE, 2006) and will not be discussed further in this thesis. Research on noise in offices and its correlated health aspects has focussed mainly on the effects of equipment noise. Most research has also been dominated by field studies in residential areas and industry with very little on occupational noise in offices. In this thesis we will focus on research or literature that highlight the link between indoor environment noise to the level of dissatisfaction experienced by occupants.

More focus is also on the A - weighted sound pressure level which is commonly associated with medium to low frequency noise. Studies by Kjellberg et al (1997) showed the A weighted sound pressure level underestimated the contribution of noise frequencies below 200 Hz although in general it correlated well with annoyance and speech intelligibility feedback from subjective measurements (Pierre and Maguire, 2004). The Kjellberg et al (1997) study also highlighted that very little improvements (1.4%) on the A weighted pressure levels were observed when the dB(C) – dB(A) difference was used instead. An earlier study by Kjellberg et al (1990) has found not difference in annoyance ratings between the A weighted sound pressure level and other weighting methods (B – D). Nillson (2007) approached his study of perceived loudness or annoyance with road-traffic noise with an understanding that the A-weighting had been criticized for not properly integrating energy at low frequencies and found that A weighted approach differed with the C – A difference by as little as 0.4dB.

Standards for ensuring appropriate acoustic performance of office buildings are widely available for their design and construction. Noise weighting curves are most often used for evaluating ambient noise. For most acoustic design purposes noise curves that have been developed include the noise criterion (NC) curves, the balanced noise criterion (NCB) developed by Berane; the noise rating (NR) developed by Kosten and Van Os; the preferred noise criterion (PNC) by Beranek; the room criterion (RC) by Blaizer; and the loudness and loudness level by Stevens and Zwicker. Table 2.7 shows a comparison between RC and NCB values and shows design values for different types of offices spaces.

Table 2.7 Design values for different types of offices spaces, Source: (Acoustics.com, 2009; Bies and Hansen, 2009)

Type of Office	RC-Curve Value	NCB Value
Executive	25-30 (N)	25-30
Conference rooms	25-30 (N)	25-30
Private	30-35 (N)	30-35
Open-plan areas	35-40 (N)	35-40
Business machines or computers	40-45 (N)	38-43
Public circulations	40-45 (N)	-

Table 2.8 shows a comparison of Noise Weighting Curves for purposes of specifying the indoor acoustic environment. Values in dB(A) corresponding to connotations expressed by occupants (subjective evaluation) can help determine the level of dissatisfaction with the acoustic environment associated with background noise levels in offices.

Table 2.8 Comparison of Noise Weighting Curves for Purposes of Evaluation the Indoor Acoustic Environments, Source: (Acoustics.com, 2009; Bies and Hansen, 2009).

dB(A)	Average dB(A)	NR	NC, NCB & RNC	RC	Comment
25-30	27.5	20	20	20	Very Quiet
30-35	32.5	25	25	25	
35-40	37.5	30	30	30	Quiet
40-45	42.5	35	35	35	
45-50	47.5	40	40	40	Moderately Noisy
50-55	52.5	45	45	45	
55-60	57.5	50	50	50	Noisy
60-65	62.5	55	55	-	
65-70	67.5	60	60	-	Very Noisy

Most of these indices are frequency-weighted measurements that are most applicable in environments occupied by healthy adults and they are explained in both texts by Bies et al 014 (Bies and Hansen, 2003; Bies and Hansen, 2009). Given the nature of the noise generally encountered in offices, it was found that Equivalent Continuous Noise Level (L_{eq}) in dBA was the best index, although Zwicker's loudness level has been found by Bies et al to be almost as good if not better (Nilsson, 2007).

2.6 LIGHTING (VISUAL) COMFORT

2.6.1 Overview of Lighting in Office Buildings

Light is defined as the electromagnetic radiation that stimulates our visual response and therefore helps us determine our perception of the indoor environment (Zelinsky, 2011). Illuminance is defined in the CIBSE handbook as the ratio of the light flux (lumen) to the illuminated surface area (m^2) and is quoted in lumens per meter or lux (CIBSE, 1994). The human visual system is part of the central nervous system (CNS) that processes surrounding information by capturing and processing visible light (Ganong, 2003, CIBSE, 2006). The system responds physiologically to the luminance distribution in the field of view and this helps occupants perceive the lighting environment. More information of visual perception can be found in literature (Malik, 2004; Ganong, 2003; Zelinsky, 2011).

Lighting quality has been defined by Chung and Burnett (2000) as "a term used to describe all of the factors in a lighting installation that affect human comfort**,** health and well being". In order to provide a comfortable lighting environment factors such as illuminance, illumination uniformity, luminance distribution, colour characteristics (rendering and appearance), day lighting factors, room surface reflectance, glare and flicker rates need to be in the right balance. Recommended values for these parameters are shown in tables later in this chapter. Lighting installations need to be assessed for their ability to provide comfortable indoor environments in office buildings and lighting indices are required for that purpose. A strong link between lighting quality and work performance is also highlighted in most recent studies (Chung and Burnett, 2000; Ratcliffe and Day, 2003).

Although there is undisputed evidence of this correlation very little is known about the causal relationships between lighting and occupant comfort, performance, or health and well being. For example a window location is reported by Hartkopf as one of the main influences on an occupant's degree of satisfaction with the indoor environment with incidences of health complaints reduced by 20-25% (Hartkopf, 2003).

There is currently very limited literature available on the development of lighting indices for office buildings and most office lighting designs rely on lighting guides (e.g. CIBSE, 1994, CIBSE, 2006; ASHRAE, 1999; Howley, 1999) and standards e.g. (EN12464, 2002; EN 15251, 2006). Quoting from Chung and Burnet "any general agreement on how the lighting quality should be defined does not exist" therefore horizontal illumination of surfaces has acted as an acceptable guide for offices and this relates to the amount of light falling on a working plane (Chung and Burnett, 2000). Although the quantity of light falling on the working plane (illumination) is generally accepted as an indicator of lighting quality, it only forms a part of many contributing factors to lighting quality.

Saunders carried out studies on the effects of the level of task illuminance on quality of lighting perceived by occupants and found a positive correlation between the two (Saunders, 1969). This relationship has stood the test of time and has been presented in many lighting handbooks including the CIBSE code for interior lighting (CIBSE, 1994). Several other studies have used illuminance as an indicator of lighting, for example, Linhart (2011) performed experiments to determine the effect of energy efficient lighting on the visual performance of 20 individuals carrying out computer tasks during an evening and used illuminance levels as a measure of the amount of lighting received on working planes. That study showed that relationships between illuminance and occupant acceptance of the lighting environment exist.

Some studies have used illuminance and glare to compare the visual performance of office buildings and one such study was carried out to evaluate visual comfort in highly luminous offices environments receiving high solar radiations (Ochoa and Capeluto, 2006). A study by Yun et al on occupants of open plan offices revealed that there were close relationships between prevailing illuminance levels on the work plane and luminous comfort (Yun et al, 2010). Perhaps the most ideal approach is to develop a single index that takes into account various aspects of lighting such as illumination uniformity, luminance, distribution, colour characteristics, room surface reflectance, glare and flicker rates. The closest to such an index is the Comfort, Satisfaction and Performance (CSP) index developed by Bean and Bell (1992).

The CSP index was developed as the attempt to find an index or indicator of lighting quality intensified in the 1990s. The model assumes that there is an interaction between the three elements of visual quality and these are comfort *(C*)*, satisfaction *(S*)*, and performance *(P*)*. According to Bean and Bell the comfort *(C*)* element is related to the glare index and is given a maximum value of 10 when the glare index is less or equal to 14. The satisfaction *(S*)* element is derived from the multiplication of the ratio of cylindrical illumination to horizontal illumination by a factor of 15. S is equal to 10 when this ratio is greater or equal to 2/3. The performance *(P*)* element is a complex derivative of the horizontal illumination, the ratio of cylindrical to horizontal illumination, the uniformity and colour rendering index. Each of the elements if given a value between 0 and 10, then the CSP index has values between 0 and 100 (Bean and Bell, 1992). The CSP index is given as:

$$3 \times \frac{C^* S^* P^*}{(C^* + S^* + P^*)} \qquad 2.1$$

A different calculation criterion is used for offices with video display units (VDU) and this method is explained by Bean and Bell (1992), and in Chung and Burnett (2000).

Chung (2000) also found a poor correlation between subjective assessment of the lighting environment and the CSP index among occupants of a retrofit building in Hong Kong. The reason for the poor performance of the index is that it is based on measurable photometric data and hence it does not take into account most human behavioural factors. This method therefore cannot be accepted solely as an indicator of lighting quality hence it needs to be complemented by subjective assessment.

2.7 CURRENT STANDARDS IN OPERATION OF OFFICES

2.7.1 Recommended Criteria for the Thermal Operation of Mechanically Ventilated Buildings

The EN ISO 7730 (2005) standard proposes that criteria for the design of thermal environment shall be based on thermal comfort indices, i.e. the PMV-PPD (Predicted Mean Vote - Predicted Percentage of Dissatisfied), with assumed typical activity levels and clothing values for winter and summer. Using a reasonably assumed combination of activity and clothing levels, an assumed relative humidity (approximately 50%) at low air velocities, it is possible to establish a corresponding range of operative temperatures and therefore express comfort categories as a temperature range. Operative temperatures have a significant impact on the amount of energy used in the office therefore mechanically ventilated offices have been classified into categories based on summer and winter design operative temperatures as shown in Table 2.10. Recommended comfort categories based on PPD are illustrated in Table 2.9. The importance of relative humidity, air speed and air conditioning on improving thermal comfort in mechanically ventilated buildings is discussed in the next sections.

Table 2.9 Thermal Comfort Categories for Offices, Copied from the EN 15251 Standard, Annex A (2006).

Thermal State Of the Body as a Whole		
Category	**PPD %**	**Predicted Mean Vote**
I	< 6	- O.2 < PMV < + 0.2
II	< 10	- O.5 < PMV < + 0.5
III	< 15	- O.7 < PMV < + 0.7
IV	> 15	PMV < - 0.7; OR + 0.7 < PMV

Table 2.10 Examples of Recommended Indoor Temperature Design Values for Buildings and HVAC Systems, Adapted from (EN15251, 2006)

Type of building/ space	**Category**	**Operative temperature ^{o}C**	
		Minimum for heating (winter season), ~ 1,0 clo	**Maximum for cooling (summer season), ~ 0,5 clo**
Single office (cellular office) Sedentary ~ 1,2 met	I	21	25.5
	II	20	26,0
	III	19	27,0
Landscaped office (open plan office) Sedentary ~ 1,2 met	I	21	25.5
	II	20	26,0
	III	19	27,0
Conference room Sedentary ~ 1,2 met	I	21	25.5
	II	20	26,0
	III	19	27,0

Mean Radiant Temperature (MRT)

Mean radiant temperature represents the radiant energy exchange between the human occupant and the surfaces around and it is defined in Fanger's textbook on thermal comfort (Fanger, 1973) as "the uniform temperature of the surface of an imaginary enclosure where the radiant exchange of heat between this enclosure and a man would be equal to the radiant exchanges in the actual environment". Occupant thermal comfort depends significantly on the balance of radiation exchange between them and the surrounding surfaces.

When all surfaces in a room are at the same temperature, mean radiant temperature remains uniform throughout the room. However, in some cases surface temperature may vary from one surface to another, resulting in variation in operative temperature (resultant temperature) (CIBSE, 1986). Mean radiant temperature may be higher or lower than the air temperature in a room although in most cases the two are regarded as the same for thermal comfort calculation purposes. It is measured using a Globe thermometer which consists of a thin-walled copper sphere painted black and containing a thermometer with its bulb at the centre of the sphere. The thermometer is suspended in the room and allowed to reach thermal equilibrium with its surroundings (about 20 minute's time). The equilibrium temperature depends on both convection and radiation transfer between the sphere and the surrounding surfaces.

Air Velocity

Moving air has a cooling effect on the human skin therefore increased air velocity can be used to compensate for increased temperatures inside buildings under summer conditions (operative temperatures > 25°C). Fans have been used for many years as a quick solution to local thermal discomfort in naturally ventilated buildings and to provide personalized thermal comfort in mechanically ventilated buildings equipped with Personalized Ventilation Systems (PVS). However higher air velocities are known to cause draughts and feelings of local discomfort in offices and other buildings therefore control of air speed is important. The effects of air velocities on thermal comfort (above and below set temperatures) will be discussed further in Chapter 6, Section 6.1.1.

The upper limits of neutral temperatures in naturally ventilated office (Figure 2.8) can be increased by a few degrees in correlation with increased fan speeds. Figure 2.4 shows the air velocity (V_a) required to offset increased temperature (CIBSE, 1986; EN15251, 2006; ASHRAE, 1984). The curves are plots of differences between t_{mrt} and t_a while the x-axis represents the temperature rise (Δt) above a set point of 26°C (This should depend on the climate of the area).

For occupants performing light primarily sedentary activity temperature rise (Δt) must be below 3°C and air velocity below 0.82 *m/s* as bound by the blue lines and the axes. Beyond the lines the model cannot guarantee reliable estimations. Figure 2.8 also shows that the larger the t_{mrt} (or the smaller the t_a), the lower the air velocities required to offset temperature changes (Parsons, 2008).

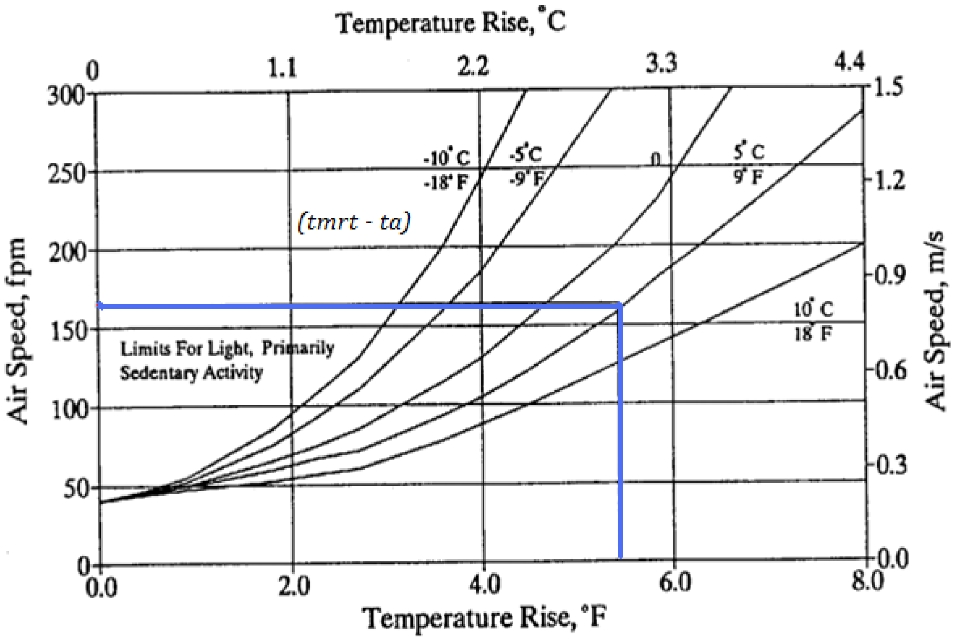

Figure 2.4 Air velocity required to offset increase in air Temperature, Adapted from (EN15251, 2006)

The Role of Air Conditioning in Improving Building Comfort

Air-conditioning is defined as the control of temperature, humidity, purity and motion of air in an enclosed space, independent of outside conditions (Encyclopaedia Britannica, 2011). The primary function of air conditioning systems is to achieve thermal comfort through heating and cooling thereby providing the range of indoor air temperatures appropriate for the comfort needs of the occupants (Muhic and Butala, 2004). Virtually all air conditioning systems are designed to filter out particulates in supply air therefore they are also responsible for providing good quality indoor air.

Air conditioning is used to control indoor humidity levels and improve air quality. The moisture content of the indoor air has to be high enough to meet the respiratory needs of occupants and low enough to prevent cases of dampness and condensation. Air circulation within buildings is important for thermal comfort as explained earlier. Too fast moving air could result in discomfort due to draughts while too slow air speed could lead to poor mixing of air or result in pockets of spaces with very poor air quality.

A typical air conditioning system is shown in Figure 2.5.

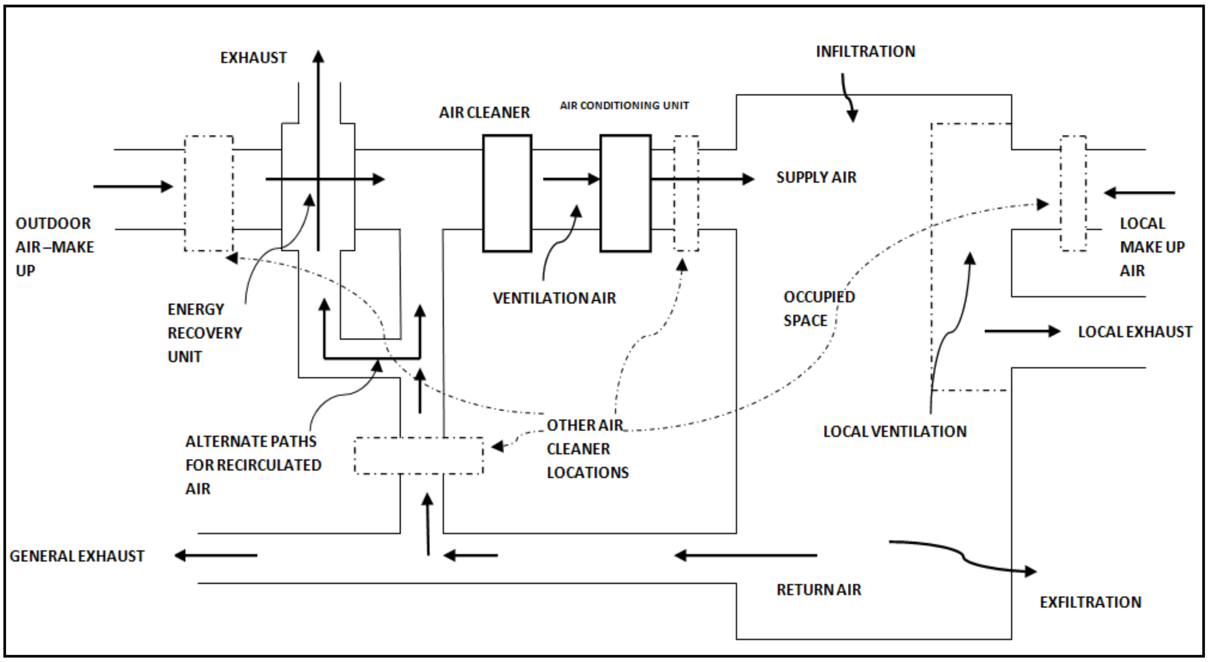

Figure 2.5 Illustration of a ventilation system of a centrally conditioned space; Adapted from ((WHO, 1985).

The diagram shows an air conditioning system filtering of supply air to remove particulates, preheating or cooling, humidification or dehumidification before blowing the air into the occupied space via supply air grills. As air enters the building it is warmed up as it comes into contact with warm equipment, human occupants, solar gains, and other heat producing processes and therefore its temperature is raised. Fresh air supplies or recirculating room air maintains indoor air temperatures within comfortable levels. The same process improves indoor air quality since indoor air is polluted by bio effluents, equipment and elements in the building fabric that release particulates and odours into the occupied space.

Air conditioning systems can be categorised into three main types namely:

i) Local Comfort Cooling systems;

ii) Centralised Air systems; and

iii) Partially Centralised Air/Water systems.

Typical systems can be found in the HEVACOMP knowledge base (Bentley, 2010) and other texts.

Humidification and Dehumidification of Indoor Air

The relative humidity of air needs to be controlled to ensure thermal comfort for occupants. Although relative humidity has a relatively small effect on thermal sensation or perceived air quality long term high humidity could result in microbial growth and poor IAQ. Low humidity is associated with drying of the skin, eyes and airways. Research shows that human occupants are likely to accept a higher temperature at a lower humidity than the same temperature at a higher humidity (Fiala, 2008; Fanger, 1973; Toftum and King, 2002). A criterion for humidification or dehumidification depends on thermal comfort and air quality requirements of the building. The design of humidification and dehumidification equipment has a bearing on the energy performance of a building.

Dehumidification of indoor air is achieved via two processes; (1) cooling air temperature below dew point in order to dump moisture and (2) chemical adsorption. Cooling air below dew point is an energy intensive process that involves passing air over a cold coil in the air handling unit. This causes some of the air to condense and the amount of moisture removed depends on the temperature of the coil and the air flow rates across the coil. Air then needs to be reheated to bring it back to the required comfort temperature (ASHRAE, 1984, 1985). Using an evaporator and condenser coil saves energy since only compressor power is needed for both cooling and heating in the dehumidification cycle.

A typical dehumidification air conditioning cycle is shown in Figure 2.6 below.

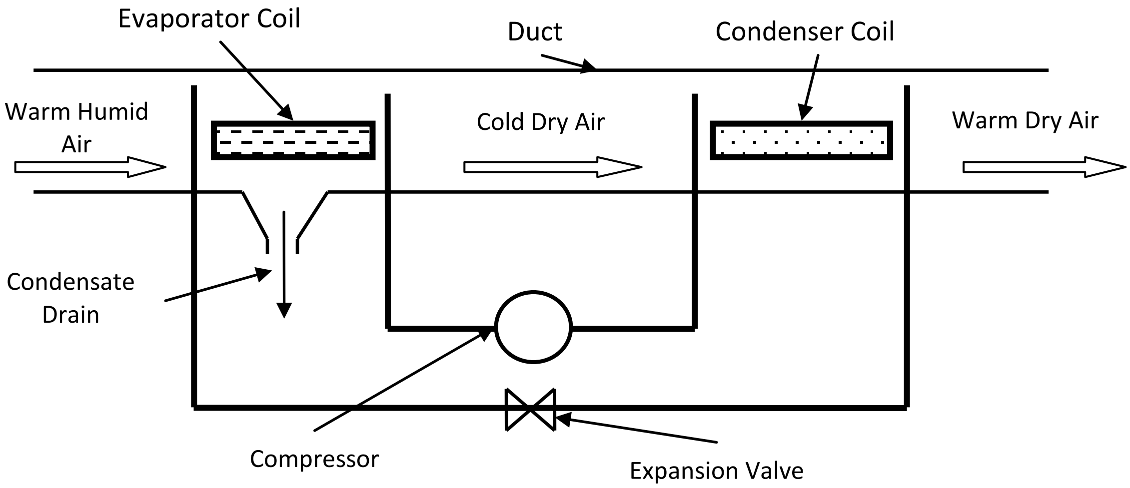

Figure 2.6 An illustration of a dehumidification system that involves cooling air below dew point, Adapted from (ASHRAE, 1985)

Chemical sorption involves the use of desiccants to remove water vapour from air. Most desiccant systems are based on a slow rotating desiccant rotor, which is a solid wheel (Figure 2.7) that is packed with solid desiccant materials. Air is forced through the dehumidification section of the wheel where moisture is absorbed and the desiccant becomes saturated. The desiccant wheel goes through a regeneration process where heated air is forced through it to remove moisture. This method is less energy intensive compared to the dew point approach. A typical desiccant wheel is shown in Figure 2.7.

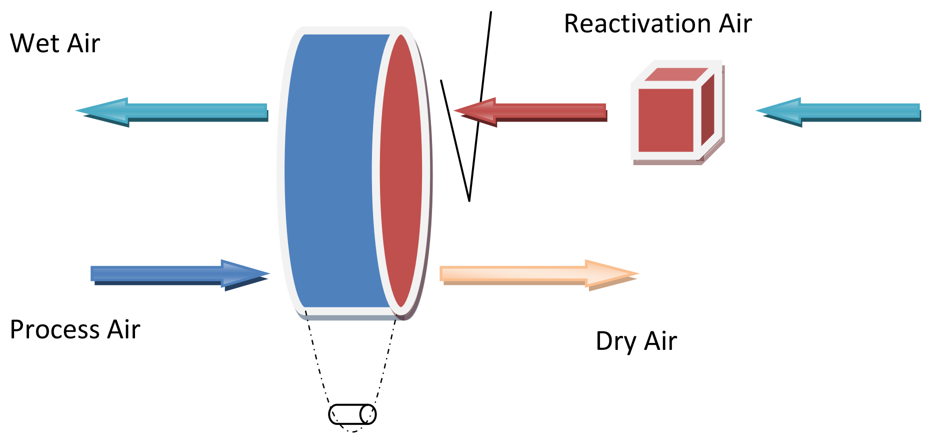

Figure 2.7 Desiccant based dehumidification system, Adapted from: (Fang et al, 2005)

Design values for humidity levels required for most buildings including offices are shown in Table 2.11. Different design limits are required for special environments such as process areas, museums and churches where humidity plays an important role in the preservation of equipment and materials.

Table 2.11 Example of Recommended Design Criteria for the Relative Humidity in Occupied Spaces Where Humidification or Dehumidification Systems are Installed

Source: (EN15251, 2006)

Type of building/space	Category	Design RH for dehumidification, %	Design RH for humidification, %
Spaces where humidity criteria are set by human occupancy.	I	50	30
	II	60	25
	III	70	20
	IV	>70	<20

2.7.2 Criteria for the thermal operation of naturally ventilated buildings – Adaptive Comfort

A different indoor environment criterion exists for offices without mechanical ventilation i.e. naturally ventilated offices because occupants tend to adapt to the indoor environment based on outdoor conditions. Figure 2.8 is an example of recommended design indoor operative temperatures and categories for naturally ventilated offices in the UK (Auliciems, 1981). The operative temperatures (room temperatures) presented in the graph below are valid for offices and other buildings of similar type where occupants carry out mainly sedentary activities, have easy access to operable windows and they may freely adapt their clothing or any other aspects that may improve their comfort depending on the indoor and/or outdoor thermal conditions (Humphreys, 1994). This method is therefore strictly used in naturally ventilated spaces where no mechanical heating or cooling exists otherwise the methodology does not apply during periods when the heating or cooling systems are operational.

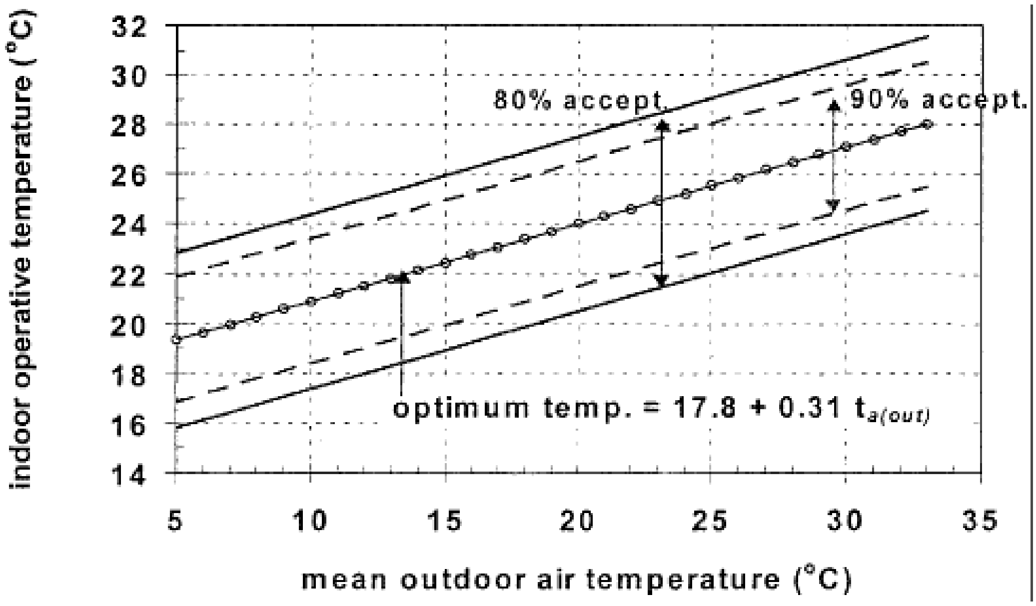

Figure 2.8 Recommended design indoor operative temperatures for naturally ventilated offices in the UK using the Auliciems Model, Copied from deDear and Brager (2001).

In most naturally ventilated spaces people often tolerate their indoor environment, for example, higher operative temperatures can be acceptable in warmer climates than in colder ones hence higher PMV values than expected are usually observed. However studies by Fanger (1986) made a distinction between adaptation and tolerance. He suggested that people cannot adapt to preferring warmer or colder temperatures, but they may tolerate the situation better than others from a different climate.

The quality of the thermal environment in naturally ventilated buildings also depends on outdoor thermal conditions. The building envelope provides an interface between the two and the choice of building materials and building orientation has a remarked effect on what is perceived inside the building. Clothing levels in different parts of the world tend to suggest a response to outdoor thermal conditions as people in warm or cold climates tend to tolerate uncomfortably high or low temperatures by maintaining relatively higher levels of performance at under those conditions.

2.7.3 IAQ and Ventilation Standards

Air is supplied to office buildings through passive and active ventilation systems. Passive systems supply air into the building through thermal stack effects or take advantage of wind power which pushes air into the building via windows or air vents. Mechanical ventilation systems are active ventilation systems which are mainly powered by grid electricity and they include mixing, displacement and personalised ventilation systems (PVS). The systems are responsible for maintaining the required IAQ standards in offices and fresh air needs throughout the occupancy periods if good air quality standards are to be achieved.

In some cases air supply into the building may even start before occupancy begins in order to avoid that "warm up" period that may be responsible for many building related illnesses. At present there are no universally accepted standards for IAQ in the UK hence different categories of Indoor Air Quality in buildings have been created based on the amount of ventilation air supplied, concentrations of CO_2 above outdoor and pollution levels in decipol, as presented in Tables 2.12, 2.13 and 2.14 respectively. It is also generally accepted in most ventilated areas that ventilation rates for comfort will cover ventilation rates for health.

Table 2.12 Air Quality Categories Based on Amount of Ventilation Air Supplied to the Building, Source: (Commission for European Communities, 1991)

Category	**Expected Percentage Dissatisfied**	**Airflow per person (l/s/person)**
I	15	10
II	20	7
III	30	4
IV	>30	<4

Design ventilation rates can be calculated by adding ventilation rates required for removal of bio effluents and ventilation rates required for removal of pollution due to the building's fabric and its systems. In some cases ventilation rates per square metre floor area can be used instead and the recommended values can be found in Annex B of the EN15251 standard.

Table 2.13 Air Quality Categories Based on CO_2 Concentration Above Outdoors, Source (EN15251, 2006)

Category	Corresponding CO_2 (ppm) Above Outdoors
I	350
II	500
III	800
IV	> 800

Table 2.14 Expected Quality of Supply air in Various Locations in the UK (Commission for European Communities, 1991)

Location	Perceived Air Quality (decipol)	Air pollutants			
		CO_2 mg/m^3	CO mg/m^3	NO_2 µg/m^3	SO_2 µg/m^3
At Sea	0	680	0-0.2	2	1
Towns	<0.1 good	700	1-2	5-20	5-20
Towns	<0.5 poor	700-800	4-6	50-80	50-100

Annex C of the EN 15251 standard provide guidelines on how to define low and very low polluting buildings. The standard states that safe and low polluting building materials must fulfil the following requirements:

- The emission of total volatile organic compounds (TVOC) is below 0.2 mg/m²h;
- The emission of formaldehyde is below 0.05 mg/m²h;
- The emission of ammonia is below 0.03 mg/m²h;
- The emission of carcinogenic compounds (IARC) is below 0.005 mg/m²h; and
- The material is not odorous (dissatisfaction with the odour is below 15 %).

More information on indoor air quality standards and exposure limits to indoor pollutants can be found in the WHO - Environmental Health Criteria (EHC) documents (WHO, 1994).

2.7.4 Criteria for Acoustic Operation of Office Buildings

An important aspect of acoustic comfort is to establish criteria for the indoor environment. Thus where total elimination of noise in offices is impractical, appropriate guidelines must be set to determine how much noise is acceptable. Also it is important to determine how noise levels impact on the performance of office occupants, and how noise reduction strategies impact on the energy bill. Table 2.15 gives some examples of ranges of acceptable A-weighted indoor sound levels in office buildings. A full list of maximum acceptance A-weighted sound pressure levels for various buildings can be found on the Australian and New Zealand standards, AS2107 (Australian Standard, 1987, Australian & New Zealand Standard, 2000).

More information on acoustic measurements, construction materials and systems that minimise indoor noise levels can be found in BSI – EN 12354 (BSI, 2000c; EN12354-1, 2000; BSI, 2000a; BSI, 2000b; EN12354-6, 2003; EN12354-5, 2009). These standards also give information on acoustic properties and phenomena, airborne sound insulation, general sound insulation, rooms, mathematical calculations, mathematical models, acoustic waves, frequency bands, technical documents, acoustic performance of domestic and commercial facilities.

Table 2.15 Examples of Design A-weighted Sound Pressure Level (Ayr et al., 2003)

Type of Office	Typical Range [dB(A)]	Default Design Value [dB(A)]
Small offices	30 to 40	35
Conference Rooms	30 to 40	35
Landscaped Offices	35 to 45	40
Office Cubicles	35 to 45	40

2.7.5 Lighting Recommendations in Office Buildings

The lighting environment of office buildings is designed to provide and interesting and stimulation lit environment for people to work in. Lighting recommendations for office buildings in the UK are contained in the CIBSE Lighting guide - LG7 (CIBSE, 2006) and other texts (Tate and King, 2008; Metrel, 2002).

Lighting design in offices is based on the following aspects:

- Illuminance (lux on a working plane);
- Discomfort Glare (including UGR);
- Colour qualities of light (including R_a); and
- Directionality of lighting.

Generally office lighting is concerned with the provision of uniform lighting across each task area. Task areas consist of relatively small areas around the workstations where visual tasks are carried out. The immediate surrounding area is the area surrounding the task area within the visual field and this is usually a band of about 0.5 metres wide around the task area. The task area and the surrounding area are shown in Figure 2.9. Generally surrounding areas have illuminance distributions (g_i) of ≥ 0.5 and the task areas have $g_i \geq 0.7$.

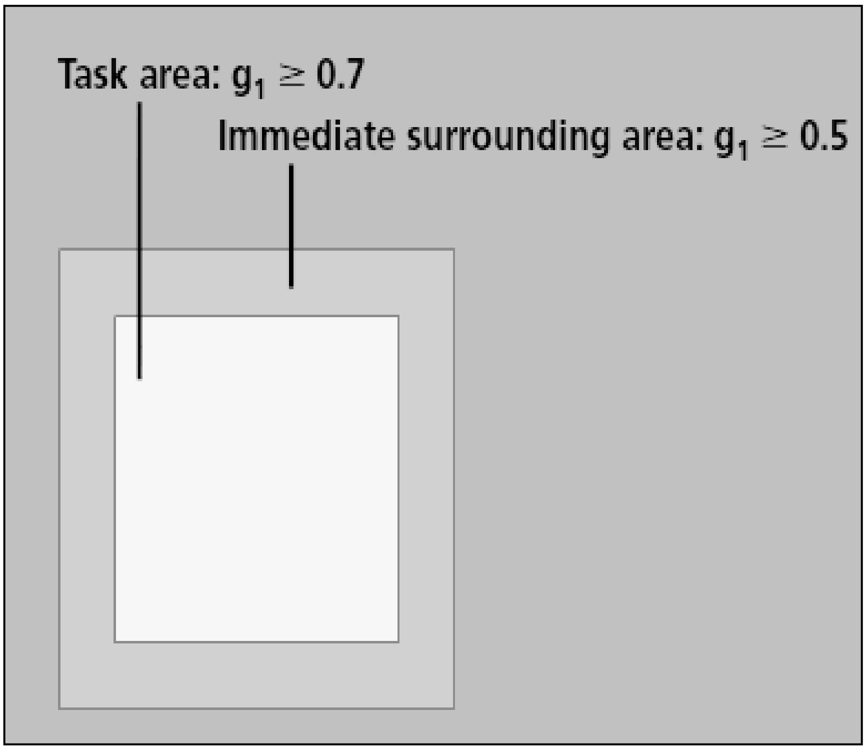

Figure 2.9 Task area & immediate surrounding area, Copied from (EN12464-1, 2002)

The selection of the type of lighting suitable for an office space depends on the physical constraints of the space, the intended decor, the capital investment intended, energy implications, and maintenance costs. The procedure for selection of luminaries is explained in the Lighting Guide 7, 2005 and will not be discussed here. Some recommended illuminance values for offices are shown in Table 2.16 while typical outdoor illuminance levels are shown in Table 2.17.

Table 2.16 Recommended Design Indoor Lighting for Offices and Other Buildings in the UK, Source: (EN15251, 2006)

Type of Office	Maintained Illuminance, at working areas, lux	UGR	R_a	Height of Working plane (m)
Single/cellular	500	19	80	0.8
Open Plan	500	19	80	0.8
Conference rooms	500	19	80	0.8
Circulation areas/stairs	150	25	40	0.1
Corridors	100	28	40	0.1

Table 2.17 Typical Illuminance Levels at Outdoor Places, CIBSE LG7 Guide (CIBSE, 2006)

Condition	Illuminance
Bright Sun	50,000 – 100,000
Hazy day	25,000 – 50,000
Cloudy bright	10,000 – 25,000
Cloudy Dull	2,000 – 10,000
Very Dull	100 – 2,000
Sunset	1 – 100
Good Street lighting	~ 20
Poor Street Lighting	~0.1
Full Moon	0.01 – 0.1
Star Light	0.001 – 0.001
Overcast Night	0.00001 – 0.0001

The design of day lighting for offices is critical since it is a universal worker requirement as explained earlier. UK Regulation 8(2) of the Workplace Regulations states that “the lighting in every workspace shall, as far as reasonably practicable, be by natural light” (Energy Information & Administration, 2006). In order to maximise the amount of natural light received by occupants, reduce glare and save energy good lighting designs are required. One of the simplest methods of achieving satisfactory luminance range is to avoid users looking directly out onto potentially bright patches of sky or having windows behind them reflecting on their screens. This includes making sure that the display screens are placed perpendicular to the plane of the windows so that the user’s viewing axis runs parallel to the windows (CIBSE, 2006). A recommended minimum daylight factor of 2% gives an illuminance level of 1000 lux for much of the working year but is difficult to achieve the same for areas over 6m from the window (Chung and Burnett, 2000).

Daylight levels near to the windows can be more than ten times higher than elsewhere in the office and this may have a profound effect on the body’s biological clock, leading to what is commonly referred to as the Seasonal Affective Disorder (SAD). In many cases however, if not correctly checked, the amount of day lighting could have a negative impact on the occupants visual comfort, contribute to heat gains leading to thermal discomfort and windows with outside views could lead to invasion of privacy (Bean and Bell, 1992). Efficient use of day lighting could contribute significantly to reducing energy consumption in offices.

2.8 CONCLUSIONS

Office buildings are one of the main contributors of carbon emissions in the UK. In order to tackle the effects of climate change it is essential that the energy consumption of offices is reduced to a sustainable level. Reducing carbon emissions means operating buildings within sustainable comfort levels. However the quest to reduce carbon emissions in office buildings should not sacrifice the comfort of those who work within those buildings. In order to help building designers, owners and users use offices more efficiently there is need to develop tools to help them assess the impact of their indoor environment standards on the environment.

This can be done by developing energy and IEQ assessment methodologies that could be compared easily. IEQ assessment methodologies rely on the ability to develop indices that accurately evaluate thermal comfort, IAQ, acoustics and lighting comfort. Although thermal comfort and IAQ indices are well developed lighting and acoustic comfort indices still require extensive research. The next chapters (Chapter 3, 4 and 5) attempt to develop a methodology for assessment of IEQ in offices based what has already been discussed in this chapter and case studies.

3. The IEQ Assessment Model

3.1 ITRODUCTION

This Chapter presents a methodology for the IEQAT (Indoor Environment Quality Assessment Tool) tool for rapid assessment of IEQ in office buildings in the UK. The chapter also explains how each of the proposed indices is developed and includes a step by step guide on how to carry out an assessment. The tool is tested in selected case studies buildings and the results of analysis are presented in Chapter 5. The relative weightings of each of the contributing parameters obtained from subjective assessment will be compared to those of the IEQAT (obtained using the AHP).

The IEQAT tool is based on the IEQ model. In the context of this thesis a single index, called the IEQ_{index}, is a function of four contributing environmental factors and it is explained by means of some mathematical formula or expression. The contributing factors are sub-indices that are associated with individual environmental aspects of the indoor environment such as thermal comfort, IAQ, Acoustic comfort, and Lighting. The IEQ_{index} represents perceived IEQ; the quantity from overall perception of the quality of the indoor environment is derived therefore it should communicate to the building designer, manager and user, the state of the office environment relative to other similar environments in the UK. The state of the office environment is its rating and it provides an effective framework for assessing building performance and offers an opportunity to create high performance buildings that have less negative impacts on occupants and the environment. The results of the tool should reflect the advantages if any that are associated with investing in energy efficiency and therefore leave it to the building designer, manager and user to take appropriate action where necessary.

Three most important steps in the study include the development of the indices for assessing each of the four proposed aspects of the indoor environment, evaluating the indices using data obtained from case study buildings and developing a methodology to be used to derive the relative weightings of each of the contributors.

The tool measures the following aspects (quantities) of the indoor environment:

- The state of its thermal environment;
- The quality of indoor air;
- The quality of the acoustic environment;
- The quality of the visual (lighting) environment; and
- The overall (combined) state of the indoor environment.

3.2 DEVELOPMENT SOFTWARE

The tool can be developed using approved building simulation software such as MATLAB, Simulink, Eclipse and the Visual Basic (VB) Application Programs. MATLAB is a high level language and interactive numerical computing environment that enables one to perform complex tasks more quickly when compared with traditional programming such as C, C^{++} and FORTRAN. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and FORTRAN. It has been widely used in research and industry and has been very useful in carrying out thermal comfort assessments in office buildings (Mendes et al, 2003). Simulink, a product of MathWorks is an additional package that can be added to MATLAB to provide a graphical multi domain simulation capability.

Labview is a VB language developed by National instruments. It is a smart development environment that can be very useful for carrying out real time monitoring of the indoor environment. It can be incorporated into the BMS and hence log in important IEQ data whilst displaying the results in real-time. ECLIPSE is an Integrated Development Environment (IDE) with an extensive plug in system. It can be written in many languages including Java, C, C++ COBOL, etc and it is one of the options for the development of computer based assessment tools. The Visual Basic (VB) program is probably the most applicable and readily available software at the University of Nottingham. The VB program which is offered by Microsoft Corporation is available free to student designers and developers worldwide. The VB application is relatively easy to learn from a programmer's point of view since most people are familiar with interfaces associated with Microsoft and Apple applications. The formulae used here are relatively easy to solve using basic excel and the only exception is the thermal comfort estimation which requires a computer program.

3.3 DEVELOPING THE ASSESSMENT MODEL

The development of the IEQ assessment model begins with the identification of main contributing factors which include thermal comfort, IAQ, acoustics and lighting. The contributing factors constitute what is referred to as sub-indices and their development is described in the following sections.

3.3.1 Development of Thermal Comfort sub – index (TC_{index})

The thermal comfort sub index is based on Fanger's studies in the 1970s, which constitutes what is now known as the ISO 7730 standard (EN-ISO7730, 2005). The standard presents methods for predicting the general thermal sensation and degree of thermal dissatisfaction which can be expressed by a large group of people exposed to moderate thermal environments of mechanically ventilated and air conditioned offices. Different assessment criteria exist for offices that are naturally ventilated and where the adaptive comfort model is used (see later part of this section. The standard is applicable to the following situations:

- Environmental conditions considered acceptable for both general and local thermal discomfort.

- Healthy men and women exposed to indoor environments where the thermal environment plays an important part of the general comfort.

- The standard does not include local discomfort factors such as draught, radiant temperature asymmetry, vertical air temperature differences and floor or surface temperatures. These need to be assessed separately and recommendations are corrective measures need to be implemented to eliminate local discomfort conditions.

ISO 7730 proposes four physical parameters that affect thermal comfort as Air temperature*, Mean radiant temperature**, Relative Humidity*** and Air velocity; and two personal factors as Clothing Insulation and Activity Levels. These factors have already been described in the previous chapter (Chapter 2). Their contribution to thermal comfort is explained later in this chapter. A flowchart for the calculation of thermal comfort is illustrated in Figure 3.1.

---

* Air temperature (t_a) refers to the normal "room temperature"

** Mean radiant temperature (t_{mrt}) is the uniform temperature of the surface of an imaginary enclosure where the radiant exchange of heat between this enclosure and a man would be equal to the radiant exchanges in the actual environment (Fanger, 1973). Mean radiant temperature may be higher or lower than the air temperature in a room however in most cases it is taken as equal to air temperature (t_a).

*** Relative humidity is defined as the ratio of mass of water vapour present in air at a temperature/ maximum water vapour content of that air at that temperature.

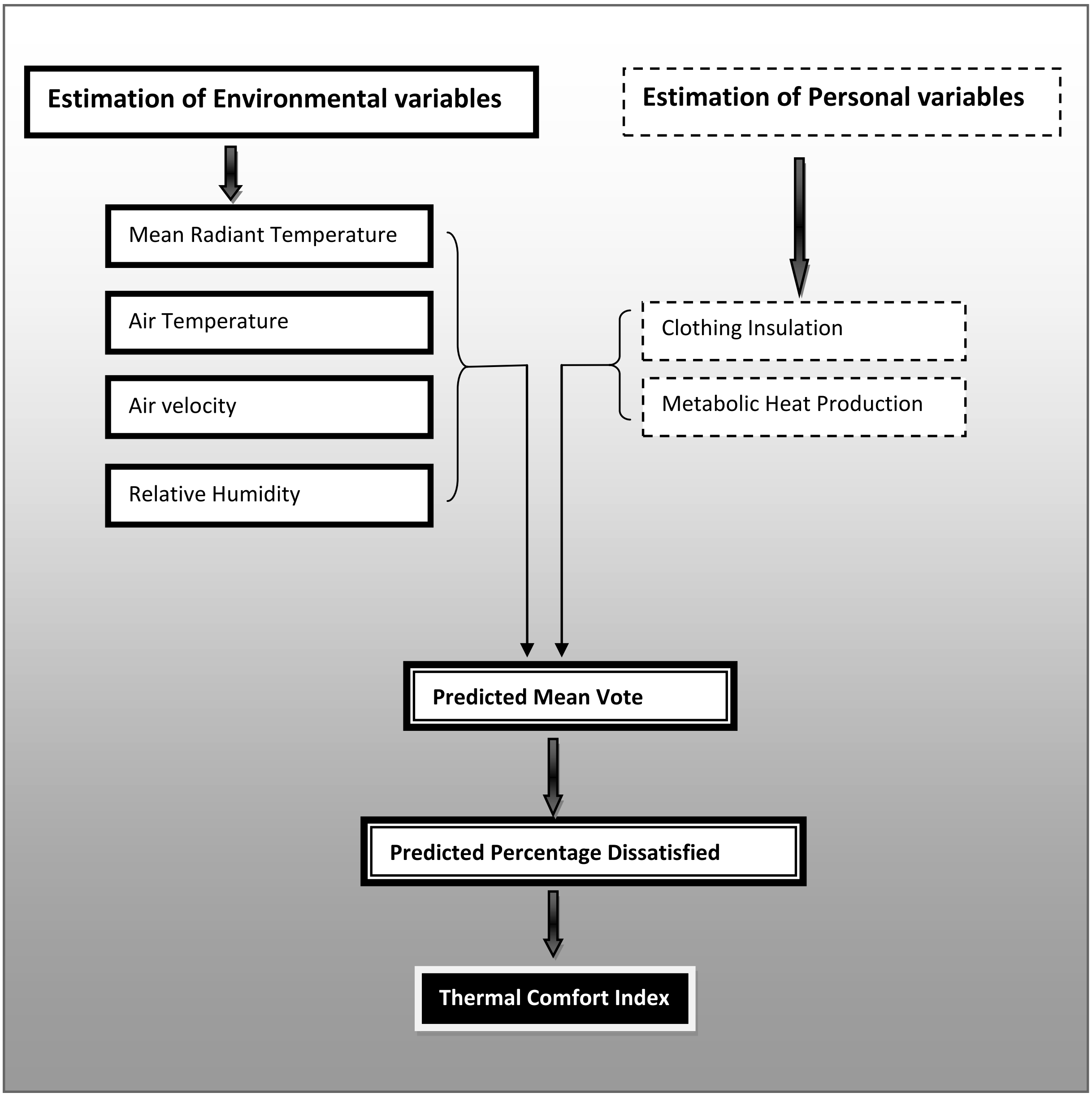

Figure 3.1 Thermal Comfort Estimation Flowchart

Calculation of thermal comfort begins with the heat balance equation which states that in order for the core body temperature to remain constant heat produced in the body must be equal to heat lost from the body.

$$\text{Heat Produced in body} = \text{Heat loss from body} \qquad \mathbf{3.1}$$

In other words heat retention (which affects core body temperature) is 0 when metabolic heat production is cancelled out by losses due to external work, heat loss due to conduction, convection, radiation, evaporation and respiration as shown in equation 3.2.

$$M + W - E - C - R - K - RES = \text{Heat Storage} \qquad \mathbf{3.2}$$

More information on the development of the equation (s) can be found in Fanger's textbook on thermal comfort (Fanger, 1973). In this thesis the most relevant equation for thermal comfort calculation is the comfort equation which is given as follows:

$$\begin{aligned} H - 0.31 \times (57.4 \times 0.07 \times H - P_a) - 0.42 \times (H - 58) - 0.0017 \times M \times (58.7 - P_a) \\ - 0.0014 \times M \times (34 - t_a) \\ = 3.9 \times 10^{-8} \times f_{cl} \times \{(t_{cl} + 273) - (t_{mrt} + 273)^4\} + f_{cl} \times h_c \\ \times (t_{cl} - t_a) \end{aligned} \qquad \mathbf{3.3}$$

Where: $H = M - W$ and;

$$\begin{aligned} tcl = 35.7 - 0.0275 \times H + 0.155 I_{cl} \times\times \{H - 0.31 \times (57.4 - 0.07 \times H - P_a) - 0.42 \\ \times (H - 58) - 0.0017 \times M \times (58.7 - P_a) - 0.0014 \times M \times (34 - t_{cl})\} \end{aligned} \qquad \mathbf{3.4}$$

And;

$$h_c = \begin{cases} 2.38\,(t_{cl} - t_a)^{0.25} & for\ 2.38\,(t_{cl} - t_a)^{0.25} > 12.1\sqrt{Var} \\ 12.1\sqrt{Var} & for\ 2.38(t_{cl} - t_a)^{0.25} < 12.1\,\sqrt{Var} \end{cases} \qquad \mathbf{3.5}$$

$$fcl = \begin{cases} 1.00 + 0.2 I_{cl} & \text{for } I_{cl} < 0.5\ clo \\ 1.05 + 0.1 I_{cl} & \text{for } I_{cl} > 0.5\ clo \end{cases} \qquad \mathbf{3.6}$$

The predicted mean vote (PMV) is an index that can be calculated using the comfort equation. PMV is equal to zero at thermal neutrality rising to +3 for the warm side and -3 for the cold side as shown in the ASHRAE assessment scale (Table 2.7) explained in Chapter 2. The PMV equation is given below as:

$$PMV = 4 + \left(0.303e^{(-0.0036H)} + 0.0275\right) \times \{6.57 + 0.46H + 0.31P_a + 0.0017HP_a + 0.0014Ht_a - 4.13f_{cl}(1 + 0.01\Delta T)(t_{cl} - t_{mrt}) - h_c f_{cl}(t_{cl} - t_a)\} \quad \mathbf{3.7}$$

Where:

$$t_{cl} = 35.7 - 0.0028\ (H) - \ 0.155I_{cl}\ [3.96 \times 10^{-8} \times f_{cl}\ (t_{cl} + 273)^4 - t_{mrt} + 273)^4\} + f_{cl}h_{cl}(t_{cl} - t_a)] \quad \mathbf{3.8}$$

And h_c and f_{cl} conditions in equations 3.5 and 3.6 still apply.

The accuracy of the thermal comfort index depends on the accuracy of the methods used to collect data. It is important that recognised data collection techniques are employed when collecting data about the input variables. The minimum characteristics of instruments for measuring physical quantities are specified in the ISO 7726 standard (ISO-7726, 1988). The standard is very informative and gives tips on precautions to take when measuring each quantity. Similarly the accuracy of information from simulated and surveyed will depend on the credibility of the data collection technique. The most accurate method for determining met is through laboratory studies, where heat or oxygen production is measured for participants conducting specific activities (Havenith, 2008; Olesen and Parsons, 2002). Alternatively, the participant’s heart rate can be measured and compared to previously developed tables of heart rate for specific activities. All of the methods mentioned above, however, are time-consuming and invasive, and are generally not practical for use by most thermal comfort researchers. Instead, these researchers rely on estimates based on tables of met rates for specific activities and occupations that are developed from laboratory studies (ASHRAE, 2005; Fanger, 1973). In most studies, an average met rate is assumed for the group (usually 1.2 met for sedentary office work). More recent studies ask occupants to record activities carried out in the last hour, with this information being used to develop a more accurate average for the group, or individualised met estimates for each participant (Cena, 1994). Methods for estimating metabolic heat production are described in the ISO 8996 standard (1989). Simpler tables comparing heat production to activity levels have been developed and they are commonly used for the general assessment of metabolic heat production. Table 3.1 is a summary of met values for people doing typical office tasks.

Table 3.1 Metabolic Rates for Typical Tasks (Fanger, 1973)

Activity	Metabolic Rate (met)
Reclining	0.8
Seated, quietly	1.0
Sedentary activity (office, dwelling, lab, school)	1.2
Standing, relaxed	1.2
Light activity, standing (shopping, lab, light industry)	1.6
Medium activity, standing (shop assistant, domestic, etc)	2.0
High activity (heavy machine work, garage work)	3.0

The estimation of insulation levels of known types of clothing ensembles is specified in the ISO 9920 (1995). The standard examines the influence of body movement and air penetration on the thermal insulation and water vapour resistance of particular types of clothing. Values for various clothing ensembles are shown in Table 3.2.

Table 3.2 Clo and f_{cl} Values for Typical Clothing Ensembles (Fanger, 1973)

Clothing type	Clo Value	f_{cl} Value
Naked	0	1
Underpants only	0.1	1
Underpants only	0.2	1
Shorts & T-shirts	0.3	1.05
Shorts & T-shirts	0.4	1.05
Trousers & shirt	0.5	1.1
Trousers & shirt	0.7	1.1
Light Business Suit	0.8	1.1
Light Business Suit	1.2	1.15
Business Suit plus Thermals	1.3	1.15
Business Suit plus Thermals	1.7	1.15
Jacket & Overcoat	1.8	1.15
Jacket & Overcoat	2.2	1.15
Heavy Winter Wear	2.3	1.3
Arctic type Clothing	2.8	1.3
Arctic type Clothing	3	1.3

The PMV equation is a long and complex equation that is difficult to solve by hand and therefore it can be better solved by using a computer program and some of the results of the solutions have been plotted in comfort diagrams that are widely available in many texts (Fanger, 1973). A VB code has been developed for thermal comfort calculations and it is found in Appendix 1.

The Predicted Percentage Dissatisfied (PPD) with the thermal environment is obtained from PMV values obtained using the comfort equation (equation 3.9).

$$PPD = 100 - 95 \times e^{(-0.03353 \times PMV^4 - 0.2179 \times PMV^2)} \qquad \mathbf{3.9}$$

The Thermal Comfort Index *(TC_{index})* (i.e. the Predicted Percentage Satisfied with the thermal environment) is given as 100 – (minus) the Predicted Percentage Dissatisfied with the thermal environment as shown in equation 3.10.

$$TC_{index} \cong (100 - \ PPD_{TC}) \qquad \mathbf{3.10}$$

A plot of PMV vs. PPD produces a U shaped graph as shown in Figure 3.2. The graph also shows that there can never be a case of 100 percent satisfaction with the internal environment in natural and mechanically ventilated offices. However providing Personalised Ventilation Systems (PVS) could decrease the PPD with the thermal environment to below 5 percent (Zeng and Zhao, 2005). PVS could also be used to improve perceived air quality in offices.

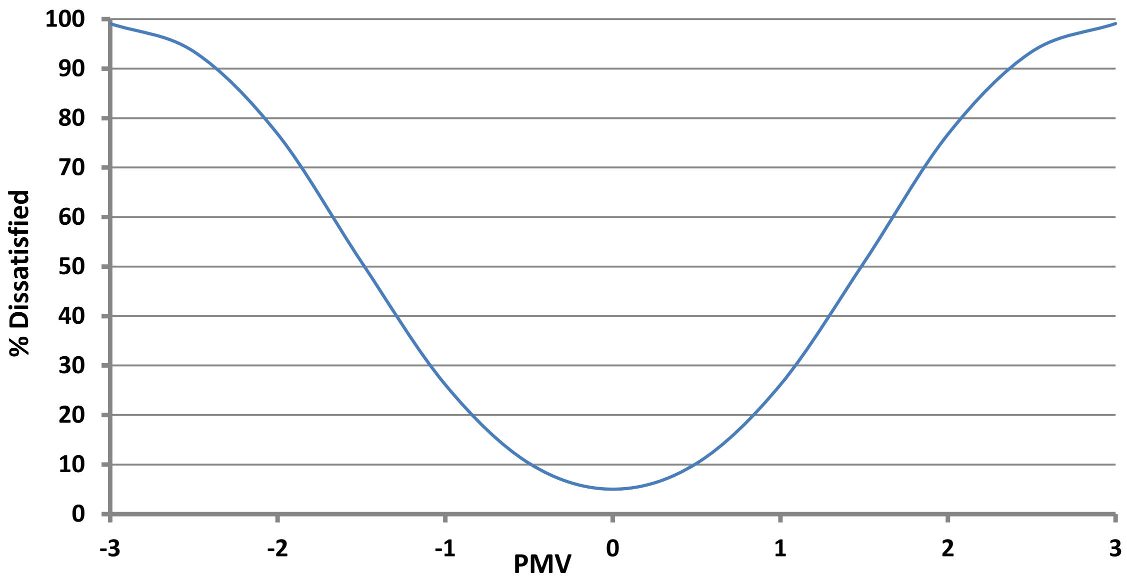

Figure 3.2 Predicted Percentage Dissatisfied Plotted against PMV Values (Parsons, 2008)

For a given PMV value, a predicted distribution of sensation votes was developed based on the results of a study of 1300 occupants as shown in Table 3.3.

Table 3.3 Predicted Distribution of Thermal Sensation Votes (Parsons, 2008)

PMV	PPD	Persons Predicted to Vote (%)		
		0	**-1 or +1**	**-2,-1,0,+1,+2**
+2	75	5	25	70
+1	25	30	75	95
+0.5	10	55	90	98
0	5	60	95	100
-0.5	10	55	90	98
-1	25	30	75	95
-2	75	5	25	70

The PMV model relies on the absence of local discomfort factors such as draughts, vertical temperature difference, cold surfaces, etc. Dissatisfaction with local discomfort factors can be assessed separately using additional models, e.g. the draught models, PPD due to vertical temperature differences, cold floors, etc. the percentage of people dissatisfied with draught is given by the Draught Rating *(DR)* shown in equation 6.1.

$$DR = (34 - t_a)(v - 0.05)^{0.62}\,(0.37 v t_u + 3.14) \qquad \mathbf{3.11}$$

Discomfort caused by vertical air temperature difference is given as:

$$PD = \frac{100}{(1 + e^{(5.76 - 0.856\Delta t_{a,v})})} \qquad \mathbf{3.12}$$

Discomfort caused by warm or cold floors for people wearing light indoor shoes is estimated by:

$$PD = 100 - 94 \times e^{(-1.387 + 0.118 t_f - 0.0025 t_{f^2})} \qquad \mathbf{3.13}$$

Discomfort caused by radiant temperature asymmetry can also be calculated and the methodology is found in the EN ISO7730 (2005) and is explained further in chapter 5.

For naturally ventilated offices a different assessment criteria will be adopted based on adaptive thermal comfort models. A number of adaptive models have been developed and many of these give similar predictions of comfort zones (Humphreys, 2000; Auliciems, 1981). In this thesis we shall adopt the Auliciems model which is based on the concept of neutrality temperature, which is defined as the temperature at which most people feel comfortable. Auliciems (1981) and other researchers found that the comfort temperature inside the building is a function of temperatures prevailing outside the building, and we adopt this mode because it is based on a much more diverse set of building types. Using the model the limits of thermal comfort categories in naturally ventilated buildings (see Figure 2.8, Chapter 2) are bound by equations derived from the relationship below, for $5 < T_{oave} < 35^{\circ}C$ for both the upper and the lower limits:

T_n value = $0.31*T_{oave} + 17.6 \pm$ Factor where Factor = 2.5 for Category I, 3.5 for category II and 4.5 for category III (deDear and Brager, 2000)

It is therefore reasonable to assume that by adding more categories (for example category IV has a factor of 5.5, and so on) we can produce the limiting equations for further categories and therefore be able to plot percentage acceptance against operative temperatures as shown in Appendix 5. Category I corresponds to 90% acceptance of the indoor environment and category II and III correspond to 80% and 65% acceptance respectively, and so on (EN15251, 2006).

3.3.2 Development of the IAQ sub - index

The IAQ index is based on information obtained from European air quality guidelines (Commission for European Communities, 1991; European Collaborative Action, 1992; NOHS, 2003; WHO, 2000). The performance requirements for ventilation and space conditioning systems are presented in European standards (Meier et al, 2001; EN13779, 2006).

The quality of indoor air in an office building can be determined using any one of the three indicators:

- the concentrations of physical, chemical or biological pollutants in indoor air;

- CO_2 concentration (for bio effluents) could be used to indicate air quality where no other known chemical pollutants are present; and
- Ventilation rates can also be used to indicate the quality of indoor air.

The three IAQ assessment input options are explained using the choices below.

Choice I: *Calculate PD using Ventilation rates*

A way of expressing the IAQ is by measuring the amount of fresh air supplied to a building space. The quality of indoor air (PD_{IAQ}) can therefore be expressed in terms of ventilation rates (q) as shown in equations 3.15 and 3.15.

$$PD_{IAQ} = 395 \times e^{(-1.83q^{0.25})} \; for\; q \; \geq 0.32\frac{l}{s} \times olf \qquad \mathbf{3.14}$$

And;

$$PD_{IAQ} = 100 \; for\; q < 0.32\frac{l}{s} \times olf \qquad \mathbf{3.15}$$

A plot of PD versus ventilation rates is shown in Figure 3.3. The effect of increasing ventilation rates is higher at low ventilation rates (between 2 and 12 l/s*standard person) and reduces gradually as ventilation rates increase. This shows that building designers and users need to strike a balance between ventilation rates and comfort. For example increasing ventilation rates to values above 35l/s could have a diminishing effect on occupant comfort resulting in the waste of energy. The curve is based on European studies where 168 subjects judged air polluted by bio effluents and (Commission for European Communities, 1991).

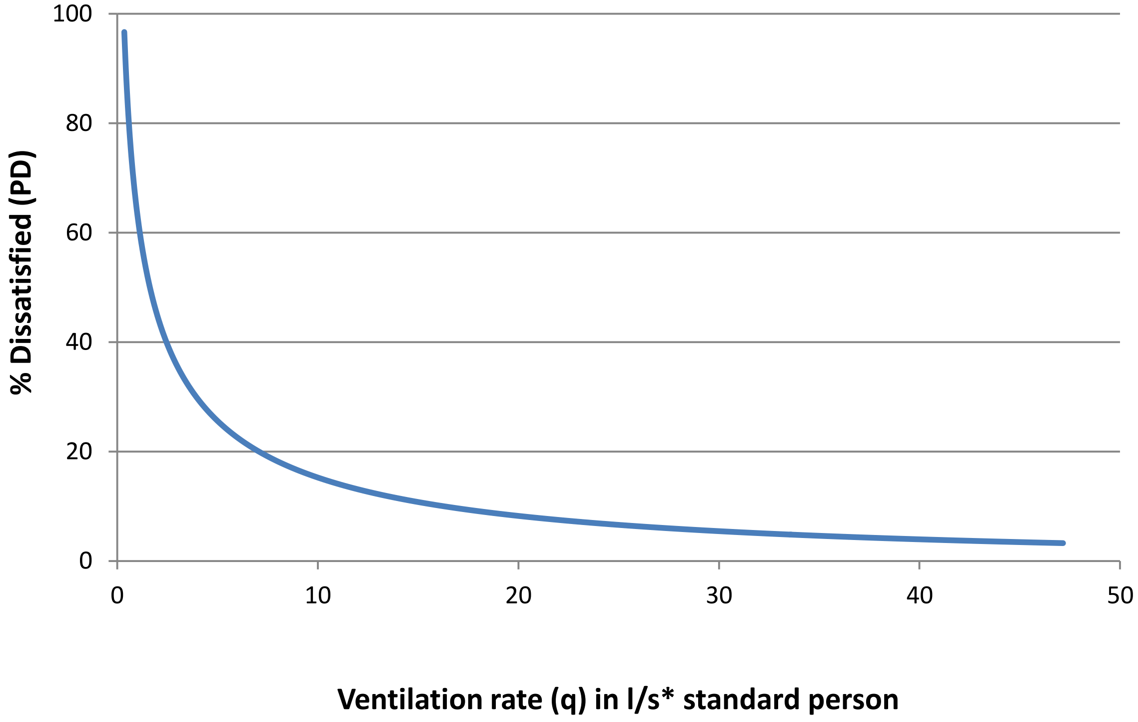

Figure 3.3 Percentage Dissatisfied (caused by one person, 1olf) Plotted Against Ventilation Rates in l/s, Source: (Commission for European Communities, 1991)

Choice II: *Calculate PD from CO_2 concentration above outdoors*

The Percentage of occupants dissatisfied with the quality of air in a building can be calculated using equation 3.16 below, where C_{CO2} is the concentration of CO_2 above outdoor concentration.

$$PD_{IAQ} \sim 395 \times e^{\left(-15.15 \times C_{CO_2}{}^{-0.25}\right)} \qquad \textbf{3.16}$$

Figure 3.4 is a plot of percentage dissatisfied occupants against CO_2 concentration.

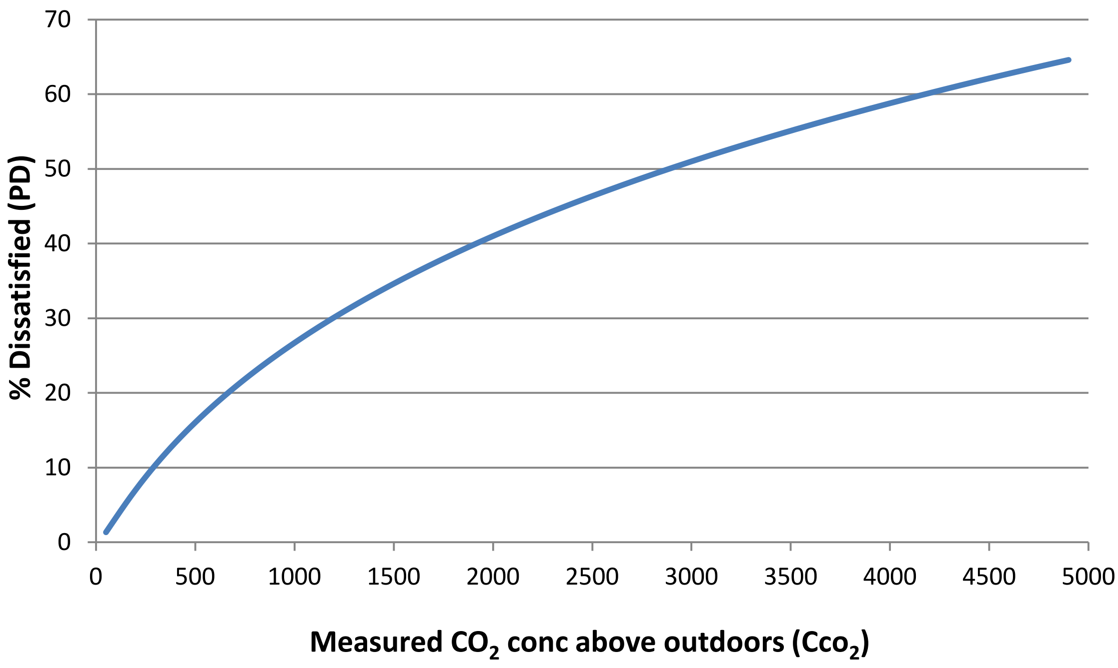

Figure 3.4 Plot of PD versus Measured CO_2 Concentration Above Outdoor Concentrations, Source: (Commission for European Communities, 1991)

Choice III: *Calculate PD from air pollution levels (decipol)*

PD can also be expressed in terms of perceived air quality measured **in** decipol (C_i). One decipol is the perceived air quality in a space with a pollution source strength of one olf, ventilated by 10 ***l/s*** of clean air, i.e. 1 decipol = 0.1 olf/(***l/s***) (Commission for European Communities, 1991).This approach has led to the grading of office buildings into three categories as shown by Figure 3.5. Equation 3.17 shows the relationship between air pollution level in Decipol and PD.

$$C_i\,(decipol) = 112\,\{\ln(PD_{IAQ}) - 5.98\}^{-4} \qquad \mathbf{3.17}$$

Rearranging equation 3.17 we get:

$$\{\ln(PD_{IAQ}) - 5.98\}^{4} = \frac{112}{C_i} \qquad \mathbf{3.18}$$

$$\ln(PD_{IAQ}) - 5.98 = \left(\frac{112}{C_i}\right)^{\frac{1}{4}} \qquad THEN; \qquad \ln(PD_{IAQ}) = \left(\frac{112}{C_i}\right)^{\frac{1}{4}} + 5.98$$

And finally:

$$PD_{IAQ} = e^{\left\{-\left(\sqrt[4]{\frac{112}{C_i}}\right)+5.98\right\}} \qquad \mathbf{3.19}$$

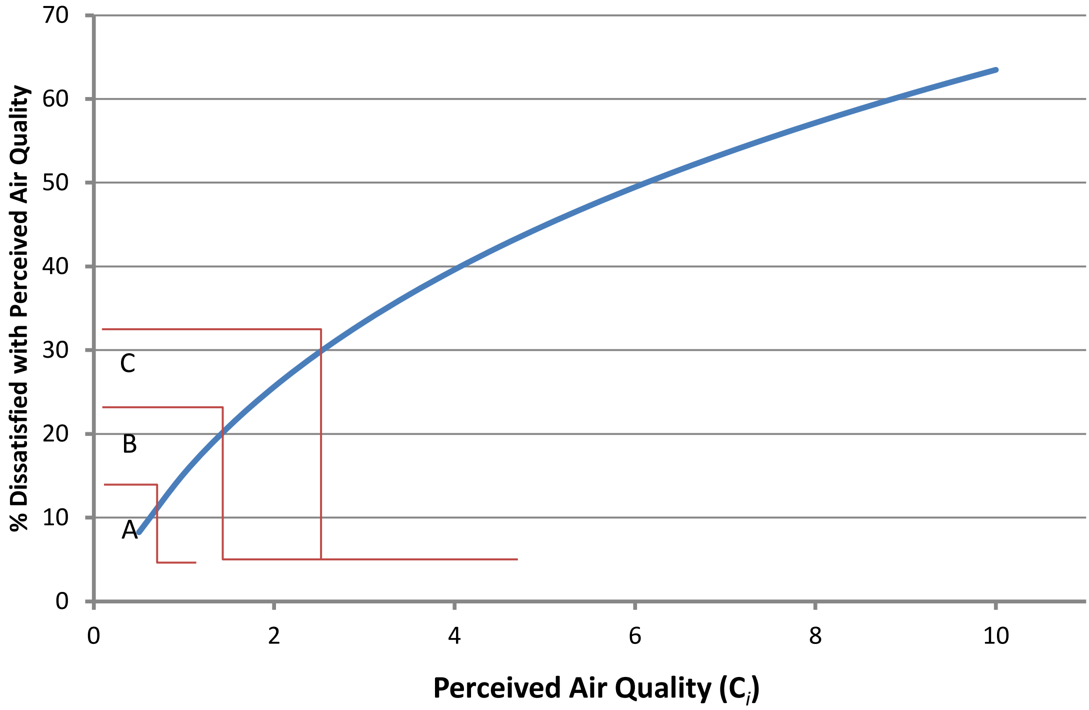

Figure 3.5 Relationships Between Perceived Air Quality Expressed by the % of Dissatisfied & Expressed in Decipol. The three indoor air quality levels, categories A, B & C are shown. Source: (Commission for European Communities, 1991)

Based on the percentage of persons dissatisfied with the aural environment, the IAQ index (comfort) is therefore given as:

$$IAQ_{index} = 100 - PD_{IAQ} \qquad \mathbf{3.20}$$

A flowchart for the calculation of IAQ is illustrated in Figure 3.6. The figure illustrates the choices that can be made by the surveyor depending on the information available. Selecting the appropriate variable is followed by the calculation of PD and finally the IAQ index. Further information on the calculation of IAQ will be explained later in the Chapter.

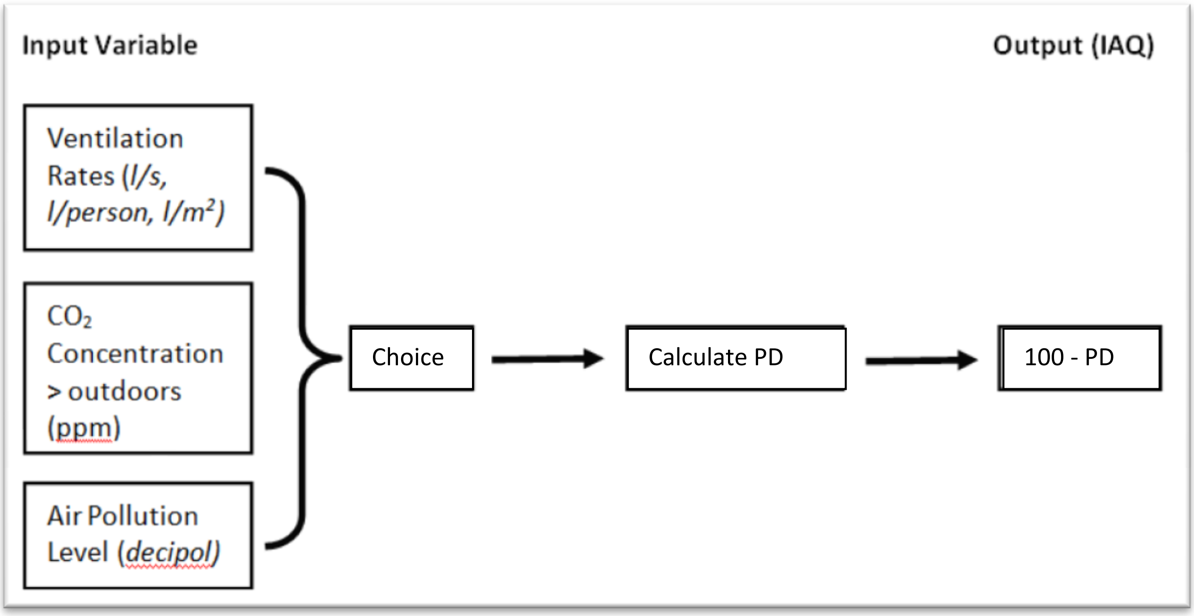

Figure 3.6 IAQ Estimation Flowchart

3.3.3 Development of the Acoustic Comfort sub - index

This index is based on literature review of studies conducted in different countries. The first significant study was conducted using questionnaire and objective physiological laboratory studies on building occupants (WHO, 1985) who were exposed to background (mainly originating from traffic) noise in the USSR. The results of the questionnaires are summarised in Table 3.4.

Table 3.4 Equivalent Sound Level vs. Number of Complaints, (WHO, 1985)

Equivalent sound level - dB(A)	Number of Complaints in (%)
80	85
70	70
65	52.5
55	33
50	5

The second study which was carried by Kjellberg et al (1997) et al in Sweden investigated the importance of frequency weighted sound level measurements on noise annoyance. It showed a scenario where the rate of occupant annoyance increased with increasing sound level (dBA). The study however produced a rather low correlation of 0.42 between noise levels and rated annoyance. The third study carried out by Nilsson (2007) also developed a relationship between A weighted sound pressure level and perceived annoyance in Sweden (Nilsson, 2007). By plotting A-weighted equivalent sound level against number of complaints for some of these studies and including information from Bies et al (2009), we produce the curves in Figure 3.7.

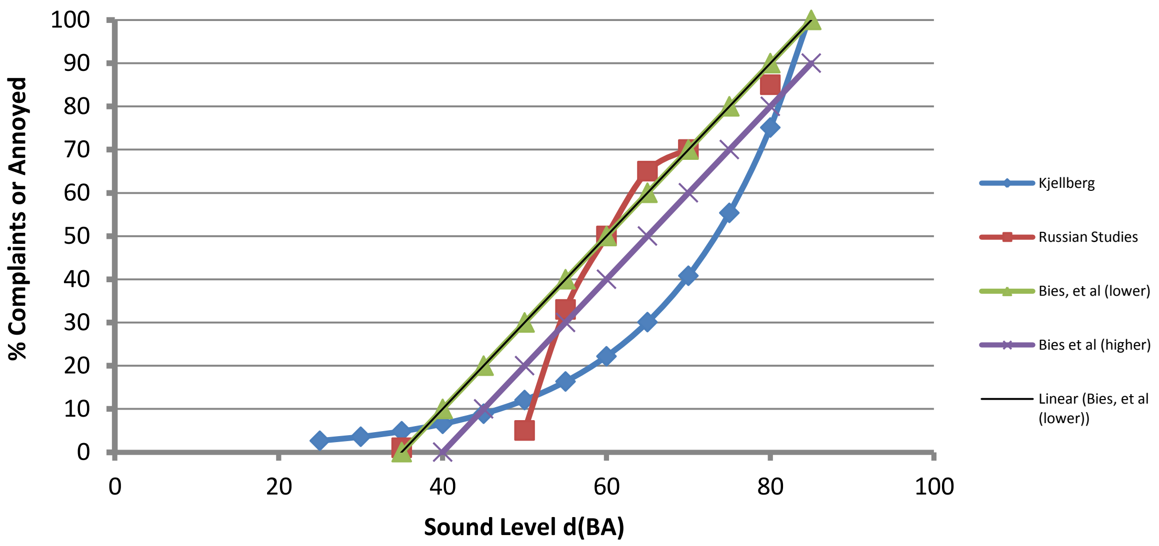

Figure 3.7 A-weighted Equivalent Sound Levels against % Complaints

The graphs in Figure 3.7 could be used to show the general impact of background noise levels on room occupants. The results correlated well with the arguments presented in Berglund et al (Bies and Hansen, 2009), who based correlations on adaptations of the Australian standard (Australian Standard, 1987; Australian & New Zealand Standard, 2000), and agreed that when measured noise levels exceed relevant adjusted background noise levels, complaints begin to arise. Figure 3.8 shows the relationship between background noise level (dBA) and comments likely to be obtained from room occupants and the graph was derived from Table 2.11 (Chapter 2). Comparison of Figure 3.7 and 3.8 indicates that the Bies scenario is probably the most relevant to the office situation in the UK.

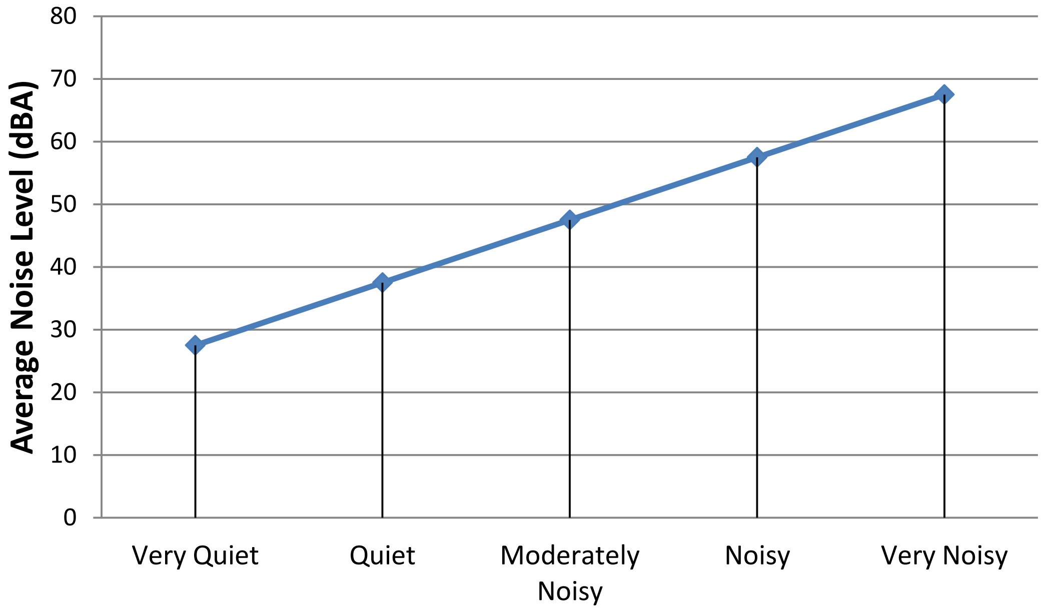

Figure 3.8 Relationship between background noise level (dBA) and comments likely to be obtained from room occupants, Derived from Bies and Hansen (2009) and the Australian & New Zealand Standard (2000)**.**

A general equation linking percentage dissatisfied to background noise in dB (A) can be given as follows:

$$Y = 2x - C' \qquad \mathbf{3.21}$$

Based on the arguments above we can formulate the following methodology:

1. Begin with a base level for acceptable noise in the space (we use target design values) for this purpose;
2. Based on *equation 3.21* above, the design value = 0.5*intercept on the x axis (C), i.e. when Y=0, x=C/2, (taking a rather conservative assumption that a minimal number of complaints will arise at that value);
3. For example assuming that complaints will only begin to rise in an office where the acoustics design value is 35 dB(A), the equation becomes:

$$(PD_{Acc}) = 2(background\ Noise\ Level\ (dBA) - 35) \qquad \mathbf{3.22}$$

4. For an office with average background noise levels of 49 dBA, i.e 14 dBA above the design value (35dBA), then PD = 28.

$$(PD_{Acc}) = 2\left(Actual_{Sound\ Pressure\ Level} - Design_{Sound\ pressure\ level}\right) \qquad \mathbf{3.23}$$

Y = % dissatisfied with noise and *x* = the background noise level in dB (A)

The Acoustic Comfort index is therefore estimated as:

$$Acc_{index} = 100 - PD_{Acc} \qquad \mathbf{3.24}$$

The Acoustic Comfort estimation Flowchart is shown in Figure 3.9

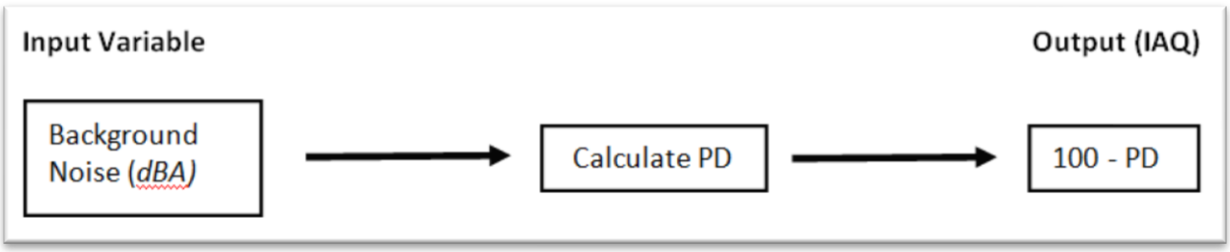

Figure 3.9 Acoustic Comfort Estimation Flowchart

3.3.4 Development of the Lighting Quality sub - index

This index is based on the amount of light falling on the working plane. Saunders in 1969 showed the effects of increasing working plane illumination on workers' satisfaction with the quality of lighting. The results of his work are summarised in Table 3.5.

Table 3.5 Measured Illuminance and Quality of Lighting Results, Source: (Saunders, 1969)

Illuminance on working plane (Lux)	Quality Of Lighting on a Working Plane
93.61702	26.24
153.1915	40.016
204.2553	48.544
229.7872	51.824
272.3404	61.664
306.383	63.632
400	68.224
469.7872	71.504
612.766	74.784
800	76.096
1242.553	80.032
1710.638	82
1800	82
1850	82

By plotting the natural logarithms (ln, twice) of illumination against Quality of lighting we obtain the graph in Figure 3.10 below.

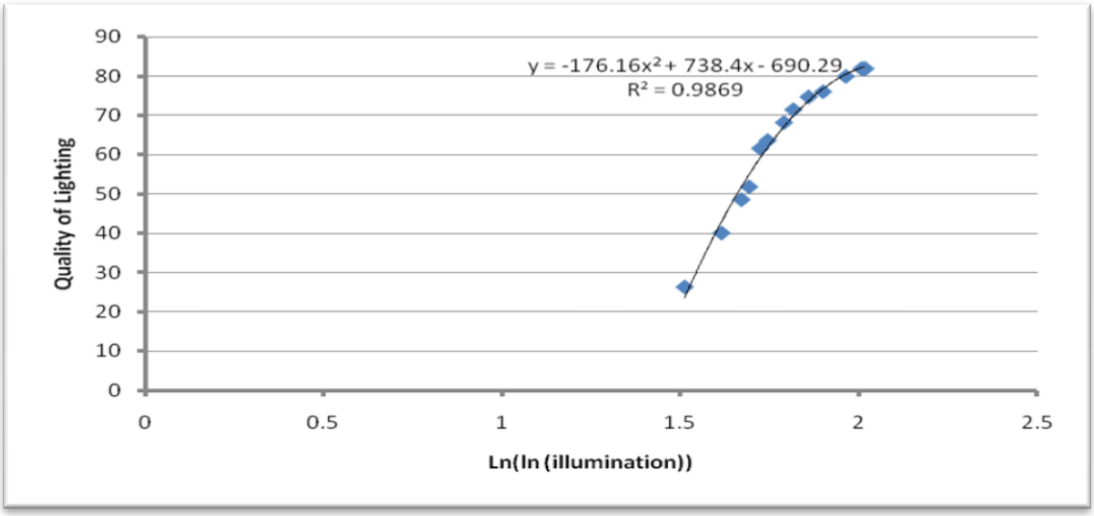

Figure 3.10 Plot of ln(ln (lux)) Against Quality of Lighting

The R^2 value is 0.9869 which represents a good fit. The equation linking Lighting quality and illumination is therefore given as:

$$L_{index} \sim -176.16X^2 + 738.4X - 690.29 \qquad \mathbf{3.25}$$

Where:

$$X = \{\ln(ln(lux)\} \qquad \mathbf{3.26}$$

Although it only demonstrates the importance of one aspect of to the overall quality of lighting, horizontal illumination can act as a guide to the quality of office lighting. Horizontal illumination is also directly related to the amount of natural and/or artificial lighting and energy use in offices. This index will only take illumination (lux) on a horizontal working plane as input and use it to calculate the level of satisfaction with the lighting environment as explained above. Its limitations are highlighted in Section 6.1.3 of Chapter 6. The Flowchart for the estimation of lighting quality is illustrated in Figure 3.11.

Figure 3.11 Lighting Comfort Estimation Flowchart

3.3.5 Developing the Perceived IEQ index and the Weightings

Very little research has been attributed to the development of single index based IEQ tools because it is difficult to establish how individual factors contribute to overall IEQ. In this thesis the IEQ model relies on the establishment of a linear relationship between perceived IEQ and contributing factors as described in the Chiang and Lai IEQ model (2002). We adopt the linear approach as a credible indicator of the indoor environment and accept that the impact of the contributing factors, i.e. the sub-indices or sub-indicators represent sanitary risk factors to the occupants (Hult, 1998). For example, a thermal comfort score of 50% PD represents a certain level of risk of causing discomfort to the occupant. We therefore assume that a cumulative effect of risk factors (contributing parameters) could impact on the occupant's perception of the indoor environment. We also accept that a reduction in risk means a better environment for occupants.

Within each sub-indicator, there are specific metrics that can be utilized in determining an acceptable quality of an indoor environment based on existing knowledge as explained earlier. However the true impacts of each of the contributing factors on perceived IEQ are not yet fully understood and more research is needed in this area. In this study we will take full advantage of the predictive nature of empirical regression models simply because they are derived from subjective measurements.

The model is not based on causal relations, and does not claim that a causal relation exists between the index and its contributors, but it takes advantage of the predictive ability of correlational relationships. As such, it should be used with caution. The Overall IEQ index **(**IEQ_{index}**)** is expressed as a function of thermal comfort, IAQ, acoustic comfort and lighting quality as shown in the expressions 3.27 – 3.30 below.

$$IEQ_{index} = \mathrm{f}\,(Tc_{index}\,, \quad IAQ_{index}, \quad ACc_{index}, \quad L_{index}, \ldots, \ldots\ldots, \ldots\ldots\ldots.) \qquad \mathbf{3.27}$$

$$IEQ_{index} = \sum_{i=0}^{n} \beta_i SI_i \qquad \mathbf{3.28}$$

$$IEQ_{index} = \beta_1 \times Tc_{index} + \beta_2 \times IAQ_{index} + \beta_3 \times ACc_{index} + \beta_4 \times L_{index} + \cdots, .. \mathbf{3.29}$$

Where $\beta_1 - \beta_4$ are the weighting coefficients that can be derived from regression results obtained from questionnaire data or by other means and *SI* is the sub index.

Several methods that can be used for estimating the weightings of each of the contributors are available in literature. The two most important are the use of the Analytical Hierarchy Process (AHP) and the fitting of results of subjective evaluation to regression models. The latter process and methodology will be explained in Chapter 4. Chiang and Lai (2002) derived the weightings associated with five main factors contributing to perceived IEQ (β_i) using the AHP and tested the model in built buildings in Taiwan. The Analytic Hierarchy Process (AHP) is a mathematical decision-making technique that provides an effective means of dealing with tasks that need complex decision-making techniques.

The process was first developed by Saaty (1979) and is now widely applied in science and engineering decision making processes. More information on the AHP in science and engineering can be found in Jurgen et al (20101). Chiang and Lai (2002) involved consulting experts in the field and using the consistency ratio to filter out the null hypothesis. This involved decomposing a decision problem (in this case the effects of contributing variables on overall IEQ) into a hierarchy of easier to understand sub units that could be assessed individually. A comparison of units (contributors) in terms of their relative impacts on IEQ was carried out, and weightings were assigned to each unit using subjective judgements.

Using the adjusted results of the consultation the overall IEQ for an office interior was therefore expressed using a multivariate model as follows:

$$IEQ_{index} = 0.24 \times TC_{index} + 0.34 \times IAQ_{index} + 0.19 \times ACc_{index} + 0.23 \times L_{index} \qquad \mathbf{3.30}$$

The AHP is less informative compared to evaluations made by the actual office occupants although it provides some insight into the relative importance of each of the contributors to IEQ. Weightings based on occupant evaluations will provide us with empirical evidence of the relative importance of the contributors and these are described in Chapter 5. The IEQ index ranges between 0 – 100 and the contributing sub-indices also range between 0 – 100, i.e. (100 – PD) therefore the weightings of equation 3.30 give an idea of which parameters carry more important weightings and it will only for comparison purposes. The implications of the weightings will be discussed in Chapter 5.

In order to determine the probability of occupants accepting the overall indoor environment quality we need to introduce the logistic curve to equation 3.30. The logistic regression model forms part of a group of models called generalized linear regression models and these are commonly employed in predicting modelling. These methods were formulated by John Nelder and Robert Wedderburn as a way of unifying various statistical models, including linear regression, logistic regression and poisson regression, under one framework. This work can be found in the textbook, Generalized Linear Models by Nelder and McCullagh (1989). These approaches have been used extensively in statistical analysis, however most models give strange results especially in cases where the dependent variable is an event. Since the probability of an event must lie between 0 and 1, it is impractical to model probabilities especially with linear regression techniques because linear regression models allow the dependent variable to take values greater than 1 or less than 0 (Merton, 1968) in some cases.

The solution to this problem would be to generalize the linear model by coupling it with a sensible distribution for the dependent variable. This approach is called Logistic Regression Modelling and it makes use of several predictor variables that may be either numerical or categorical. Binary logistic regression has been found to be most useful when one wants to model the event probability for a categorical response variable with two outcomes (Merton, 1968). It could also be employed in situations where predictions are difficult or impossible to make, where tails fit badly and where variance cannot be constant (Wong et al, 2007). Logistic regression (or logit) has been extensively employed in social research, medicine, engineering, agriculture (Hahn and Soyer, 2005) and more specifically in modelling of the indoor environment by Wong et al (2007). Wong used the model to predict the probability of acceptance of IEQ in offices in Hong Kong by fitting questionnaire data to a logistic curve. The Logistic Regression Model can be explained as follows:

Let us begin by considering the existence of an unobserved continuous variable, Z, which can be thought of as the "propensity towards" the acceptability of IEQ and in this thesis, Z = IEQ_{index}. In such cases larger values of Z correspond to greater probabilities of acceptance of the indoor environment while lower values of Z correspond to lower probabilities of acceptance of the IEQ. The logistic function and its inverse link are illustrated by equations shown below.

$$f(Z) = \frac{e^Z}{(e^Z+1)} \ or \ \frac{1}{(1+e^{-Z})} \ or \ Z = log\frac{f(Z)}{[1-f(Z)]} \qquad \textbf{3.31}$$

The model assumes that Z is represented by the expression on the RHS (Right Hand Side) of equation 3.29. And $f\ (Z)$ is the probability (or odds) that a case experiences IEQ acceptance. A logit function that has been developed for this thesis is illustrated in Figure 3.12 below.

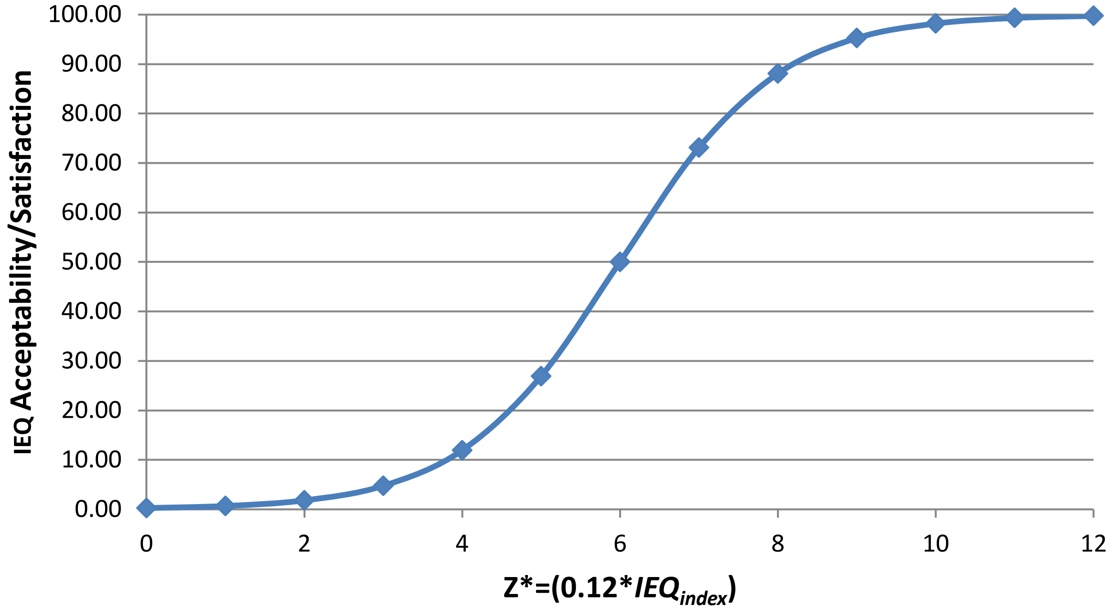

Figure 3.12 Illustration of the Logistic Function Curve: Adapted from William Lowe (2009)

The logistic function is useful because it can take as an input any value from negative infinity to positive infinity, whereas the output is confined to values between 0 and 1. In this exercise the output is multiplied by 100 in order to produce IEQ values ranging between 0 and 100. Calculation of IEQ is carried out in 5 steps or sections called blocks and they are depicted as Block A to E as illustrated in Table 3.6.

Table 3.6 Main Building Blocks of the IEQ Assessment Tool

Block	Index
A	Thermal comfort
B	IAQ
C	Acoustic Comfort
D	Lighting Comfort
E	Overall Perceived IEQ

Figure 3.13 below is a flowchart of the calculation of perceived IEQ.

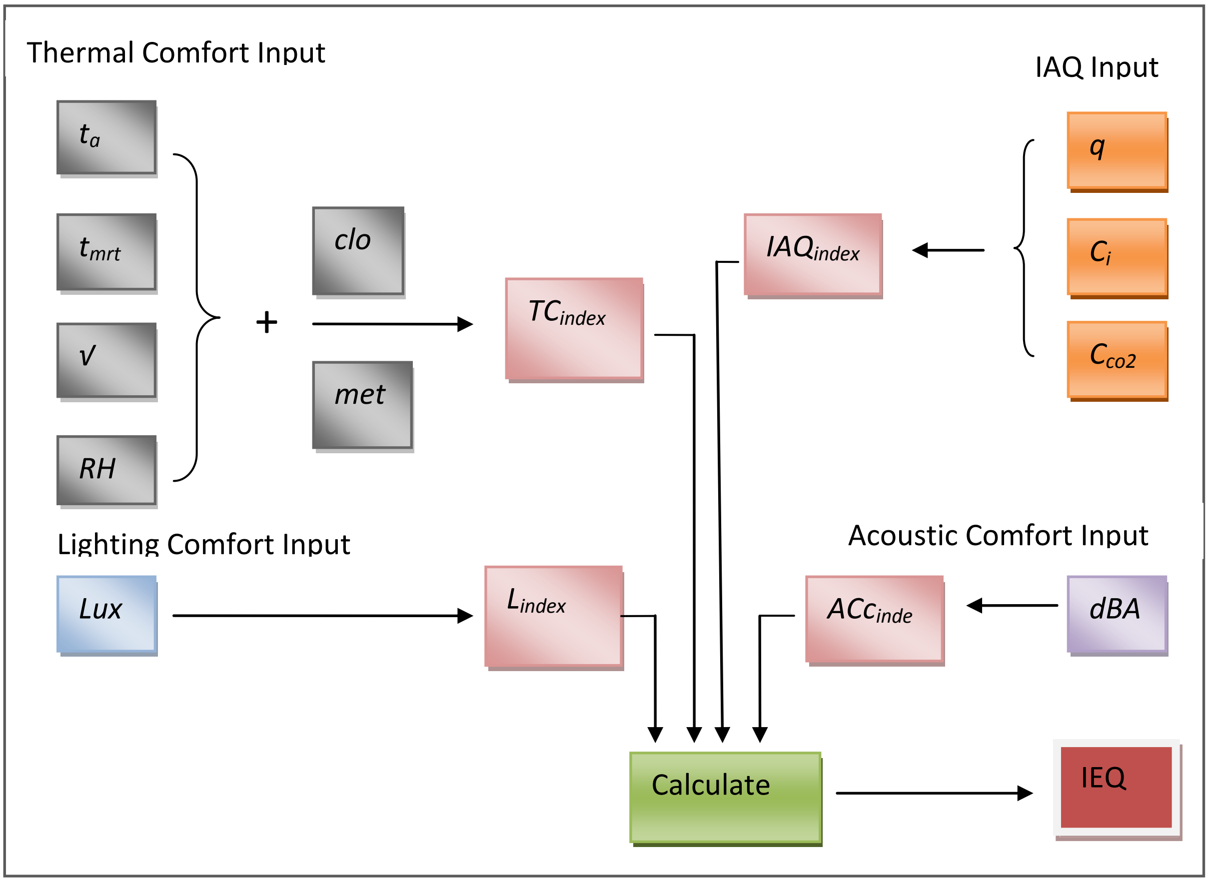

Figure 3.13 IEQ Estimation Flowchart

3.4 ENERGY PERFORMANCE ASSESSMENT METHODOLOGIES

The variables used as input in IEQ assessment must have an impact on the energy performance of office buildings so that comparisons between the two quantities can be made. This information is very helpful to building users, owners, and designers because it allows them to make informed decisions on the impact of energy efficiency initiatives on the overall comfort perceived by occupants. Variables used as input for the calculation of the energy demand of a building when the space is occupied are found in the EN 15265 standard (2007). Table 3.7 lists some of the variables. A more exhaustive list can be found in the European Standard EN 15251 (2006).

Table 3.7 Parameters are Used in Both Energy and Comfort Calculations, source: (EN15251, 2006)

Variable	Application in Energy Calculations	Application in IEQ Calculations
Temperature (*T_a, T_{mrt}*, - *°C/ °F)*	Space Heating & Cooling Estimation	Thermal comfort
Relative Humidity *(%)*	Ventilation, dehumidification or humidification requirements	Thermal comfort
Air Velocity (*m/s* or *ft/s*)	Ventilation requirements	Thermal comfort
Illuminance *(lux)*	Lighting Demand	Quality of Lighting
CO_2 Concentration *(ppm)*	Ventilation Rates	IAQ
Background Noise Levels *(dBA)*	Ventilation rates (window/opening closing), choice of building fabric, heating/cooling loads	Acoustic Comfort

Figure 3.14 illustrates the process that can be followed when making decisions about the energy and IEQ performance of office buildings at design stages. The process begins by specifying criteria for the indoor environment (EN 15251, 2006). Criteria used for the indoor environment affects the energy performance of the building and its energy performance rating. An energy performance rating methodology that closely matches actual building performance may be used to determine energy performance.

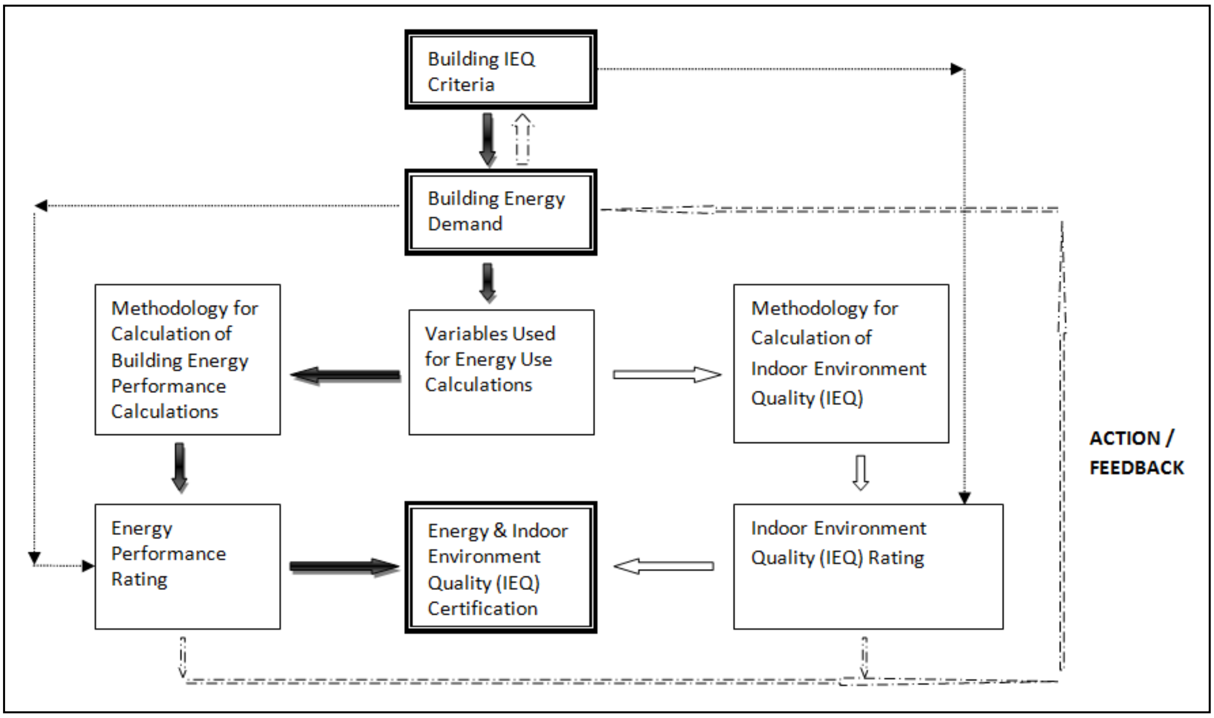

Figure 3.14 Summary of the Variables Used for IEQ and Energy Calculations.

Standard input values for energy calculations that were discussed earlier are also specified in Article 3 of the EN ISO 13790 (2008) standard. The standard recommends that all energy calculation methodologies should at least include aspects such as the thermal characteristics of the building (shell and interior partitions, etc.), the heating installations and hot water supplies, air conditioning systems installed, ventilation systems, passive solar systems, indoor climatic conditions, building orientation factors and built in lighting systems.

The standards also suggests that the positive influence of sustainable technologies and design systems such as active solar technologies, the use of natural lighting, district heating systems and CHP systems should also be taken into account. The National Calculation Methodology (NCM, 2010) which is based on the Energy Performance of Buildings Directive (EPBD) allows the actual calculation of the building's energy performance to be carried out by approved software or by a simplified tool based on a set of CEN standards (EN13790, 2008). Some of the approved tools and methodologies used in the UK include the following:

- SAP 2005 which is used for domestic properties (BRE, 2005);
- the Simplified Building Energy Model (SBEM) (NCM, 2010); and
- Dynamic Simulation Modelling Software for commercial applications.

Approved Dynamic Modelling Software includes the Integrated Environmental Solutions (IES) (Integrated Environmental Solutions), Thermal Analysis Simulation (TAS) Software (EDSL, 2010) and Bentley's HEVACOMP (Bentley, 2010) among many others. The Integrated Environmental Solutions (IES) software is a building performance modelling software that incorporates an energy analysis component. The software allows designers to undertake energy performance snapshots in order to assess impact of design decisions at early stages of design, develop building loads and impact of conservation strategies, develop footprint reduction strategies, assess passive/hybrid/renewable systems, assess the impacts of daylighting and solar gains, bulk air flow, ventilation, IAQ and assess compliance with regulations. This software is available at discounted rates for students at the University of Nottingham.

The Thermal Analysis Simulation (TAS) Software is capable of performing dynamic thermal simulation of buildings including the ability to predict energy consumption, CO_2 emissions, operation costs and occupant comfort (thermal comfort). The software can be used to calculate heating and cooling loads, design natural or passive ventilation systems, evaluate ventilation regimes, simulations, daylighting calculations and to check compliance with legislation. The software is available free at selected computers within the University of Nottingham.

Bentley's HEVACOMP software is a leading tool in building services design and CAD software that uses industry standard calculation procedures such as CIBSE, ASHRAE, British Standards or IEE as applicable. The software has found applications in Mechanical design for Load calculations, Pipe & duct sizing and Mechanical CAD. Both 2-D & 3-D CAD drawings can be produced. Energy calculations based on the Energy Plus analysis engine can be carried out to examine room heat losses and gains, summer overheating, peak design months, overheating frequency, building energy and therefore equipment sizing. CFD simulations for heat flow (T°C), air movement (ventilation) and particulate concentrations (pollution) including electrical design conforming to the requirements of IEE 16th Edition wiring regulations, Lighting systems design and electrical CAD can also be carried out. This software was also available free for purposes of this research at the University of Nottingham and at Hoare Lea & Partners.

The energy performance of office buildings is highlighted using Energy Performance Certificates (EPCs) which can be produced using software such as explained above. EPCs are used to grade buildings on a scale of A to G with A being the most efficient and G the least. Figure 3.15 shows a typical building rated at Grade D with a potential to rate Grade C. In commercial buildings asset certificates measure the intrinsic energy performance of the building based on its design while operating certificates measure how the building is managed and how it actually performs. The certificates are renewed annually and displayed in public buildings. EPCs are based on the SAP 2005 ratings and SBEM (BRE, 2005).

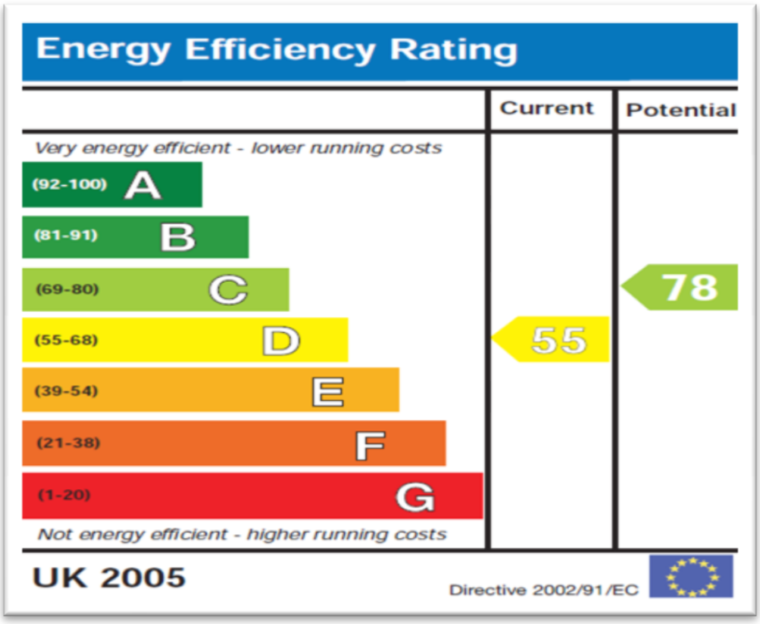

Figure 3.15 Energy Performance Certificate Showing a D Rated Domestic Building: copied from: (Directgov, 2011).

3.5 THE IEQAT

Based on the findings of the previous sections of this Chapter that included the identification of factors influencing IEQ and their respective variables, the development of sub indices, the use of weighting coefficients developed by Chiang et al to develop the IEQ index and a list of appropriate programming software the IEQAT could be assembled and used as shown in the example sheets (data entry and assessment sheets). The IEQAT consists of numbered data entry sheets where information relevant to building assessment model is entered. It also consists of assessment sheets that summarise IEQ performance of buildings. A general outline of the steps followed when using the proposed tool is illustrated using the flowchart in Figure 3.16.

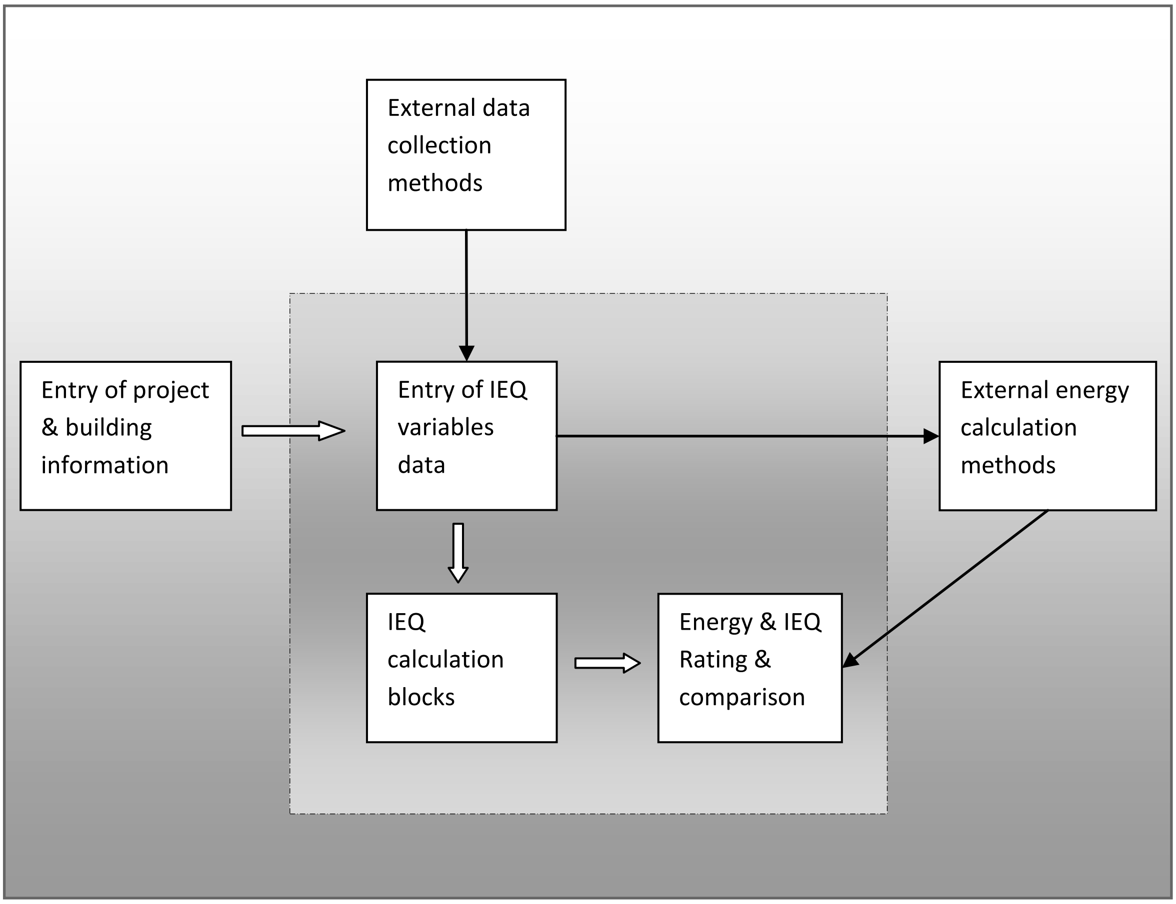

Figure 3.16 Flowchart of IEQ Calculation Steps

The Tool begins with the collection and entry of project and building information as illustrated. This is followed by the entry of IEQ variables data obtained using approved (external) data collection methods. The information is passed into the five main calculation blocks of the tool where sub indices are computed. The same variables are used for energy performance calculations using methods external to the tool. Approved energy calculation methodologies and software have been discussed in earlier (section 3.4 of this Chapter). The final step involves calling Energy and IEQ ratings as outputs so that comparisons between the two can be made and decisions on the course of action can be taken can be made.

3.5.1. Data Input

The IEQ tool has the ability to capture user and project data using a data entry sheets or windows (for computer based programs, see screenshot). The main sheet where the user makes the first input is shown in Figure 3.17.

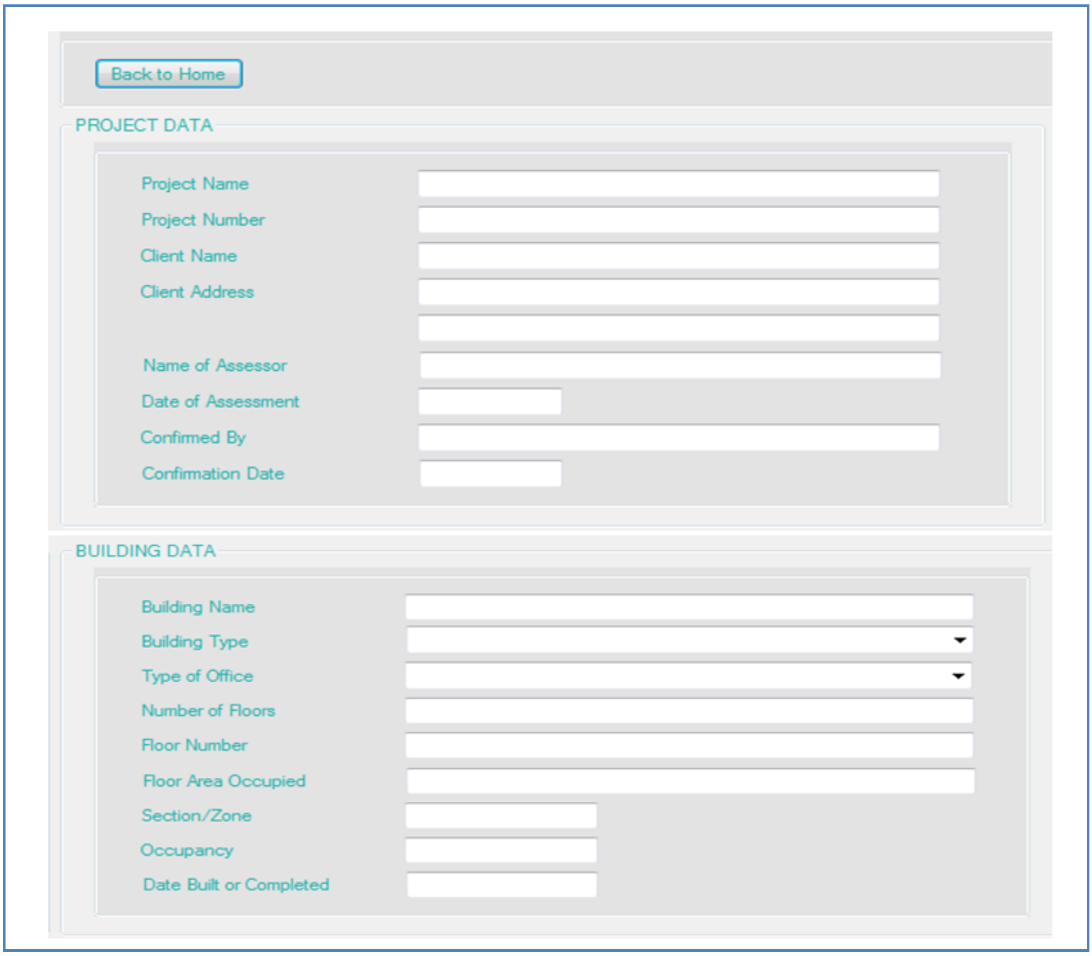

Figure 3.17 Data Entry Sheet 1/1– Project and Building Data

The first data entry sheet allows the assessor to input information which is important for identifying projects. The information required here consists of basic information necessary to carry out an assessment. The second set of information required by this sheet is the building data. In this section information that identifies the building is entered. Most of the information requested is self explanatory and fairly easy to comprehend by qualified assessors.

For computer based products the creation of IEQ projects using the normal windows or MAC procedures is expected. As in most cases the program may ask the user to identify themselves by way of logins and ask them to either create new projects or work on existing ones. The *type of office* refers to whether the office is an open plan, cubicle, or a mixture of the two and also requires the user to specify the type of HVAC system present. There are four generic types of office in the UK and they are listed below.

Naturally Ventilated Cellular offices are relatively simple and small offices that are mostly converted from residential accommodation. They have typical floor spaces ranging from 100 to 3000m^2. Local comfort controls such as local light switches and heating controls are common practice. A different thermal comfort assessment criterion is used for naturally ventilated offices where occupants are free to adapt their clothing levels and other local comfort parameters as explained in Chapter 2, section 2.7.2.

Naturally Ventilated Open Plan offices are largely open plan but some may have cellular spaces. Typically they range from 500 to 4000m^2 in floor area and they are sometimes built in converted industrial space or specially designated areas. Equipment use is usually more intense than in cellular offices as frequent switching on and off of equipment is carried out to satisfy a larger group of occupants.

Standard Air Conditioned offices are largely purpose built with floor areas ranging from 2000 to 8000m^2. The benchmarks are usually based on Variable Air Volume (VAV) air conditioning systems.

Prestige Air Conditioned offices are usually associated with regional head offices and administrative centres with typical floor spaces ranging from 4000 to 20 000m^2. The offices are usually built or refurbished to very high standards with excellent BMS. Air conditioning is usually provided for specialist areas such as server rooms and even in parking and leisure areas. In some cases Personalised Ventilation Systems (PVS) are installed to provide individualised comfort (BRECSU, 2000).

Mixed Mode offices are those that combine both passive natural ventilation and mechanical ventilation and cooling in buildings that may otherwise have been fully air conditioned. In most cases in the UK mechanical ventilation may be used only during the cooling season. More information on the benchmarks for all office types can be found in the Energy use in Offices Guide 19 (BRECSU, 2000).

The *number of floors*, *floor number* and *floor area* are self explanatory and they are important aspects that help provide clues about energy use and comfort. Floor area and *occupancy* levels give the population density within the office (number of occupants per unit area) and these in turn affect the selection and performance of HVAC systems.

The section of the office refers to the part of the space under investigation and includes sections, zones, blocks, etc. The location and climate requires the user to enter the actual location and climatic zone for purposes of estimating the microclimatic conditions that exist in and around the building. Nowadays most software use databases containing up to date weather and pollution data. The date the office was *built* refers to the actual date of completion and if any renovations were made then they need to be stated.

For buildings still to be built or those under construction an expected date of completion may be entered. Figure 3.18 is the second part of the first data entry sheet and it requires the user to enter a general description of the building in the words of the assessor.

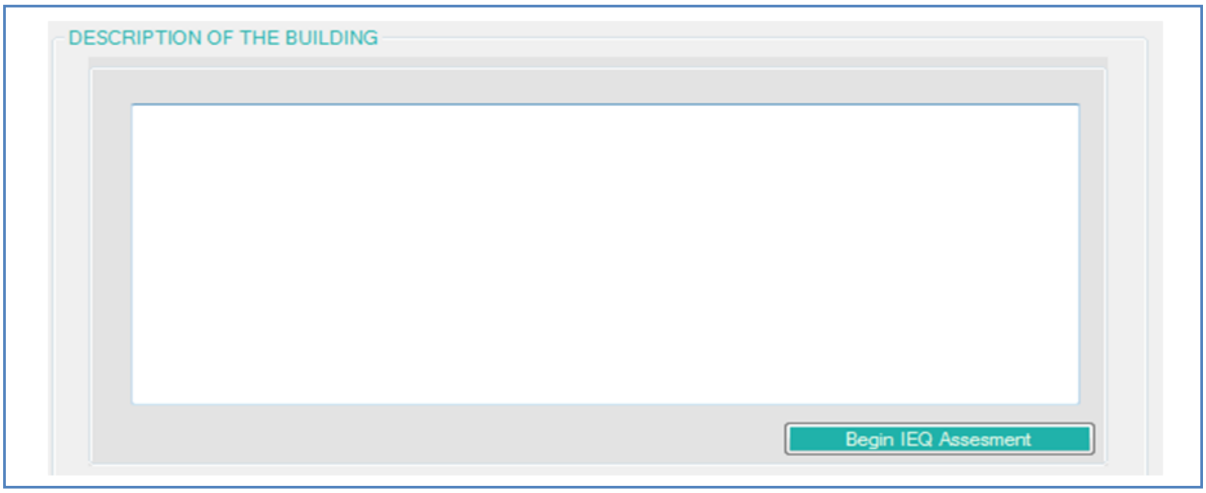

Figure 3.18 Data Entry Sheet 2 / 1 – Project and Building Data

The second step involves the selection of the type of data to be used as input for calculating IEQ. This is especially important since the data origins could have different accuracy and reliability implications (Fairfax County Department of Systems Management for Human Services, 2003). Input data selection, the source of the data and the collection interval is summarised in the tool data input sheet shown in Figure 3.19. The "type" of data especially refers to its source or origin i.e. measured, calculated, design and questionnaire data as explained below. This section also requires the user to draw or upload floor plans.

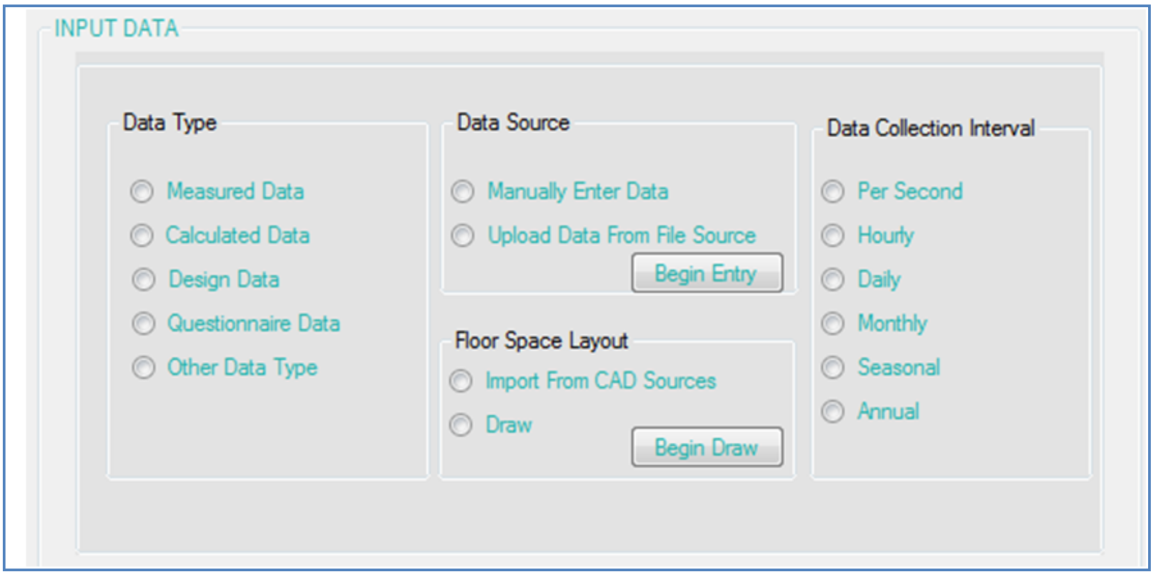

Figure 3.19 Data Entry Sheet 2

Measured data

Measured indicators include all variables that are measured before or during occupancy and these can be available on a daily, weekly, monthly, seasonal and annual basis. The standards for measurement of IEQ variables and instrumentation are described in detail in the EN ISO 7726 (1988) standard and examples of measured data may include relative humidity readings taken using an approved instrument, at regular intervals (e.g. 10 minute intervals) for a specified time period (e.g. an entire day).

These variables need to be collected at least during the heating and cooling seasons of the year especially in buildings where no air conditioning systems are installed or where these systems are used during some parts of the year period. The main advantage of the measured indicators is that they represent the actual performance of the building and its disadvantage is that this information may not be available at design stage.

Calculated data

Calculated indicators can be obtained from building simulation tools before or after the building has been constructed. Simulations provide a cost effective way of determining the actual performance (or close to) of the building and simulation programs available are validated according to EN ISO 15255/65 standards. Programs such as HEVACOMP and IES are capable of simulating the indoor temperatures, lighting, humidity and air velocities while CFD programs like Fluent can be used to determine air velocities, pollutant distributions and temperature profiles.

Design data

The use of design indicators to indicate the quality of the indoor environment is one of the first steps in the design of any office. Categories presented later in this chapter are generally used to classify buildings. Recommended design values for temperature, humidity, ventilation rates, illumination, background noise, etc have already been presented in the recommended operation of office buildings in Chapter 2. The main advantage of using design indicators is that the IEQ of the building can be determined before construction and adjustments to the HVAC systems can be made at an early stage. The main disadvantage is that buildings may not perform to intended standards.

Questionnaire (survey) Data

The use of subjective evaluation to assess building performance is probably the best option as it gives the actual information on how occupants feel inside the building. Questionnaire data may include data collected through preset questions that are handed to office occupants electronically, by interviewing or by delivering hard copies and collecting those after the occupants have expressed their opinion of the indoor environment. Questionnaires are relatively easy and cheap to administer. However the main disadvantage is that questionnaires can only be used for post occupancy evaluation. This next step involves the selection of data source files (Figure 3.18). Data can either be entered manually for single entry calculations or via file upload. Uploading data allows multiple values to be entered for example data collected over a period of time could be uploaded instantly and IEQ can be calculated for that period. In some cases data could be received from the BMS allowing calculations to be carried out instantly (real time monitoring of IEQ). Entered data can be displayed in the display area (*not shown*) and amended as required. Examples of files are shown in Tables 3.8 and 3.9.

Table 3.8 shows data that has been collected on a monthly basis for a year and Table 3.9 shows data that has been collected hourly for a 12 hour day. This data could also show average values, for example Table 3.14 could show mean monthly values of variables which have been collected on a second by second basis, hourly, daily or weekly basis. This information shows the flexibility of the input data for tool and hence the output data expected.

Table 3.8 Example of an Annual File with Data Collected Monthly

Month	T*a* (°C)	T*mrt* (°C)	RH (%)	*V* (m/s)	Clo	Met	Lux	IAQ choic	Acosutics (dBA)	
January										
February										
March										
April										
May										
June										
July										
August										
September										
October										
November										
December										

Table 3.9 Example of a 12 hour Day File with Data Collected Every Hour

Hour	T*a* (°C)	T*mrt* (°C)	RH (%)	*V* (m/s)	Clo	Met	Lux	IAQ choice	Acosutics (dBA)
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									

Data entry sheet 3 (Figure 3.20) consists of entries of physical and personal parameters necessary for the calculation of thermal comfort. The calculation methodology for thermal comfort has been explained earlier in the chapter. Data Entry Sheet 3 displays data that may have been entered or uploaded in Data Entry Sheet and also includes a general checklist of variables that have not been used in the calculations but may be helpful in providing further information about that state of the indoor environment. The general checklist also provides additional incentive to the calculation methodology, for example an office that has individual control of temperature and humidity is deemed to provide better satisfaction than one that lacks it.

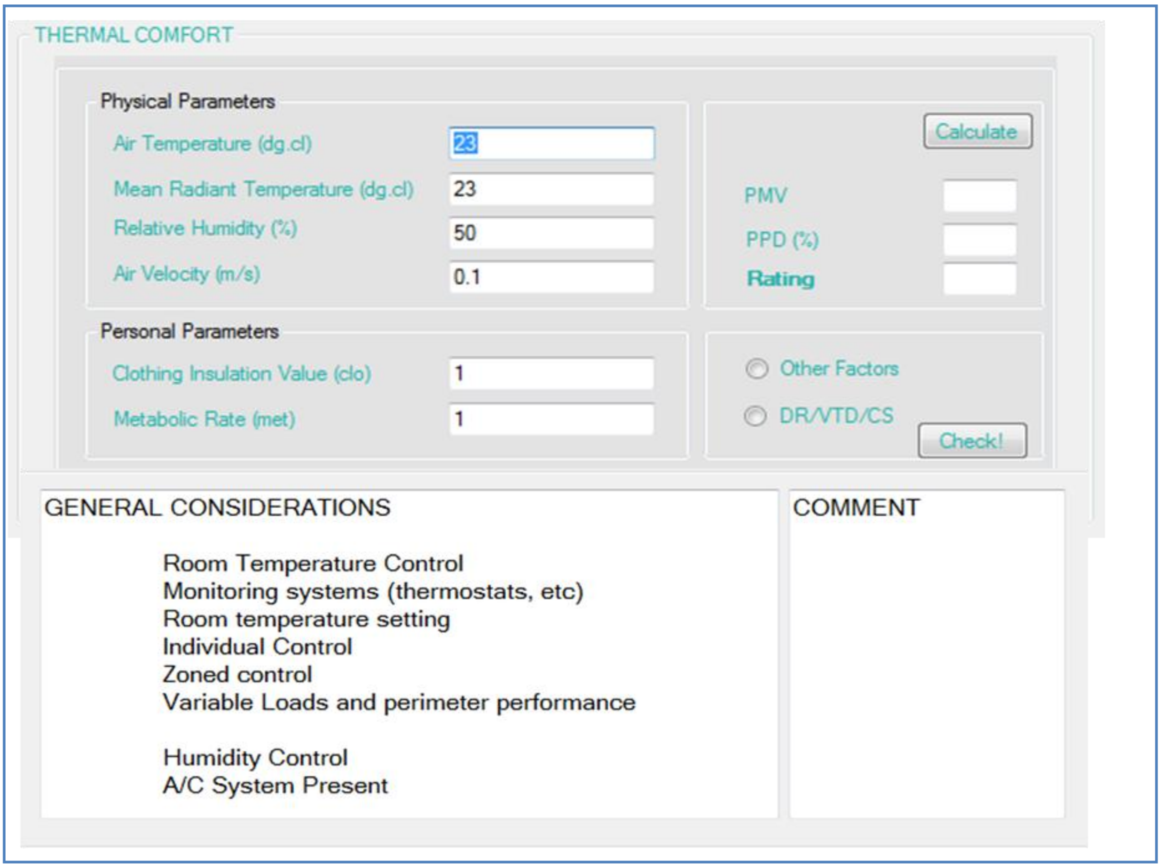

Figure 3.20 Data Entry Sheet 3 - Thermal Comfort Factors and General Checklist Record Sheet

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○ Refers to: choice must be made
❖ Refers to variables under consideration but not necessary for calculations
✓ Refers to already selected choice (necessary for calculation)
✚ Refers to the main bullet point

Data entry sheet 4 (Figure 3.21) describes variables that are necessary for the calculation of IAQ and offers the assessor a choice of which variable they wish to use to calculate perceived IAQ. Again the relevant data for variables need to have been entered in data entry sheet 2 otherwise they may have to be entered one at a time (manually) here. The sheet also contains a checklist that can be used as a guide to further IAQ related improvements in the office. Most of the considerations are centred on control, of ventilation in various zones, individual control, control of pollution sources and smoking.

Figure 3.21 Data Entry Sheet 4 - IAQ Factors and General Considerations Record Sheet

*Smoking in public areas was banned in all public indoor spaces in the UK (2007) and in most parts of Europe (The site.org)

Data entry sheet 5 (Figure 3.22) displays the variable that is used in this tool to estimate perceived acoustic comfort and the other considerations that need to be made to ensure an acceptable acoustic environment for occupants. Background noise level (dBA) is the only variable used in this sheet and its use in the estimation of acoustic comfort is also presented later in the chapter.

The general considerations checklist includes the analysis of type and intensity of equipment, people and outdoor noise. This can be observed directly by the assessor during the assessment exercise. This process is referred to as critical listening and it is a cheap, easy but effective method of identifying annoying background noise. Sound insulation properties of elements of the building fabric such as walls, floors, openings and the reverberation times of sound can be obtained from building construction data.

The information can help identify problem areas and hence help determine what sound related improvements need to be made.

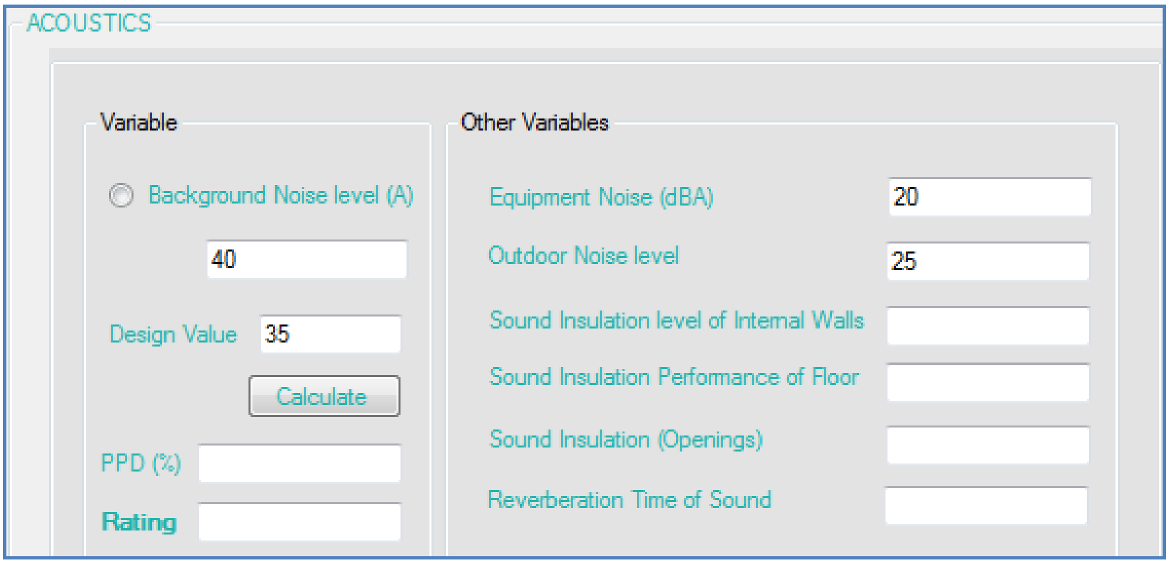


Figure 3.22 Data Entry Sheet 5 – Acoustic Comfort Factors and General Considerations Record Sheet

Data entry sheet 6 illustrated in Figure 3.23 is the final data entry sheet required for this tool and it lists the variables that are important for lighting comfort assessment. Horizontal illumination is the most important variable for purposes of calculation of lighting quality in this tool although elements such as UGR, R_a and working plane height are also important (CIBSE, 1994; CIBSE, 2006). It is important to check that the values fall within acceptable limits during the checklist. Other considerations that need to be made and recorded include daylight parameters, antiglare measures, controls and other illuminance related measures such as colour of light, rendering index, etc. Methods use to estimate quality of lighting in offices have been explained in the earlier sections.

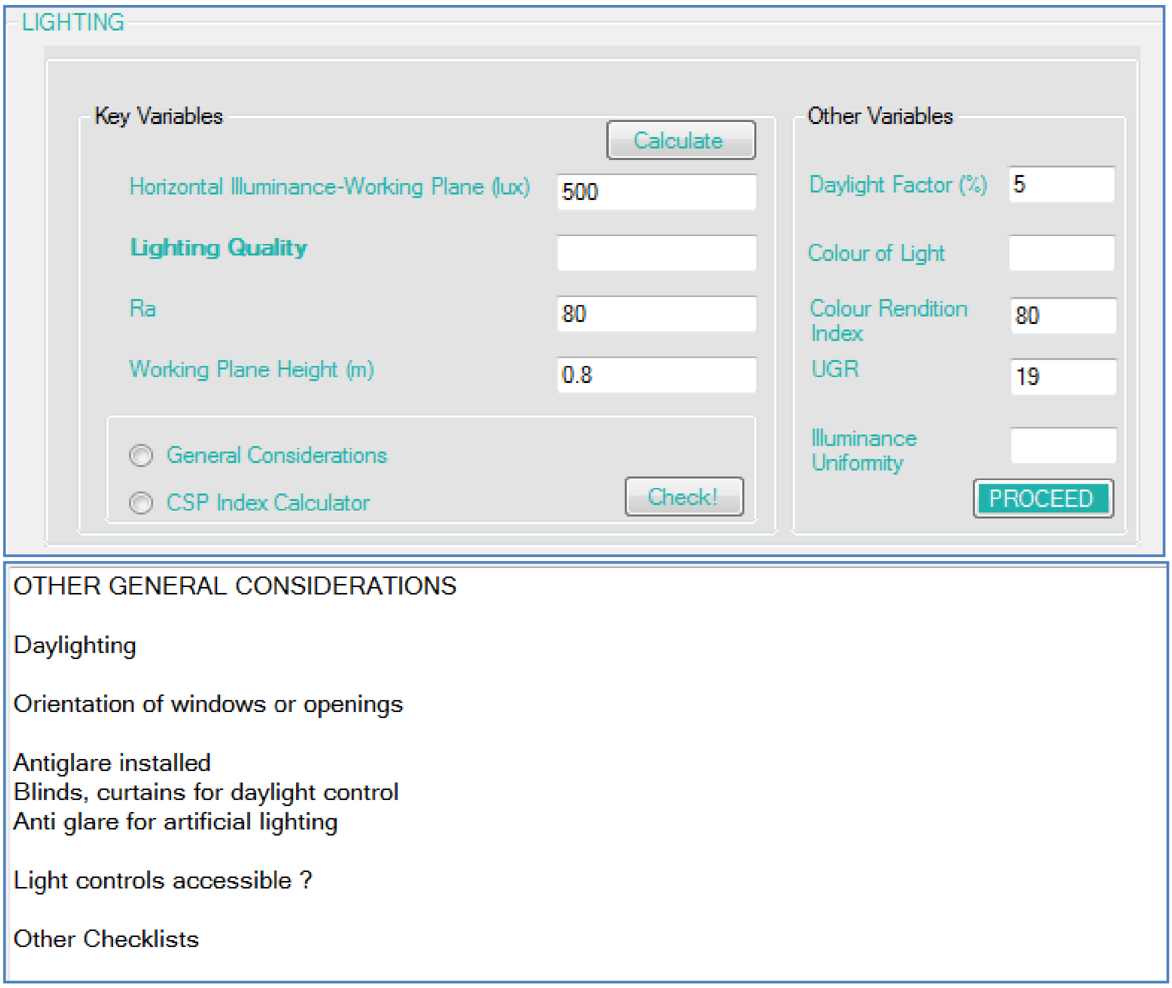
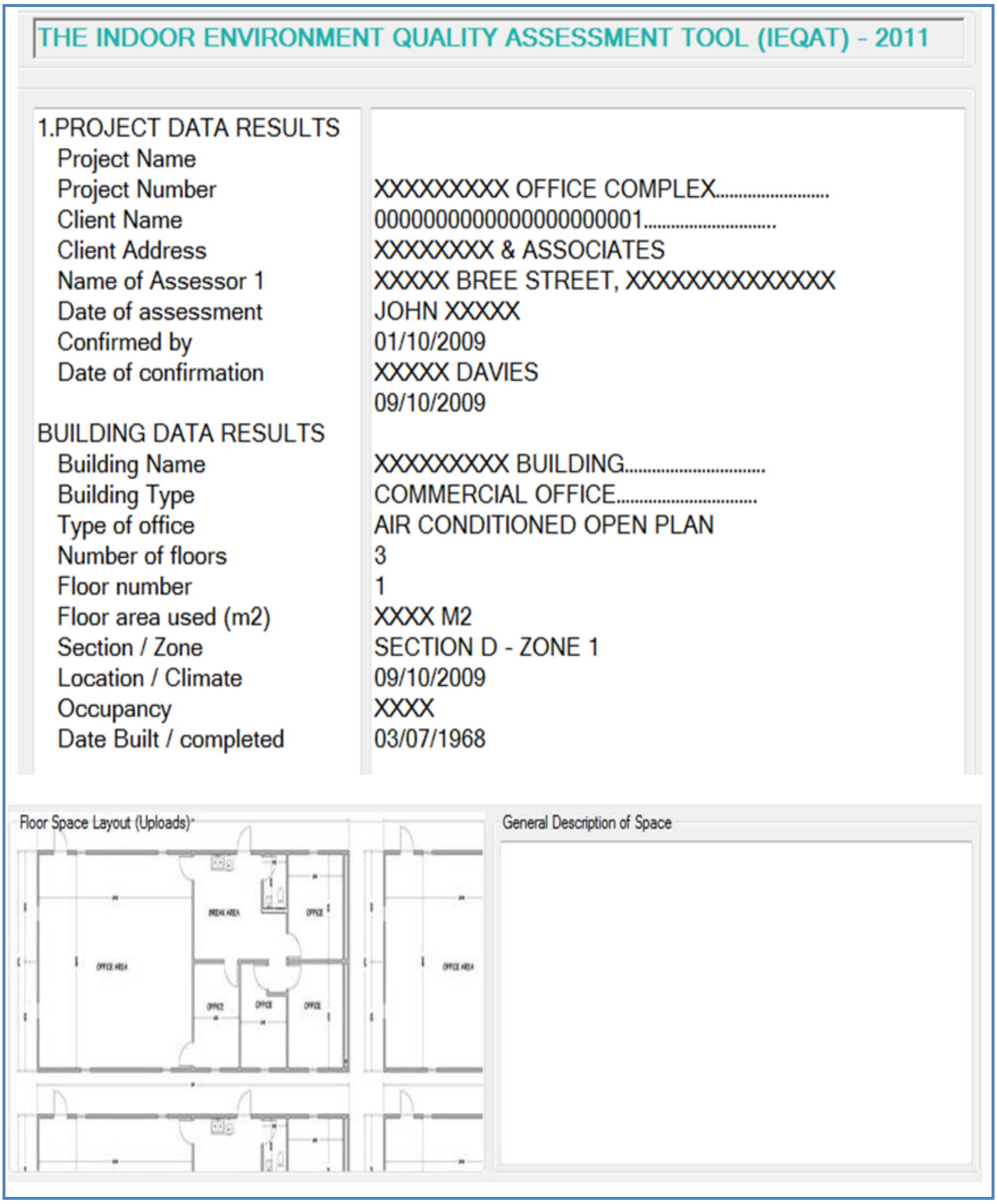


Figure 3.23 Data Entry Sheet 6 – Lighting Comfort Factors and General Considerations Record Sheet

3.5.2 Assessment Results Sheets

Figure 3.24 shows a typical results sheet for IEQ assessment of typical office spaces.



THE INDOOR ENVIRONMENT QUALITY ASSESSMENT TOOL (IEQAT) - 2011

1.PROJECT DATA RESULTS	
Project Name	
Project Number	XXXXXXXXX OFFICE COMPLEX.......................
Client Name	000000000000000000001...........................
Client Address	XXXXXXXX & ASSOCIATES
Name of Assessor 1	XXXXX BREE STREET, XXXXXXXXXXXXX
Date of assessment	JOHN XXXXX
Confirmed by	01/10/2009
Date of confirmation	XXXXX DAVIES
	09/10/2009
BUILDING DATA RESULTS	
Building Name	XXXXXXXXX BUILDING.............................
Building Type	COMMERCIAL OFFICE.............................
Type of office	AIR CONDITIONED OPEN PLAN
Number of floors	3
Floor number	1
Floor area used (m2)	XXXX M2
Section / Zone	SECTION D - ZONE 1
Location / Climate	09/10/2009
Occupancy	XXXX
Date Built / completed	03/07/1968

Floor Space Layout (Uploads)

General Description of Space

Figure 3.24 Assessment Results Sheet 1, NB: This is for illustration purposes; layout may change in the actual tool

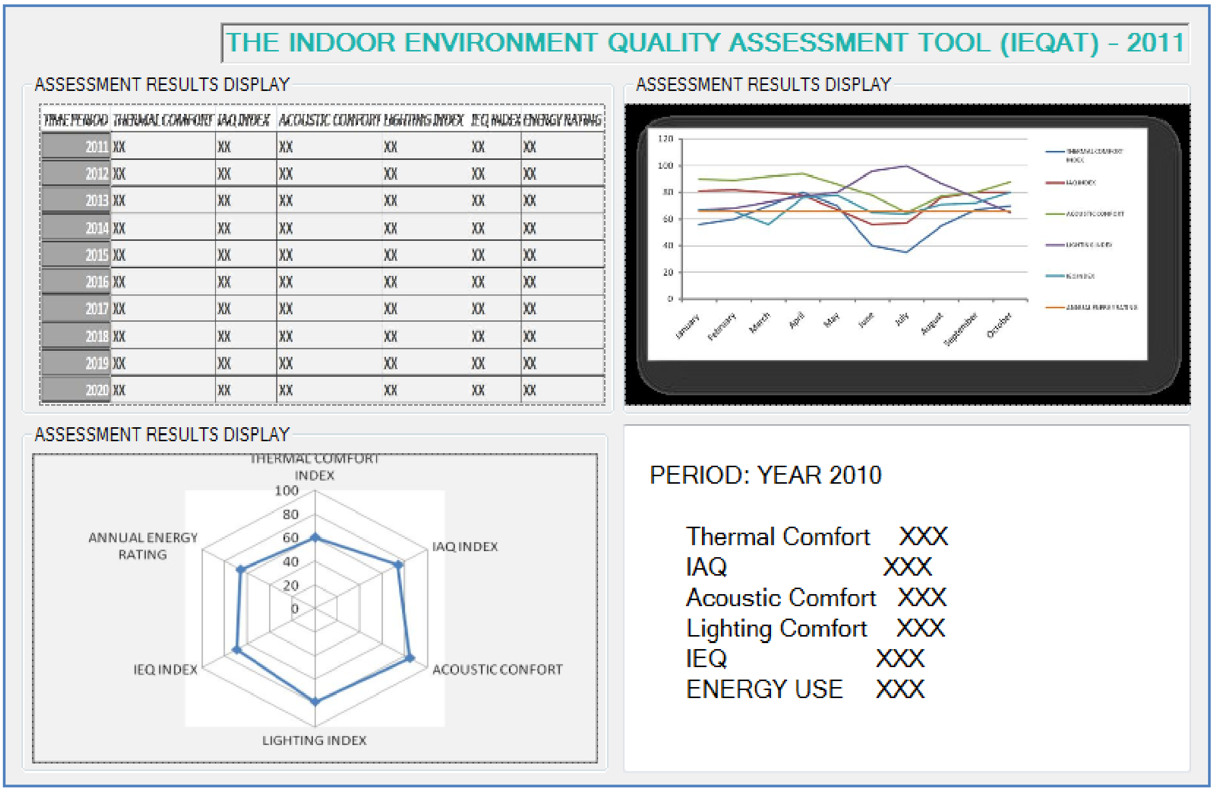


Figure 3.25 Assessment Results Sheet 2

Figure 3.25 displays results calculated using data entered during the data input stage (data entry sheets). The results are displayed in spreadsheet and graphical format. Clicking on the year will reveal results of the whole year at monthly intervals depending on whether enough variables data is available, otherwise the tool may ask the assessor to enter more data.

Similarly, selecting a month within the year will display daily results for that month and selecting a day will display hourly results for the day and so on. Selecting for example, thermal comfort will **only** display thermal comfort results for that period and so on. Real time monitoring of IEQ parameters can be carried out using this tool as long as data from sensors connected to the BMS is supplied to the software.

Comparisons between energy and IEQ ratings can be made and decisions on which parameters to adjust can be made based on the results. Figure 3.26 shows a comparison between IEQ and Energy use rating for a typical office building.

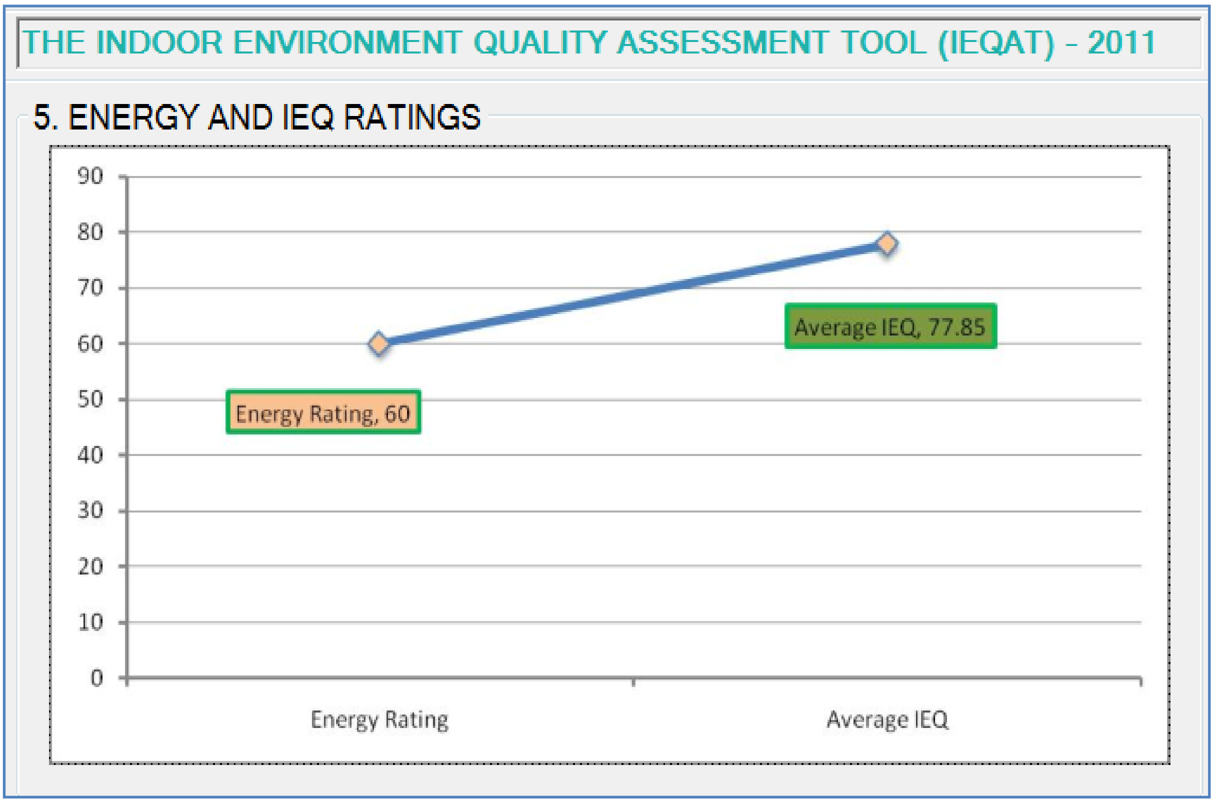


Figure 3.26 Comparisons between Energy and IEQ Ratings for Typical Office

In this tool an energy rating ranging between 1 (G) and 100 (A) is acceptable since the IEQ model values range between 0 and 100. Comparisons between the two can be made easily by way of charts and graphs. More factors could be included in the comparison thereby making it possible for the tool to be incorporated into other building analysis tools. Table 3.10 shows other indicators that can be used with the tool.

Table 3.10 Indicators that can be used with the IEQAT

IEQ indicators	**IEQ, Thermal comfort, IAQ, Acoustics, Lighting**
Energy ratings	Building energy performance, Renewable Energy Usage, Green House Gas Emissions, etc
Water Efficiency	Water conservation, water usage, innovative water reduction technologies
Materials Indicators	Local/regional materials (embodied energy concerns), Recycled materials, environmental impact of materials, reuse, renewable, sustainable materials
Cost & Economic Indicators	Site costs, materials & construction, energy costs, water costs, waste management costs,

3.5.3 Long term indicators of IEQ and recommended criteria for acceptable deviation and length of deviation from standard conditions

Another way of presenting IEQ results is to rate buildings or parts of buildings into categories. The tool suggests five categories based on the overall IEQ value as explained in the text below.

Category I

This category includes exceptional performance buildings that rate highest in IEQ, thermal comfort, IAQ, acoustics, design and lighting. The buildings can either be mechanical or naturally ventilated and those rating between 80 and 100 on the Overall Perceived IEQ scale constitute this category.

Category II

Buildings in this category demonstrate strong Overall Perceived IEQ performance and rates between 60 and 80 on the IEQ scale.

Category III

Buildings in this category display above average performance although there is room for improvements. Values range from 40 to 60 on the Overall Perceived IEQ scale.

Category IV

The building displays average performance with plenty of room for improvement and scores 20 – 40 on the Overall Perceived IEQ scale.

Category V

Poor Performance buildings that require improved IEQ management and significant steps need to be taken to improve the rating. Building scores between 0 – 20 on the Overall Perceived IEQ scale are typical of this category.

This information is summarised in Table 3.11.

Table 3.11 IEQ Assessment Categories for Rating Office Buildings.

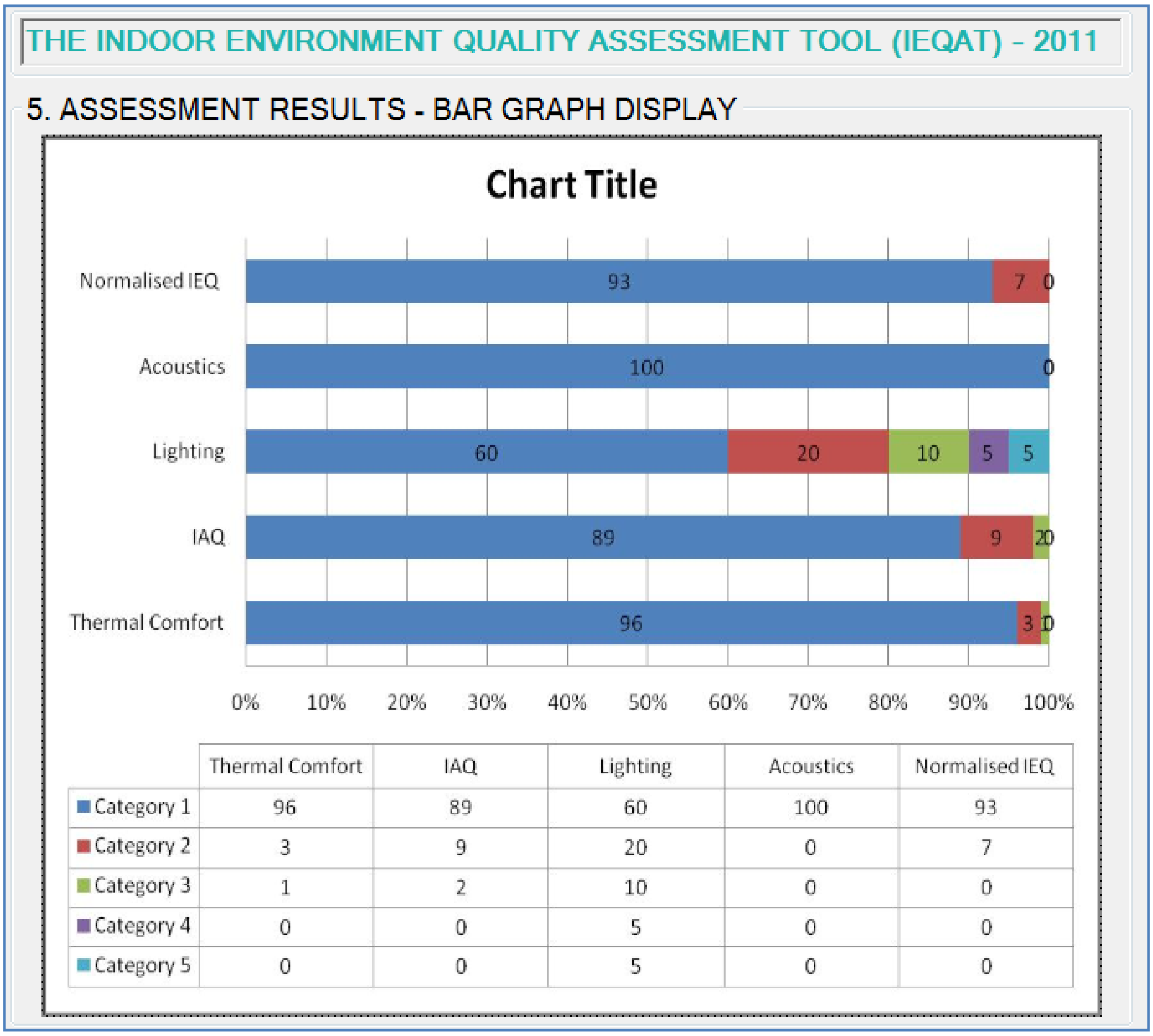
Category	Value (IEQ)	Comment
I	$80 < x \leq 100$	Very High Quality IEQ
II	$60 < x \leq 80$	High Quality IEQ
III	$40 < x \leq 60$	Medium Quality IEQ
IV	$20 < x \leq 40$	Low Quality IEQ
V	$0 \leq x \leq 20$	Very Low Quality IEQ

The percentage of time a building falls into an assessment category gives a better indication of the comfort trends in that building. A building is said to have met certain criteria for a specific category when it meets the following criteria (EN 15251, 2006):

- When its actual category in the rooms representing 95% of the occupied space does not fall outside the limits of a category for 5% of occupied hours in a day, week, month or year; and
- When the rooms representing 95% or more of building volume meet that criteria.

An hourly criterion is used to calculate the actual number of hours or percentage of the time the criterion for that category is met or not. Degree hours or days could also be used to indicate the number of hours or days a building falls outside the upper or lower boundaries for cold and warm seasons. This approach is explained further in the EN ISO 13790 standard. Another method which is based on weighted PMV and PPD values is explained in Annex F of the EN 15251 (2006).

Figure 3.27 shows a typical assessment result sheet showing the percentage of time a building falls into a particular category.



	Thermal Comfort	IAQ	Lighting	Acoustics	Normalised IEQ
Category 1	96	89	60	100	93
Category 2	3	9	20	0	7
Category 3	1	2	10	0	0
Category 4	0	0	5	0	0
Category 5	0	0	5	0	0

Figure 3.27 Assessment Results Sheet Showing % of time Office Space Falls into Particular Category

Another way of displaying the results is shown **in** Figure 3.28 and this method can be used for both real time and long term display of results. For real time monitoring the colour codes are expected to change as the quality of the indoor environment changes from one category to another.

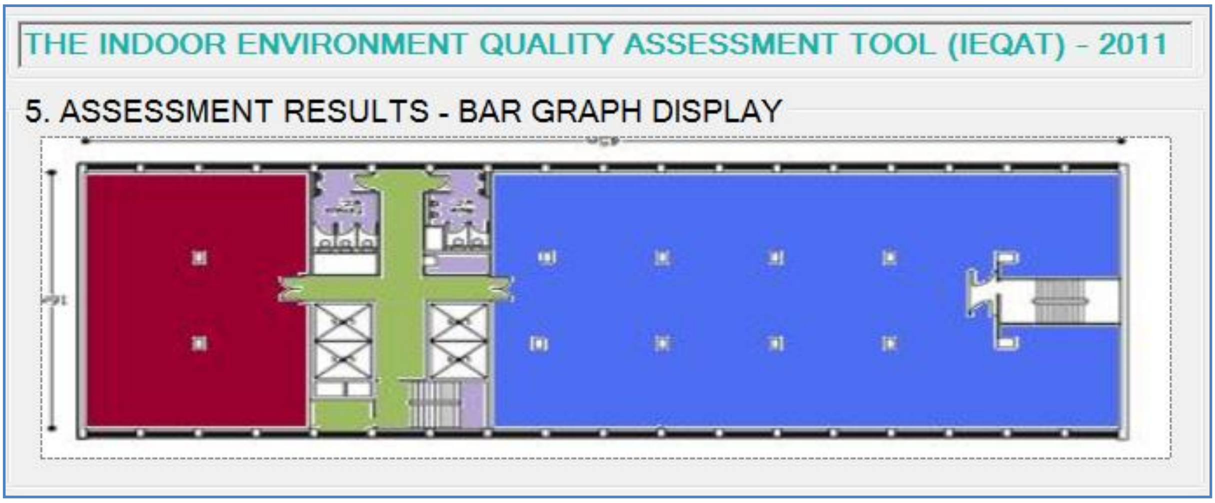


Figure 3.28 Real time or long term representation of office assessment results

Assessment of individual offices is straight forward. A different approach is required for office complexes because more than one area is considered. An average rating for an office complex is calculated as a weighted average of the assessment results for each type of office based on the ratio of floor space occupied by each space.

The score for an office complex is given as:

$$\text{Average } IEQ_{index} = \sum_{i=0}^{n} S_i A_i \qquad \mathbf{3.31}$$

Alternatively:

$$\text{Average } IEQ_{index} = \left[\left(IEQ_{index1} \times \frac{A_1}{A_{total}}\right) + \left(IEQ_{index2} \times \frac{A_2}{A_{total}}\right) + \cdots, \ldots, \ldots, \ldots, \ldots \ldots, \ldots., \ldots., \ldots (IEQ_{indexn} \times \frac{A_n}{A_{total}})\right. \qquad \mathbf{3.32}$$

Figure 3.29 graphically illustrates the method used to assess more than one office / office complex.

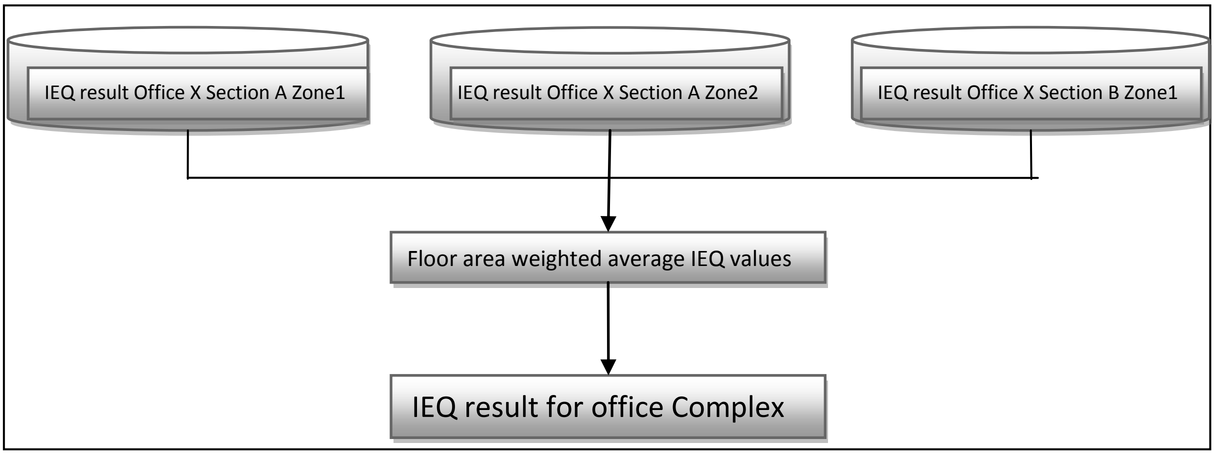


Figure 3.29 Methodology for Assessment of Multiple Offices

3.6 CONCLUSIONS

The IEQAT has great potential to offer a long lasting solution to the problem of single index IEQ based assessment of office buildings in the UK and worldwide. The main challenge is to discover how much influence each of the four contributing factors has on the overall perception of IEQ. Results from Chiang et al's Analytical Hierarchy Process (Chiang and Lai, 2002) provide some insight into the relative importance of each of the contributory factors. However the information needs to be verified and the tool developed in this chapter needs to be optimised using selected case study office buildings. The methodology used to verify the tool is described in Chapter 4 while Chapter 5 provides results of the case studies.

4. Research Methodology

INTRODUCTION

The major purpose of this chapter is to outline the approach (methodology) used to discover how much influence each of the predictors (proposed indoor environment variables) have on perceived IEQ in office buildings. The exercise will help determine the relative importance of each of the variables in determining perceived IEQ in the UK context and hence help improve the IEQ tool proposed in Chapter 3. The chapter covers research study design, selection of sample buildings, questionnaire design, measurement of physical variables including equipment used and data analysis.

4.1 RESEARCH DESIGN

4.1.1 Selection of Research Design

Research design is defined by Trochim and Donnely (2006) as “a general plan” or “glue that holds the research project together”. Several types of research designs have been proposed in literature (Rogosa, 1978; Cook and Campbell, 1984; Trochim and Donnely, 2006) and they are generally classified into three broad categories, namely the true experiments, quasi-experiments and non experiments, depending on whether certain criterion is met or not. In this thesis a flowchart illustrated in Figure 4.1 shows the decision process followed in order to determine which type of experiment to use for the study. The solid lines indicate the path followed in the selection of the appropriate type of experiment.

Figure 4.1 also shows that in studies where units (objects under investigation) are "randomly assigned" to treatments (conditions that they are subjected to) then true experiments are used. Random assignment refers to a technique that is used for assigning subjects to different treatments (or no treatments) and this technique is mainly used in situations where causal inferences are to be made (cause-effects studies). This technique is a very common feature in many scientific studies.

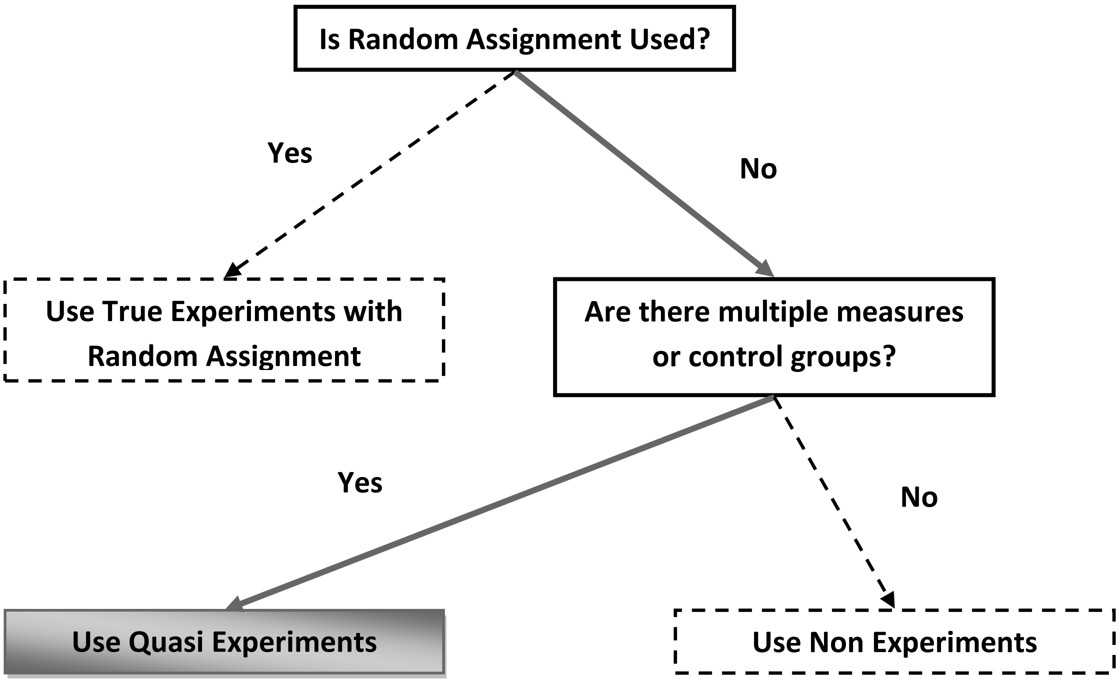


Figure 4.1 Categories of Research Designs, Source: adapted from (Trochim and Donnely, 2006)

The use of random assignment is possible mainly in laboratory settings but it is less frequent in the case of field settings such as in this study where humans are used in place of objects**.** For that reason and as explained in Cook and Campbell's 1984 text book on Quasi Experimentation (Cook and Campbell, 1984), we reject this approach. More information on the use of random assignment is found in literature (Merton, 1968) and will not be pursued further in this thesis.

Other types of study designs had to be considered and these included non experiments and quasi experiments (Figure 4.1). Non experiments are designs used in studies where no multiple measures or control groups are used, and again in our study office occupants were subjected to several IEQ parameters and this approach was rejected. Campbell and Cook (1984) placed special emphasis on a third type of experiments that have treatments, outcomes and experimental units, but do not use random assignment to create comparisons from which treatment caused change is inferred. These types of experiments have been referred to as quasi experiments and they can be used in prediction, correlation and causal studies.

Quasi experiments are traditionally divided into three groups, i.e. the non equivalent group designs, interrupted time series and correlational designs. Non-equivalent group designs are designs in which responses of a treatment group are measured before and after treatment for example, the effects of changing the temperature of a room by one degree Celsius on thermal comfort is measured before and after a central heating system is turned on. Interrupted time series methods are designs in which the conditions are measured at many time intervals before a treatment and then the measures taken at many time intervals again after the treatment has been administered. For example IEQ acceptability or thermal comfort is measured daily for a month then measured again daily for a month after a working cooling system in put in place. Correlational methods most often refer to efforts at investigating co occurrence (or causal inference in some cases) based on measures taken all at one time with differential levels of both effects and exposures to presumed causes being measured as they occur naturally without any experimental intervention.

The investigation of the effects of indoor environment conditions on an individual’s perception of the indoor environment in an office building is an example of a research study that is carried out in a natural setting. Correlational designs are relatively easy to conduct although they leave the actual reasons for association between dependent and independent variables quite unclear. More credibility is attributed to tests based on actual field studies as they are deemed to be more representative of the natural situation (Cook and Campbell, 1984).

Passive Observational Methods (POM) are forms of correlational methods that deal with "investigating covariance or inferring cause based on observations of concomitances and sequences as they occur naturally without the obvious advantages of deliberate manipulation and controls associated with experiments" (Cook and Campbell, 1984). In these methods manipulable controls are substituted with naturally occurring ones, nevertheless the aim is to discover whether variables covary or not, and whether there is any correlation or not.

POMs can also be used on non equivalent groups i.e. groups that differ from each other in many ways other than the presence of the treatment or phenomena whose effects we are trying to investigate. For example, in this study human subjects in the indoor environment have many different characteristics that make them respond differently to indoor environment conditions. Such characteristics would otherwise be absent when dealing with say, human manikins, etc. Quasi experimentation is by no means a way of justifying the use of inferior research designs, it is a powerful tool that can be used effectively in field studies in social sciences and engineering alike (Lowe, 2009). Before the process of developing the structure of the study design begins a clear distinction between the use of passive observational approaches to describe events, infer causal relations and to forecast or predict outcomes had to be made. This distinction is also explained in Campbell & Cook (1984). Moreover one can find explicit distinctions between predictive regression (forecasting) and structural regression (cause-effect) as explained in Trochim and Donnely (2006) and Panacek and Thomoson (1995) respectively. Descriptive statistics are fairly straight forward and they will not be explored further in this section.

It is alleged by Panacek and Thomoson (1995) that recent applied statistical analyses in social research have ignored any distinction between forecasting and causal inference with devastating effect . For purely forecasting purposes, it will not matter what the true causal path is as long as the predictor acts as a symptom (Vasconcelos et al, 1998; Merton, 1968; Lowe, 2009). In this case the area of interest is in how "powerful" each predictor is in predicting the acceptability of the indoor environment regardless of whether the presumed causal variable is a complex composite of which only a part produces the correlation.

However in causal inference it is important for a "treatment" given to an individual or group to "work", i.e. to be abrupt, precisely dated and probably cause change, as if it was a planned intervention (true experiment) (Nelder and McCullagh, 1989). A methodical development of correlational studies is presented in Section 4.1.2.

4.1.2 The Methodological Basis of Correlational Designs

The methodology begins with a case in Figure 4.2 (a) where no distinction is made between dependent and independent variables, and no prior knowledge is supposed for the interrelations among predictor variables ($X_{1\text{-}5}$), and the dependent variable (O). Correlational research designs are founded on the assumption that reality is best described as a network of interacting and mutually causal relationships where a web of relationships in which everything affects or is affected by everything else exists. Thus, as a rule the dynamics of a system (how individual parts of the whole system affect other parts) is more important than causal relationships as seen in Vasconcelos et al (1998)'s Path Analysis Approach for the Multivariate Analysis of Infant Mortality Data.

In Figure 4.2 (b), variable *O* can be determined as dependent or influenced by the others i.e. X_{1-5}. When no distinction is made between dependent and independent variables, factor analysis (exploratory and or confirmatory shown in **F**igure 4.2 (c)) is the adequate model to use. This statistical procedure identifies underlying patterns of variables and their interrelations. When a large number of variables are correlated and high inter-correlations are present then a common underlying factor may be present.

Once confirmation of independent and dependant variables is carried out or prior knowledge of the relationship is known (This is the point where this research begins) the need to determine whether the aim of the research is to infer cause, determine covariance or investigate correlations becomes important. Two designs used to make cause-effect statements using correlational methods are path analysis and cross-lagged panel designs.

These methods are not described in this research but they can be found in Cook & Campbell (1984) and they are also written about extensively in literature (Nelder and McCullagh, 1989; Karunaratne and Elston, 1998; Wong et al, 2007; Hahn and Soyer, 2005; Movellan, 2003; Fairfax County Department of Systems Management for Human Services, 2003). For regression and predictive modelling (correlational) the most appropriate method is the Multivariate Regression analysis. The path followed in the selection of the multivariate regression model is highlighted in Figure 4.2.

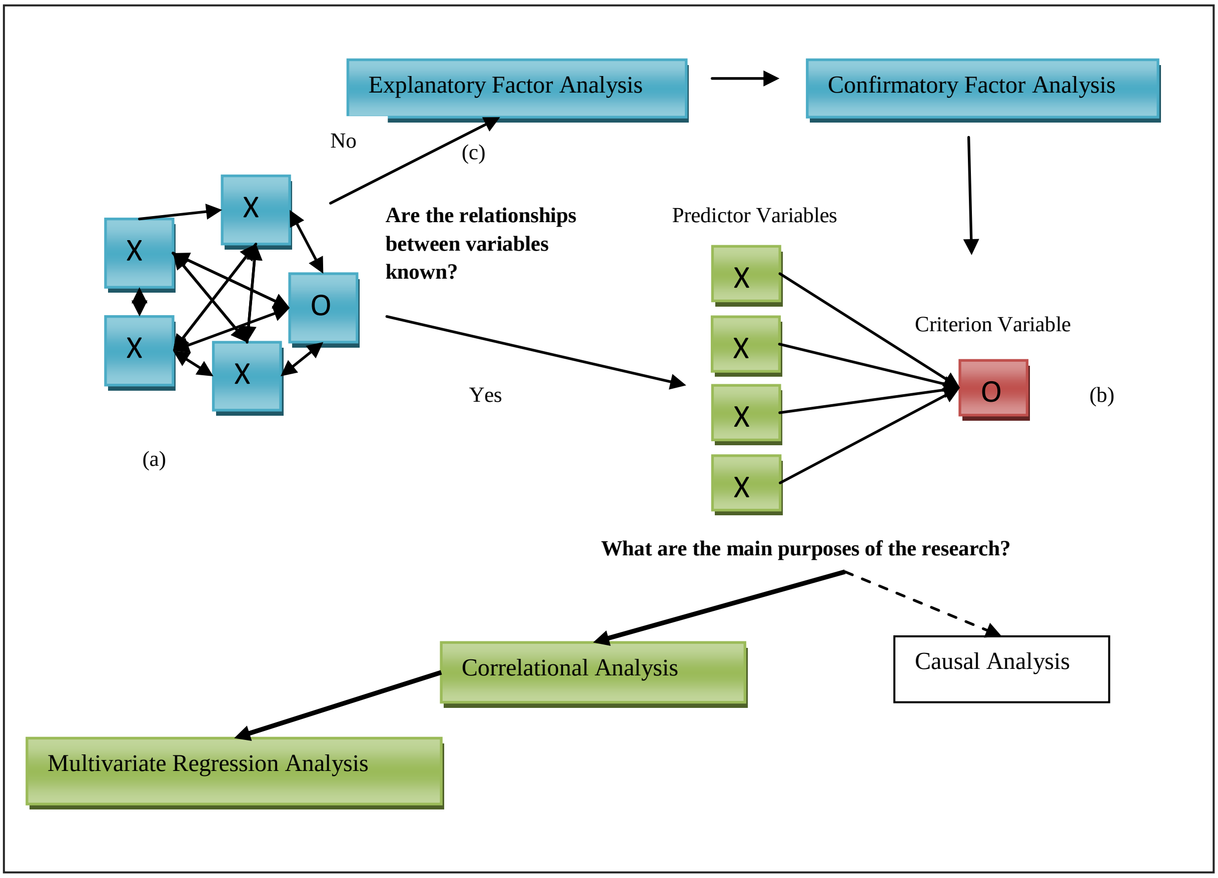


Figure 4.2 Methodological Basis of Correlational Studies, Adapted from: (Vasconcelos et al, 1998)

4.1.3 The Design Notation

Design notation is a technique used to graphically summarise complex design structures efficiently and this method is used effectively in social sciences. Design notation is easy to follow and the symbols used are relatively easy to understand. For purposes of clarity the design notation used in quasi experimentation will be employed here.

The design notation is as follows:

- Observations or Measures are symbolized by an 'O';
- Treatments or Programs are symbolized with an 'X';

- Groups - each group in a design is given its own line in the design structure;

- Assignment to Group - Assignment to group is designated by a letter at the beginning of each line (i.e., group) that describes how the group was assigned (The major types of assignment are ‘R’ = random assignment, ‘N’ = non-equivalent groups and C = assignment by cut-off); and
- Time - time moves from left to right or elements that are listed on the left occur before elements that are listed on the right.

The design structure begins by assuming that passive observational analysis takes the form of post-test only designs, with non-equivalent groups or the so called ex-post facto design (Trochim and Donnely, 2006) , i.e. in this study the observations are made after a treatment – which is the exposure of individuals to indoor environment conditions. The design notation for this study is shown in Figure 4.3.

	X	**O**

Where $$X = \begin{cases} X_1 = \text{Thermal Comfort} \\ X_2 = \text{Indoor Air Quality} \\ X3 = \text{Acoustic Comfort} \\ X4 = \text{Lighting Comfort} \end{cases}$$

O **= Indoor Environment Quality (IEQ)**

Figure 4.3 Design Notation for Occupant Exposure to IEQ Conditions

This is the simplest form of design which would otherwise be uninformative as far as causal inference is concerned but highly useful for predictive correlational studies. As one can see the groups are subjected to a treatment (indoor thermal conditions, air quality issues, acoustics, lighting and workspace design conditions) and observations (IEQ acceptance) are made thereafter. At first glance the notation appears to reflect a non experiment, however since we study more than one office and each office is subjected to different IEQ conditions, then the study ceases to become a post test only quasi experiment. In the next section the selection of sample buildings is discussed.

4.2 SELECTION OF SAMPLE BUILDINGS

In this study representative samples were drawn from a wide list of Hoare Lea and other offices across the UK. Sampling was necessary because it provided a cheaper, faster and practical way of studying office buildings (Campbell and Stanely, 1963).

The samples were selected using the probability sampling (stratified) approach because of the following advantages over non random sampling:

- It allows us to calculate the precision of the estimates obtained from the sample and to specify the sampling error; and
- It allows us to generalise the sample results to the target population

Probability sampling is also more accurate than a census of the entire population because the smaller sampling operation lends itself to the application of more rigorous controls, thus ensuring better accuracy (Fairfax County Department of Systems Management for Human Services, 2003). These rigorous controls allowed the reduction of non sampling errors such as non response problems, questionnaire design flaws, and data processing and analysis errors.

Sampling was especially important for questionnaire administration because a relatively long and difficult questionnaire could be administered to a sample more easily than a relatively short and simple questionnaire can be administered to the entire population (Campbell and Stanely, 1963). The samples that were selected consisted of offices that were different from each other in many important ways and this is crucial if sound generalizations to the target population are to be made (Oppenheim, 1992; Wong et al, 2007). Before doing this there was need to start by defining what characteristics or levels were typical of office environments (target population) in the UK. In general offices are defined by at least one of the following characteristics:

- Office design - type of office e.g. open plan, cellular, its orientation, the type (open plan or cellular), floor level, the level of furnishings, age of property, building fabric, the spatial arrangements of walls, partitions, and equipment in relation to fixed elements like windows and heating, ventilation and air conditioning. This leads to the grading of offices into grade A, B and C. **Grade A** offices are spacious and furnished with high-quality finishes, flexible layout, large floor plans, well decorated lobbies and circulation areas, effective central air conditioning, good lift services zoned for passengers and goods deliveries, professional management, and parking facilities are normally available; **Grade B** offices are of ordinary design with good quality finishes, flexible layout, average-sized floor plates, adequate lobbies, central or free-standing air-conditioning, adequate lift services, good management, and parking facilities are not essential; and **Grade C** offices are those plain with basic finishes, less flexible layout, small floor plates, basic lobbies, hardly any central air-conditioning, barely adequate or inadequate lift services, minimal to average management and no parking facilities (Wong et al, 2007);

- HVAC system in place – whether offices are naturally ventilated, mechanical, mixed mode or have personalised ventilation systems (PVS);
- Design parameters – Temperature, lighting, acoustics, IAQ, vibration, day lighting ranges (values) allowable for purposes of design or based on IEQ criteria used; and
- Location – whether they are located in urban (towns, cities, conurbations), peri urban (locations surrounding urban centres, between rural and urban areas) or rural areas (villages, hamlets, countryside), the actual city or region where they are sited, whether they are in a university campus, military base, airport terminal, etc.

Typical offices were then categorized into the following mutually exclusive groups from which three were selected:

- Mechanical or naturally ventilated offices;
- Grades A, B or C offices;
- Urban or Rural Location;
- Design standards employed e.g. part L Building Regulations 2006, etc, related to date built; and
- Cellular or open plan type.

The Granby House office in Nottingham, the Marsh-Growchoski & Associates office suite and the Leeds Town Centre House were selected. The resulting variation is illustrated in Table 4.1 and the specific characteristics of selected case study buildings are discussed in Chapter 5. The results of the three buildings are not expected to provide enough information from which generalisations across other office buildings in the UK can be made. They will however provide a good foundation on which future studies can be made and these could include multi level analysis of a large number of office buildings (e.g. > 500 observations (Nemes et al, 2009)) followed by multi level analysis.

Table 4.1 Specific Characteristics of Selected Case Study Buildings

Case Study Building	HVAC System Present	Office Grade	Office Type	Design Standards
Granby House, Nottingham	Mixed mode	A	Open Plan	Post 2006
Leeds Town Centre House	Mechanical	A	Open Plan	Post 2006
Lace Market Bng.	Natural	C	Large Cellular	Pre war

The most ideal situation would be to pick the "correct" individuals within buildings in order to assess how subjective opinions of IEQ varied among subjects. The "correct" group included healthy adults of any gender. Awareness of subject heterogeneity issues when selecting subjects from across buildings i.e. what makes people comfortable is different across persons would also help explain any discrepancies in results. Heterogeneity issues included the effects of gender, age, ethnic origin and cultural aspects. These personal characteristics and other kinds of characteristics such as local climate opinions or cultures were assessed via the questionnaire.

The problem with this approach is that the selection of individual units (people) from certain buildings would lead to clustered observations (dependence caused by physical, geographical or social proximity) which apparently violates the assumption of independent observations (Lowe, 2009).

Violation of this assumption would lead to the following consequences:

- Violation implies that the information from each IEQ observation ‘overlaps’ or ‘duplicates’ to some extent the information from other ones, making the total amount of information smaller than if the observations had been independently selected. In other words the ‘effective’ number of observations is smaller than the number of individual respondents;
- If non-independence is ignored estimated standard errors become too small, and hypothesis testing becomes too lenient (the so called alpha-inflation); and therefore the estimated IEQ coefficients or weightings may be biased;
- Ignoring the factors causing non-independence results in poorly specified models and again in biased coefficients (omitted variable bias); and
- Since clustering implies the distinction of different levels at which the empirical world can be described one needs to redefine the relationship between characteristics of units at a different level, a higher level, i.e. we need to use multi level analysis methods.

Such distinctions have been explicitly used since 1897 (Campbell and Stanely, 1963). Multi level modelling has its limitations. It is only a potential solution for violation of the assumption of independent observations, not for all other kinds of problems (violations of other assumptions, sampling defects, measurement defects, etc.) We therefore need to assess whether we need multi level modelling or not as it could yield very little difference in some cases. Multi level analysis will be discussed further in Chapter 6.

4.3 DATA COLLECTION EXERCISE - THE QUESTIONNAIRE

4.3.1 Motivation for the Questionnaire

The overall aim of the questionnaire was to identify patterns in the relationship between IEQ rating and the proposed predictor variables. The questionnaire was needed to identify and collect occupant's subjective opinion of the microclimatic conditions of the space in which they worked. It also needed to capture the occupant's opinion (rating) of the indoor environment and their opinion of several parameters that are thought to influence perceived IEQ at their workstations.

Only those occupants (group) who were present in the offices on the days of the survey were asked to complete the questionnaire to facilitate monitoring. All respondents were pre warned five months in advance and then reminded a week before the actual survey was carried out. The questionnaires were completed while occupants worked in their respective work stations. The questions took approximately 10 – 12 minutes to complete and the responses were collected and analysed later. Monitoring of IEQ parameters affecting comfort was carried out throughout the working day using standard equipment as explained in Section 4.4.2. In this way the data collected from the occupants could be compared to field measurements hence the questionnaire results could be validated.

Contradictions between survey and measured data could arise due to poor positioning of field sensors, low accuracy of apparatus collecting physical data and poor questionnaire structure. In some cases the health and well being of respondents (sensitivity to internal environment parameters or lack of due to disease, etc) could also affect subjective responses. Such factors would be considered where inconsistencies in the data existed. Once the questionnaire results were validated using field measurements, regression analysis could be used to determine the relative weightings of each of the four main parameters affecting IEQ hence the proposed IEQ model could be improved or verified. The model however cannot be used to replace current building regulations or standards, but it can be used as a guide on how much sacrifices in human comfort could be associated with proposed energy efficiency measures.

A group administered questionnaire method was used to collect data because it:

- is fast;
- is a low cost technique that required little in terms of equipment and personnel;
- offers high response rates since questions are handed out and collected after the exercise (personal contact);
- is fairly easy to judge the quality of the responses; and
- It is also possible for respondents or the administrator to make clarifications where necessary (Hahn and Soyer, 2005).

The disadvantages of the questionnaire methods include lack of quick turnarounds which limits the number of questionnaires that can be administered by one individual (the administrator). Long questionnaires are also not always possible as they can be costly, time consuming, demand more effort from the respondents and may lead to poor responses or unreliable responses (Campbell and Stanely, 1963; Cook and Campbell, 1984). Although no issues with privacy are expected the questionnaire responses needed to be made as anonymous as possible, and this was explained to the participants. Open ended questions were generally avoided, except in optional circumstances where clarifications of responses were required, as responses could be confusing to the statistician (Trochim and Donnely, 2006). Lack of open ended questions however could mean the freedom and spontaneity of answers is lost. The opportunity to probe even further could also be lost.

Post Occupancy Evaluation Methods (POEM) in buildings employ a range of techniques such as questionnaires, interviews, focus groups, measurement and observation. Questionnaires are commonly used in buildings studies to get feedback about the indoor environment from the occupants. In the UK the Building Use Studies (BUS) questionnaire is the most common tool used to evaluate IEQ, health, wellbeing and productivity of occupants against well established benchmarks. BUS questionnaires have been used to assess comfort in green buildings and the results of such studies have helped eliminate past mistakes that have caused poor indoor environment conditions in those buildings (Leaman and Bordass, 2007). A comprehensive study carried out in office in the city of Melbourne used the BUS study questionnaire and it highlighted that the productivity of office building occupants can potentially be enhanced through good building design, and provision of a high quality, healthy, comfortable and functional interior environment, that takes account of basic occupant needs (Paevere and Brown, 2008). This adds to the fact that questionnaires play an important part of building assessments because they provide feedback on the actual performance of buildings.

The Stockholm Indoor Environment Questionnaire is a standard social questionnaire that was developed to assess indicators of indoor environment such as air quality, thermal climate, noise and illumination (Engvall et al, 2003). The questionnaire was tested and validated with much success in 350 apartments in Sweden confirming that it can be used as a tool of choice for decision makers when making priorities and identifying ”risk” buildings.

Questionnaires have also been used in many other studies comparing subjectively assessed IEQ to model assessed IEQ as explained in Chapter 3 (Wong et al, 2007, Lai et al, 2009, Leaman and Bordass, 2007; Paevere and Brown, 2008). The EN15151 standard contains sample question structures that should be used when assessing IEQ in buildings and in this thesis the “types” of questions used are based on recommendations of the standard (EN15251, 2006).

4.3.2 Questionnaire Structure

The Questionnaire is divided into two sections. Section 1 tries to assess the influence of perceived thermal comfort, indoor air quality, acoustic, visual & workplace design on the overall IEQ during a particular season of the year. [Heating season (November - April) and Cooling season (May - October)]. Section 2 contains personal factors such as occupant level of satisfaction with the tasks or their general motivational levels. These questions will be optional but they may help to explain any discrepancies that may exist between field measurements and subjective opinions of respondents.

SECTION 1

This section is about building comfort.

Question 1 asks about the details of a particular building. The name of the building, the floor and the season will help explain the conditions the occupants found themselves in. Clear floor plans are provided for respondents to determine the exact location of their workstations. This will help explain environmental conditions prevailing within each area and help correlate to field and simulation results. This will also help validate the answers given by the respondents and hopefully indicate any variations in perceived comfort levels with floor level, building location, season, microclimatic conditions, etc.

Q**uestion 2** asks respondents to provide an indication of whether or not they accept the environment they work in. This question provides an insight into the quality of the building’s indoor space (all proposed five factors plus other contributing factors) and is a result of factors such as the performance of the buildings' HVAC system, the performance of the building fabric, the orientation and location of the building, floor levels, the "state of mind" of the occupants, etc.

A dichotomous assessment scale will be used to determine the respondents' acceptability of the quality of the indoor environment (IEQ). The questions will be phrased such that they will be easier to understand and respond to by the occupants, for example "Is the IEQ of your work environment acceptable to you?" with dummy variables 0, 1 (0 = No; 1 = Yes) as answer options is self explanatory. Providing a dichotomous scale will help make a clear cut distinction between acceptability and non acceptability of the conditions. This will help avoid overlapping answers or confusion when analysing data. The validity of their responses (dummy variables) will be assessed using a parallel Visual Analogue Scale (VAS) (Houser and Tiller, 2003). A validity check question "How would you rate the quality of the indoor environment in your work area?" (Indicate your answer using values 1 = Poor to 5 = Good; on the Visual Analogue Scale; would help verify responses.

Q**uestion 3** asks for direct feedback on their perception of the thermal environment. An ASHRAE assessment scale (Benton et al, 1990) which is based on the semantic differential scale, and which takes into account clothing levels, activity levels, dry bulb temperature, mean radiant temperature, relative humidity and air flow rates is provided for mechanically ventilated office. Semantic differential scales are based on the understanding that people use evaluation, potency, and activity to evaluate words and phrases (Trochim and Donnely, 2006). In this questionnaire "evaluation" is used to describe thermal comfort. A VAS which is used to evaluate naturally ventilated offices buildings is provided at the end of the questionnaire.

Question 4 asks office occupants to provide direct feedback on their level of satisfaction with the background noise (acoustic comfort) in their work spaces using a Visual Analogue Scale (VAS). In this scale respondents are asked to specify their level of agreement to a condition or statement being asked by indicating a position along a continuous line between two extremes (Oppenheim, 1992).

Question 5 asks for feedback on satisfaction with the lighting environment which is a rather interesting challenge. In the first part of this question the respondents give feedback on their levels of acceptability of the lighting environment (lighting comfort) especially on the working plane. We use a Visual Analogue Scale (VAS) as a response scale. The question specifically requires a subjective opinion of the level of satisfaction with the "amount" of light (illuminance) received on the working plane because general lighting comfort may involve many aspects such as directionality, glare, colour rendering and the amount of natural light.

The second parts require feedback on the amount of natural light entering the workspace. This is particularly important in determining the relative importance of natural lighting to the comfort of office workers.

Question 6 asks office occupants to provide direct feedback on their level of satisfaction with the quality of indoor air (including levels of pollution perceived) in their work spaces using a Visual Analogue Scale (VAS). In this scale respondents are asked specify their level of agreement to a condition or statement being asked by indicating a position along a continuous line between two extremes.

Question 7 asks office occupants to provide direct feedback on their level of satisfaction with the quality of design of their work spaces using a Visual Analogue Scale (VAS). This includes spatial arrangements, size of workspace, aesthetics, quality of furnishings, etc. Like in questions 4 - 6 respondents are asked specify their level of agreement to a condition or statement being asked by indicating a position along a continuous line between two extremes.

Question 8 asks about discomfort caused by the presence of any local discomfort factors. This question will help eliminate any influences due to the presence of local discomfort factors.

SECTION 2

The effects of personal characteristics such as gender, age, ethnic origins, cultural aspects and beliefs (idiosyncratic issues) are required to help validate the subjective, quantitative data given in section 1. There is an influence of subject heterogeneity that needs to be generalised across samples, i.e. what makes people comfortable is different across persons.

For example specifying the gender of the occupant may help to explain potential differences in opinion of the buildings thermal performance due to differing dress codes or simply gender. Age and health may also play a role in a person's perception of the indoor environment but these effects will be addressed further in the multilevel analysis of data in future studies. Please refer to Appendix 2 for the actual questionnaire.

To investigate how occupants perceived their indoor environment at "that time" a questionnaire was administered during the working days after every worker had had time to settle down and adapt in some way to their environment. In order to verify the responses spot checks of IEQ parameters was carried out on the working plane, about 0.8m above the floor level as shown in Figure 4.4.

The working plane was a representative measuring point for every individual.

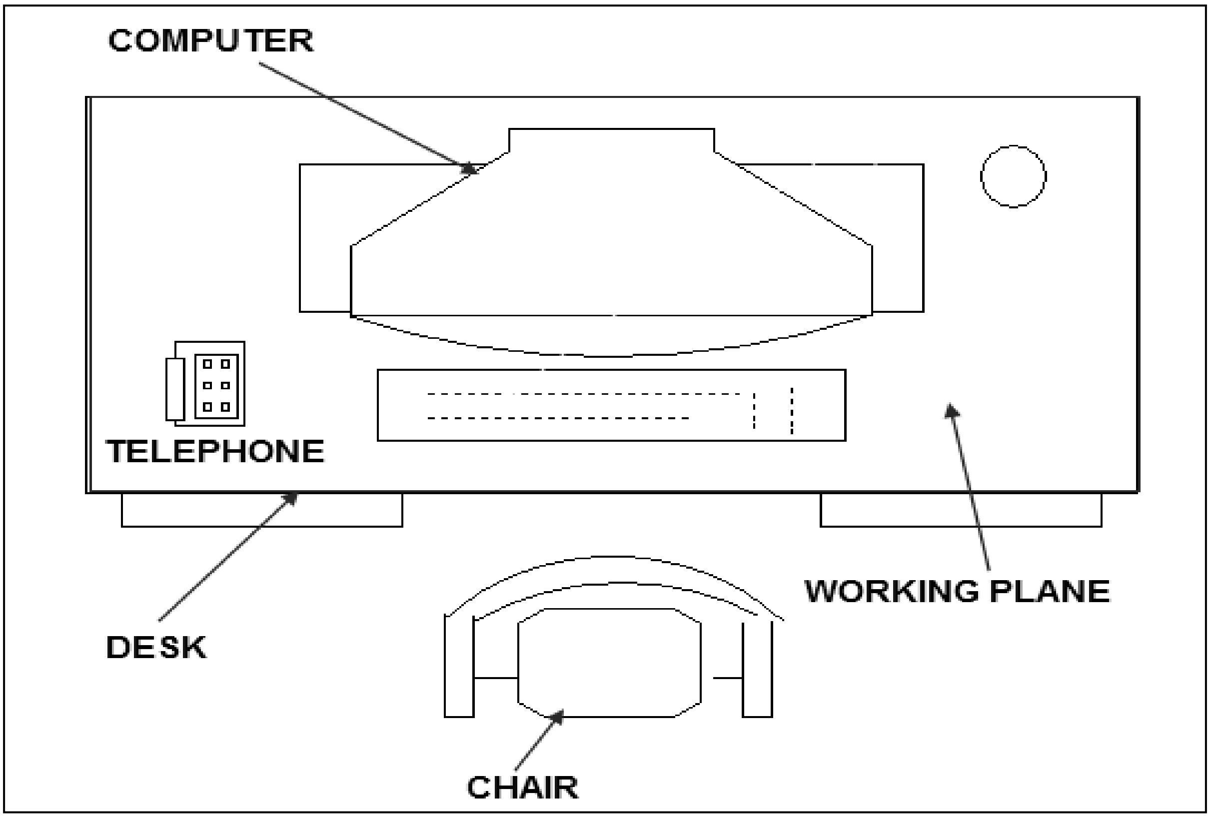


Figure 4.4 Diagram showing typical layout of the working plane

4.4 DATA COLLECTION EXERCISE – PHYSICAL MEASUREMENTS

Monitoring of the indoor environment parameters was carried out during questionnaire administration in order to check the validity of the responses given by occupants. The measured data was used to calculate microclimatic conditions prevailing in each work space using the proposed IEQ model. The indoor microclimate varies in both space and time across rooms and buildings due to, for example uneven distribution of heat or ventilation air by the HVAC systems (Stanton et al, 2004). A converging-operations approach where subjective assessments from the questionnaire are compared against measured quantities was introduced in order to determine whether questionnaires provided a true reflection of the prevailing comfort conditions in the building. Spatial considerations were taken into account and instruments were strategically placed to represent the actual location of the worker or a group of workers in a space (Benton et al, 1990). Therefore we can say the space was divided into units similar to a grid with each workstation representing a unit area (within the grid). Studies by Wong et al and others have also identified the working plane as the best to locate sensors (Wong et al, 2007).

Temporal considerations were also of paramount importance if we were to understand the patterns that existed in those spaces throughout the day, for example data on daily temperature profiles in the Leeds office had to be collected for at least a full day prior to the monitoring exercise to get a "feel" of the temperature distribution within the office. The reliability of the data collected depends on the instruments used to collect the data and the measurement strategy adopted as explained in the previous chapter. For example early thermal comfort variables measurement instruments had wider ranges of error than those available today, particularly those for measuring air velocity (CIBSE, 1986). However, it is generally accepted that modern thermal sensors are adequately accurate, especially if they are selected and used in accordance with guidelines (ISO-7726, 1988) provided by professional organisations and standards (ASHRAE, 2005; EN 15251, 2006). A detailed description of instrumentation used to evaluate indoor environment conditions is presented in Section 4.4.2.

4.4.1 Parameters to Measure

Thermal Comfort Parameters

The relative accuracy of the PMV model depends on the reliability of the four physical inputs, the instruments used to collect the data and the measurement strategy adopted. The most recent methods employ better techniques such as taking repeated measurements in large and representative sample of locations (Charles, 2003) therefore the validity of the PMV model is not seriously compromised by measurement error.

Six parameters affecting thermal comfort in intermediate thermal environments have been identified in Chapter 2 as air temperature, mean radiant temperature, humidity, air velocity, clothing levels and activity levels (metabolic heat production) (Fanger, 1973). The parameters are measured in order to compute PMV and PPD values which can then be compared with questionnaire data. Table 4.2 is a summary of thermal comfort parameters that were measured, the data collection points and data collection procedures used.

Table 4.2 Thermal Comfort Parameters Investigated

Measure	Sampling Season	Sampling location	Data Collection Method
Air Temperature	Heating/Cooling	Working Plane (Head level)	Continuously data Logged
Mean Radiant Temperature	Heating/Cooling	Working Plane	Assumed to be equal to Air temperature*
Relative Humidity	Heating/Cooling	Working Plane	Handheld instruments that allow multipoint logging
Air Velocity	Heating/Cooling	Working Plane	Continuously data Logged
Clothing Levels	Heating/Cooling	Working Plane	Direct observation
Activity Levels	Heating/Cooling	Working Plane	Direct observation

*Assumption that no significant variation in air temperature and mean radiant temperature – potential source of error.

Clothing insulation is measured in units of 'clo' (Gagge, 1940). Establishing the insulating properties of clothing is a time-consuming and detailed process that is usually conducted in laboratory experiments devoted to this purpose. As it is not practical to directly measure clothing insulation in most thermal comfort studies, researchers generally estimate these values using tables that have been developed from clothing insulation studies (ASHRAE, 1992).

Some researchers assume an average clo value for all occupants, based on the season and climate of the study location, and typical clothing ensembles for office work (typically 0.35-0.6 clo in summer, and 0.8-1.2 clo in winter). Clothing insulation levels in this study were obtained by completing the occupants complete garment checklist, which was then used to select a more appropriate clo value for the group, (or separate clo values for each participant).

Activity level is measured in terms of metabolic rate, or 'met' (Gagge, 1940). The most accurate method for determining met is through laboratory studies, where heat or oxygen production is measured for participants conducting specific activities (Havenith, 2008; Olesen and Parsons, 2002; Parsons, 2008). Alternatively, the participant's heart rate can be measured and compared to previously developed tables of heart rate for specific activities. All of these methods, however, are time-consuming and invasive, and are generally not practical for use by thermal comfort researchers. Instead, these researchers rely on estimates, based on tables of met rates for specific activities and occupations, developed from laboratory studies (EN-ISO7730, 2005). In most studies, an average met rate is assumed for the group (usually 1.2 met for sedentary office work). Met values were estimated in this study by observing occupants as they carried out their normal duties (activities) and the information obtained was used to develop a more accurate average for the group, (or individualised met estimates for each participant).

Other Parameters – IAQ, Lighting and Acoustics

Carbon dioxide concentrations were collected at strategic locations at working plane level (see Figure 4.1) to determine IAQ and pollution due to bio effluents. Illuminance levels (lux) were also measured on a working plane in order to estimate the levels of both artificial and natural lighting received in the offices. A-weighted sound levels were used to estimate the levels of background noise within the spaces. An analysis of the source and nature of the background noise will also be analysed using critical listening. Table 4.3 is a summary of IAQ, lighting and acoustics parameters that were monitored.

Table 4.3 Summary of IAQ, Lighting and Acoustics monitored

Measure	**Sampling Season**	**Sampling location**	**Data Collection Method**
Carbon dioxide concentrations	Heating/Cooling	Working Plane	Continuously data Logged
Iluminance	Heating/Cooling	Working Plane	Handheld devices, Continuously data Logged
Background Noise Levels	Heating/Cooling	Working Plane	Handheld devices

4.4.2 Monitoring Exercise and Equipment Used

Hardware used in this exercise consisted of a data logger connected to several analogue sensors. The sensors were wired to the data logger limiting the distance between the two and forcing the data collection exercise to take longer and forcing the use of handheld devices to carry out spot measurements in other parts of the space. The University of Nottingham only orders instruments from suppliers with a good track history in supplying top of the range instruments. The equipment and software used are explained in the following paragraphs.

The Data logger DT500 Series – Logging Data

Figure 4.5 Datataker DT 500 3 series data logger

A Datataker DT500 data logger (3 series) with adequate memory capacity (1,390,000 data points) and up to 37 channels was used to log room air temperature, illuminance, CO_2 concentrations and air velocity during the monitoring exercise. The data taker was calibrated in February 2010. The DT500 is DC powered with voltages ranging from 11 to 24Vdc. It also has an internal 6V battery that can last up to 10 hours between charges making it possible to move the data logger between sites without interrupting data logging activities. An additional internal back up battery (3V, 1/2AA lithium) is available for internal data storage back up. The data logger supports a wide range of sensors including thermocouples, RTDs, Thermisters and Bridge sensors. The accuracy details of the DT500 are as follows:

- Measurement of DC Voltage is at approx 0.15% at 25°C and 0.25% between -45 and 60°C;
- Measurement of DC Current is at approx 0.25% at 25°C and 0.35% between -45 and 60°C; and
- Measurement of DC Resistance is at approx 0.20% at 25°C and 0.30% between -45 and 60°C.

The accuracy details of the data logger are well within required limits hence the choice.

Thermocouples

Temperature sensing thermocouples were connected to the datalogger. Sensors used included five one metre long T-Type thermocouples (RS instruments) with PTFE welded tips, capable of measuring air temperature in the range -50 to 250°C (accuracy ±0.15°C at 21°C). The thermocouples have bare ended termination tips to increase sensitivity to temperature at specific points. A K-Type thermocouple capable of measuring air temperatures ranging from -20 to 70°C (accuracy ±0.7°C at 21°C) was also used. The image below is a picture of the T-Type thermocouple used during the exercise.

Figure 4.6 T Type Thermocouple from RS instruments

Lux Sensors - lighting

Skye Instruments SKL 2630 type (pyranometer) Lux Sensors capable of measuring illuminance in the range 0 – 500kLux were used to measure illuminance on a horizontal plane. The sensor was connected to the data logger via wires.

The pyranometer was calibrated on the 26 of June 2009. The skye lux sensor is a high output high grade silicon cell which has the following features:

- Cosine corrected sensor head;
- Silicon photocell detector with low fatigue characteristics;
- Filters made of Optical glass;
- Has a completely sealed head therefore can be left exposed indefinitely; and
- No maintenance required once calibrated.

The picture below shows one of the lux sensors used to monitor illumination in the office buildings.

Figure 4.7 SKL 2630 Lux Sensor, from Skye Instruments

The CO_2 and the Air Velocity Sensors – IAQ/Thermal Comfort

A Vaisala GM 220 CO_2 transmitter which can measure CO_2 concentrations in the range 0 – 5000ppm (30ppm+2% of the reading) was connected to the data logger to monitor IAQ. The transmitter was factory calibrated and was designed to last a lifetime of 10 years without calibration (factory delivered new on the 17th of May 2010). The instrument has an accuracy of ± (1.5% of range and +2% of reading) and has a long term stability of two years. An Omega Engineering temperature and Air velocity Transmitter (FMA1000) capable of measuring air velocities ranging from 0 – 5.1 m/s and data logging was used. It has an accuracy of 1.5% full scale. The FMA1000 was factory calibrated and delivered on the 1st of April 2010. Figure 4.8(a) below shows the FMA1000 CO_2 transmitter.

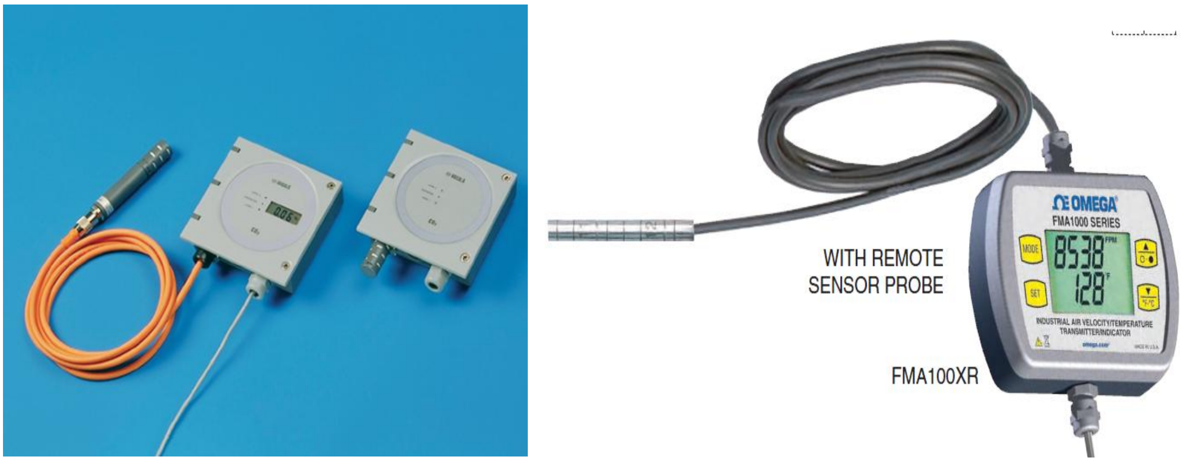


Figure 4.8 Vaisala GMT220 (1) Series and the OMEGA FMA-1000 CO_2 transmitter

The Hagner Digital Lux Meter - Lighting

Spot Checks equipment included a handheld Hagner digital Lux meter with an external detector which can measure illuminance over a range of 0.01 to 20,000lux. The detector is connected to the main instrument via a 2m cable and it is fully cosine corrected for the spectral sensitivity of the human eye in accordance with the CIE standard. The light sensitive device used in the detector is a very stable, long-life silicon photo diode detector which performs to a high reliability and minimizes the necessity of recalibration.

The instrument is powered by a 9V type PP3 battery and is calibrated every year with the most recent calibration done on the 12th of February 2010. Its accuracy is better than ±3% (±1 in the last digit on the 4 digit display) and the operating temperature ranges from -5° - +55°C. The Hagner digital Lux meter instrument is shown in Figure 4.9.

Figure 4.9 Hagner digital Lux meter

The 4 in 1 Multifunction Environment meter – Temperature, Humidity, Background Noise, Lighting

The 4 in 1 Multifunction Environment meter is a handheld instrument that was used for spot measurements. The meter is designed to combine the functions of sound level meter, light meter, humidity meter and temperature meter. The light function is cosine corrected for angular incidence of light and the light sensitive component is a stable, long life silicon diode. Temperature and humidity are measured using a K-type thermocouple and a semiconductor respectively. Sound is measured using a special microphone attached to the instrument and all measurements are displayed in a digital screen. The instrument can measure both A and C-weighted sound pressure levels. A picture of the instrument is shown in Figure 4.10.

Figure 4.10 The 4 in 1 Multifunction Environment Meter

Table 4.4 shows some of the specifications of the instrument.

Table 4.4 Specifications of the 4 in 1 Environment Meter

	Sound	Lux	RH %	Temp
Range	35-130dB	0~20,000	25~95%	-20~+750°C
Resolution	0.1dB	0.01 Lux	0.1%	0.1°C
Accuracy	±3.5dB	±5%	±5%RH	±3%Rdg +2°

The Humidity and Temperature Probe meter

The Humidity and Temperature Probe meter is a low cost handheld instrument that acted as back up during spot measurements. The main features of the instrument include:

- Rugged thermo-hygrometer with integral probe for convenient one-hand operation;
- Fast response time and quality performance;
- Illuminated LCD screen;

- User selectable °C / °F;
- Data Hold, Min/Max Function and Auto shut off; and
- Carrying case and battery included.

The specifications of the instrument are shown below.

Table 4.5 Specifications of the Humidity and Temperature probe meter

Range:	**Humidity: 0% to 100% RH**
	Temperature: -20°C to 60°C (-4°F to 140°F)
Accuracy:	Humidity: ±3.5% RH
	Temperature: ±2°C, ±3°F
Resolution:	0.1% RH, 0.1°C(0.1°F)
Battery:	PP3 9V
Dimensions:	225(h) x 45(w)x 34(d)
Weight:	200g

The Humidity and Temperature Probe meter is shown in the picture below:

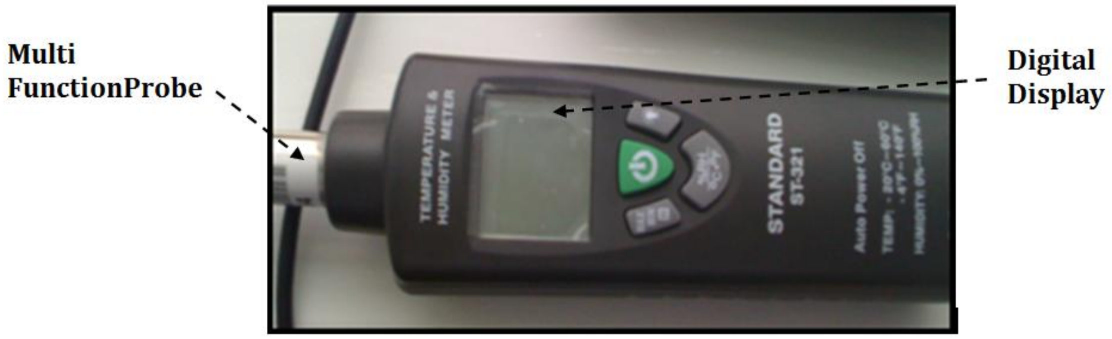


Figure 4.11 Hand held Humidity and Temperature Probe Meter

Five T-Type thermocouples, one K-Type thermocouple, a CO_2 transmitter, a lux sensor, an air velocity meter and a potentiometer were connected to the datalogger for the monitoring exercise. The data collected in the datalogger was processed by a computer equipped with a delogger software. Figure 4.12 below shows a typical data logging set up while figure 4.13 is a photograph of the data logging setup taken at the Leeds Town Centre house.

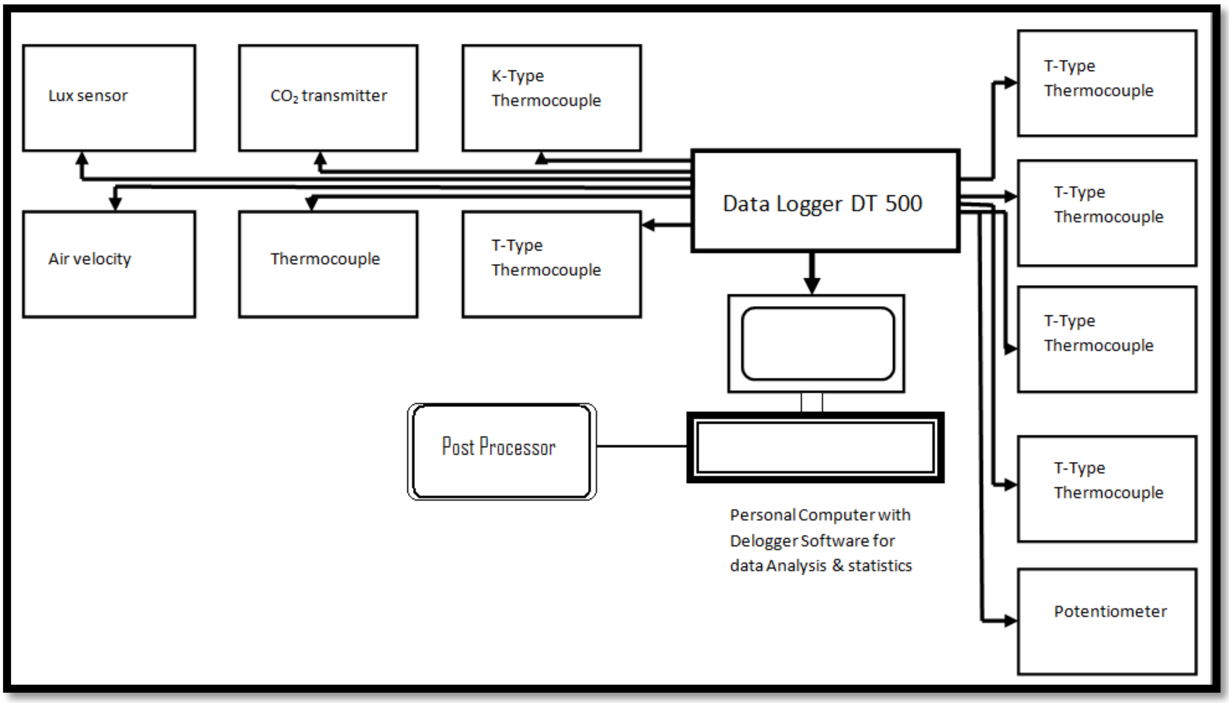


Figure 4.12 Typical Data Logging Set Up

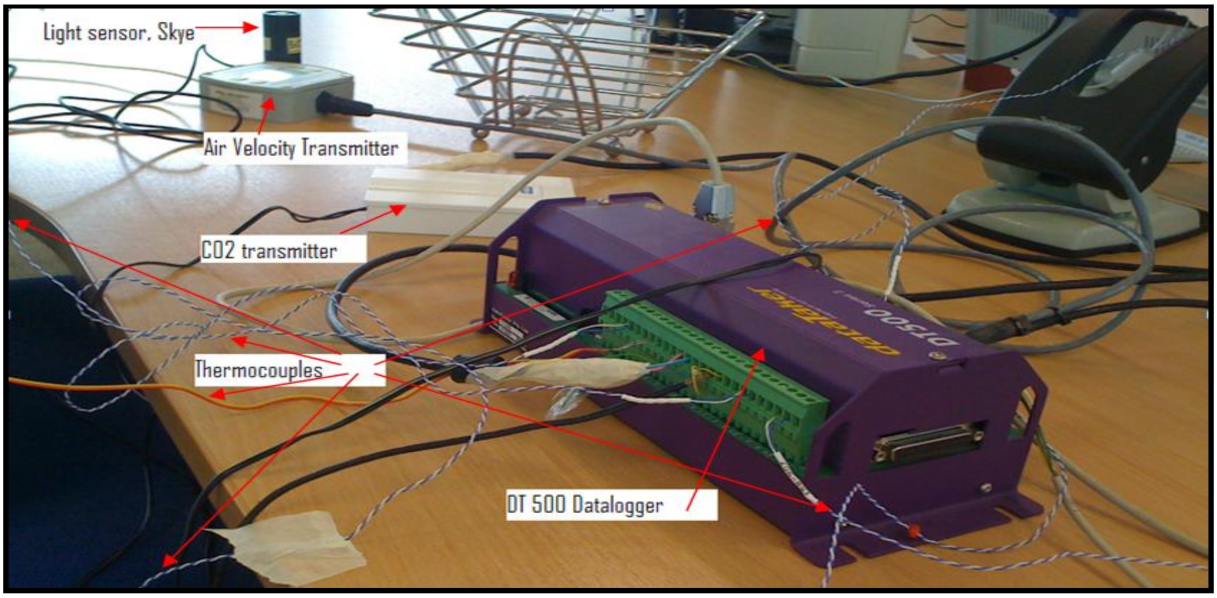


Figure 4.13 Picture of the Data Logging Set Up

The Delogger Software

The Delogger software is a windows application that was used to enable communication, supervision and data return from the DT500 data logger. It provides a powerful graphical programming and data presentation software is suitable for the DT50 / DT500 / DT600 / DT800 Series of datatakers. The software enabled easy setup, allows one to monitor sensors and alarms while logging data. The software can also display real time or logged data in the following views:

- Charts and trend plots with zoom and multi-variable capabilities;
- Mimics (analogue meters only) and text formats;
- Tabular and raw text data for simple reporting;
- Spreadsheet capabilities similar to Microsoft™ Excel;
- Unloads data to replay files and spreadsheets; and
- Supports local RS-232 direct, or Ethernet connections to dataTaker data loggers.

Software set up begins with the selection of the program (.dlp program shown by the arrow) which allows the users the users to build data collection programs. Building programs involves setting up schedules for the data logger to take readings, setting up of any trigger alarms, adding channels in the same program and the addition of all other specifications. Channels ranging from analogue to digital, to user defined types can be added in this program builder window and labelled accordingly. Figure 4.14 shows a typical program builder window of the delogger software.

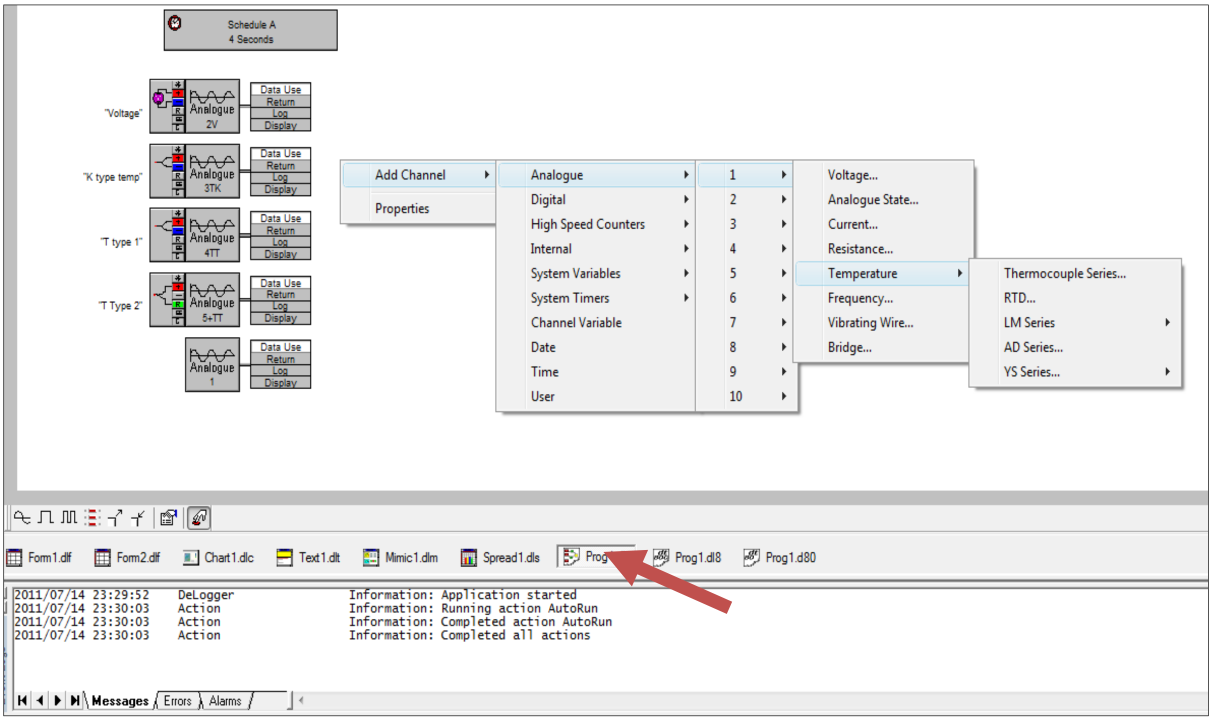


Figure 4.14 typical program builder windows

A typical user interface showing the graphs and data from the software is shown in Figure 4.16.

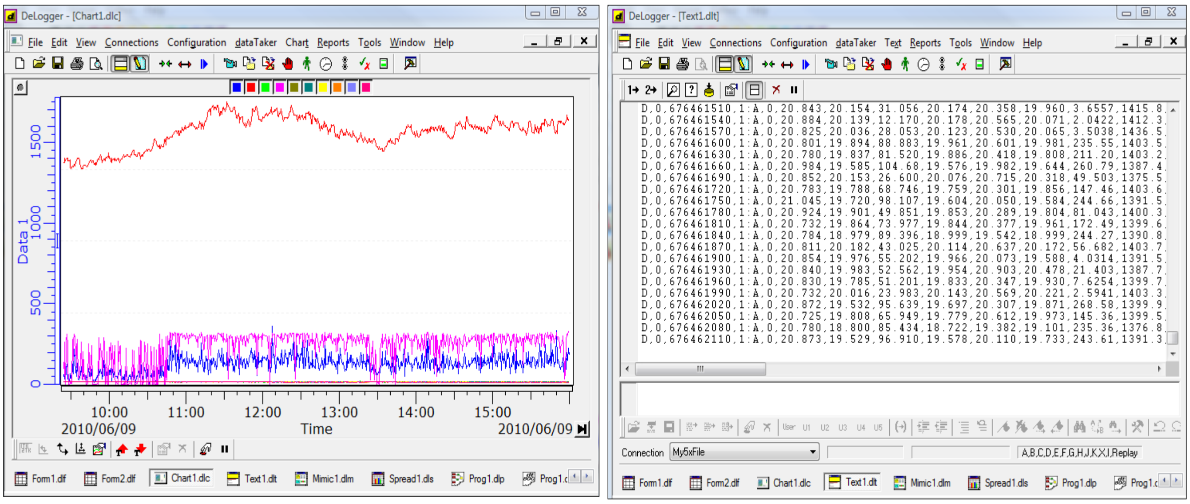


Figure 4.15 Typical Software Interface (graphical and data outputs)

4.4.3 Monitoring Layout & Positioning of Sensors

Office buildings were first divided into sections as illustrated in Figure 4.16. Places marked as Sections consisted of office areas which were separated from each other by means of partitions (as shown in Figure 4.16) or floor levels. The sections were further divided into zones which consisted of clusters or groups of workers who congregated around a specific point such as a set of desks or table. In the example diagram Zones 1 and 2 consist of a cluster of 2 occupants each. Zones were finally divided into positions (P1, P2… etc) where each individual worked (workstations).

The data taker was connected to its sensors through wires and the average length of connection was 1.5m. This restricted the amount of space that the sensors could cover and forced the use of handheld devices to cover areas not reached by the datalogger – sensor "bundle". The sensors were placed strategically on a working plane causing minimal disruption to the worker.

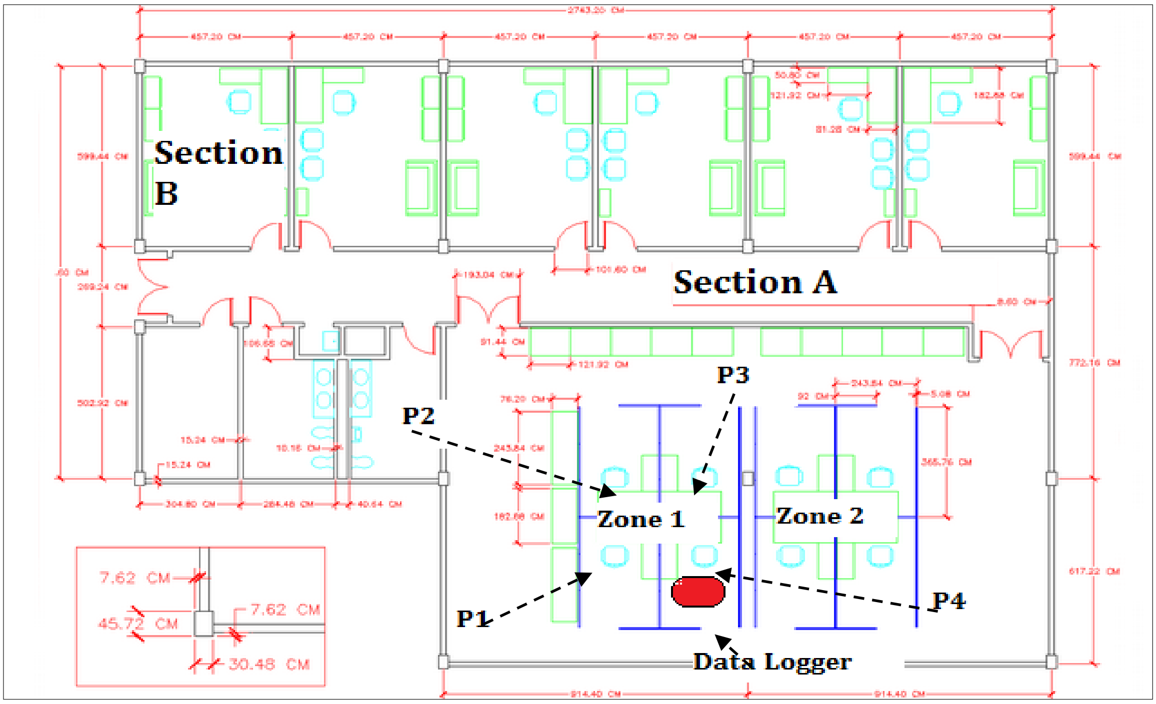


Figure 4.16 Typical Office Divided into Sections, Zones and Positions.

Some of the thermocouples were placed at different heights above floor level in order to help check for the presence of vertical temperature differences within the occupied space. A typical data collection arrangement on a working plane is illustrated in Figure 4.17.

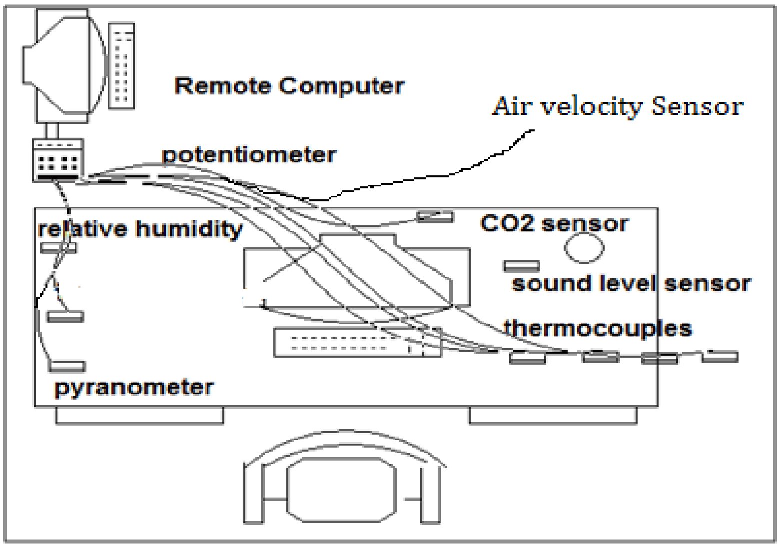


Figure 4.17 Data Collection set up on a Working Plane (Not exact layout)

The arrangement shown in Figure 4.17 was put into operation for the duration of the day and repeated in another Zone the following day. This was complemented with spot checks in order to ensure readings for various positions could be compared and a significant amount of time could be saved.

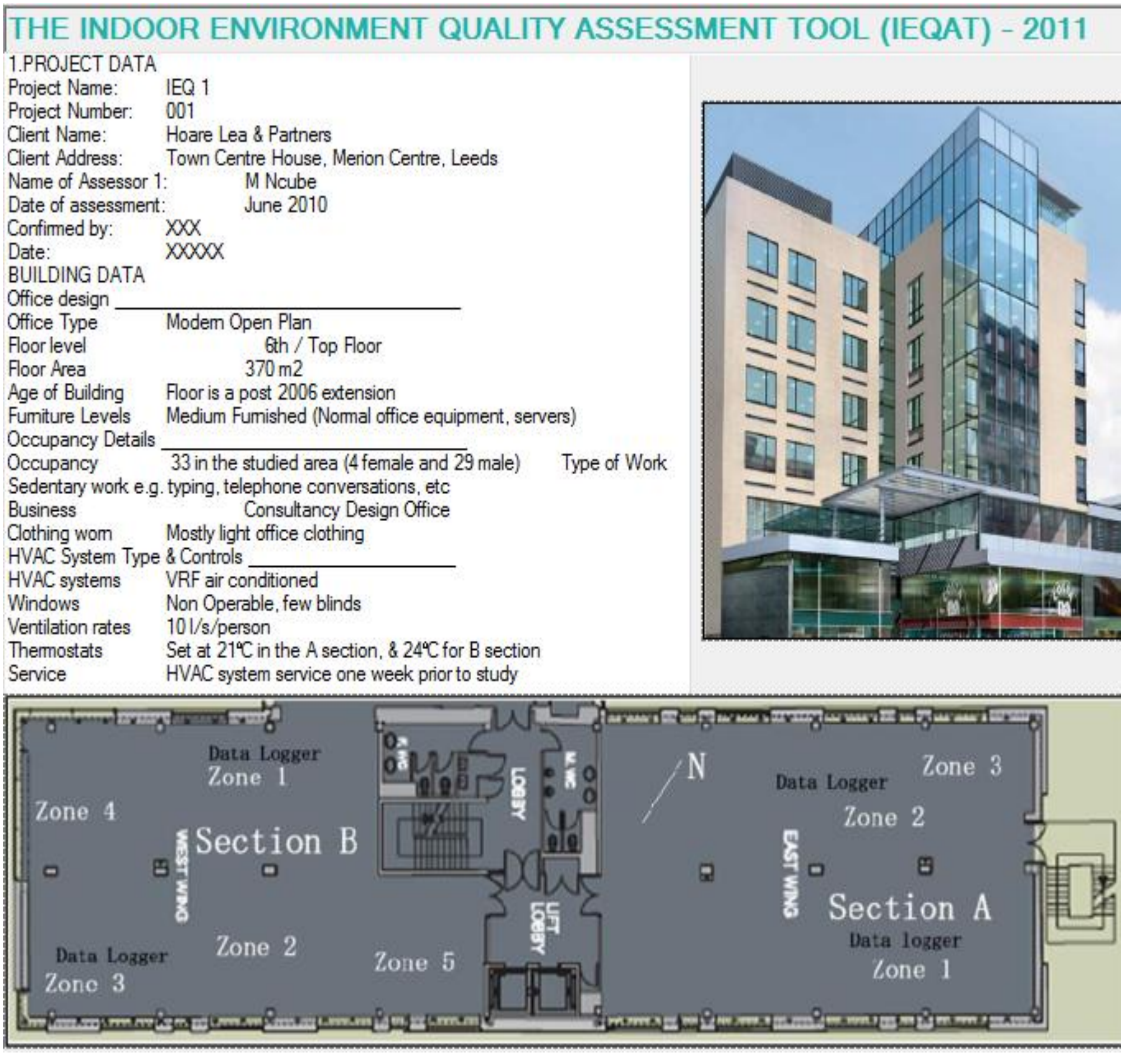
5. Results and Tool Evaluation

5.1 CASE STUDY 1: LEEDS TOWN CENTRE HOUSE

The office studied comprises modern facilities on the top floor (6^{th} floor) of Town centre House, Merrion Shopping Complex, at Leeds City Centre. The office is a light and airy open plan office. It is split into sections with a reception, bespoke meeting rooms, kitchenette or breakout areas linking the two areas. The elevated position of the building benefits the office from daylighting as well as providing excellent views across Leeds. The building is served by state of the art VRF cooling and heating system which incorporates heat recovery. This newly clad building has increased levels of insulation and reduced air leakage. It boasts a striking Yorkshire Stone façade, energy efficient passenger lifts, 24 hour CCTV security and Office Hours commissionaire.

About 1,100 car parking spaces are available within the Merrion Shopping centre. The building is fitted with LG7 (CIBSE, 2006) compliant Drop Rod Lighting System which uses a Passive infra-red (PIR) lighting system which automatically switches off lights where no movement is detected. Lights also adjust to the level of natural lighting entering the building thereby maintaining adequate light levels throughout a working day. One section (Section A) of the building is currently predominantly occupied by 8 people whilst the other (Section B) is occupied by 25 people. The sections were further split into monitoring zones, three in section A and 5 in section B.

The total floor area of the office occupied by the 33 respondents was 370 m^2 and the floor to ceiling height is 2.9m. The office was occupied by mostly by white-collar workers consisting of engineers and designers. Most of them performed sedentary work such as typing, filing, drawing, telephone conversations and they wore light office clothing. It is medium furnished and has several workstations with consisting of drawer desks and computers and filing cabinets at the edges of the occupied space along the walls. The HVAC equipment is serviced every three months by the supplier and had been serviced 6 days before the data collection exercise was carried out. A more detailed description of some of the features of the building and its activities is given in the assessment sheet presented in Figure 5.1.


THE INDOOR ENVIRONMENT QUALITY ASSESSMENT TOOL (IEQAT) - 2011

1.PROJECT DATA
Project Name: IEQ 1
Project Number: 001
Client Name: Hoare Lea & Partners
Client Address: Town Centre House, Merion Centre, Leeds
Name of Assessor 1: M Ncube
Date of assessment: June 2010
Confirmed by: XXX
Date: XXXXX

BUILDING DATA
Office design
Office Type: Modern Open Plan
Floor level: 6th / Top Floor
Floor Area: 370 m2
Age of Building: Floor is a post 2006 extension
Furniture Levels: Medium Furnished (Normal office equipment, servers)
Occupancy Details
Occupancy: 33 in the studied area (4 female and 29 male) Type of Work
Sedentary work e.g. typing, telephone conversations, etc
Business: Consultancy Design Office
Clothing worn: Mostly light office clothing
HVAC System Type & Controls
HVAC systems: VRF air conditioned
Windows: Non Operable, few blinds
Ventilation rates: 10 l/s/person
Thermostats: Set at 21°C in the A section, & 24°C for B section
Service: HVAC system service one week prior to study

Figure 5.1 Project and Building Data – Town Centre House - Leeds

The weather conditions for the Leeds City Centre area during the three survey days were obtained from the UK metoffice (Met Office, 2010) and weather underground (Weather Underground, 2009) websites. The weather data is summarised in Table 5.1.

Table 5.1 Weather in Leeds during Data Collection, Source - Weather Underground

(Weather Underground, 2009)

Date	Weather summary
09 June 2010	Av. t_a = 11 ; Av. t_{dp} = 11; Av. RH = 100; Partially Cloudy, midday-afternoon, fog
10 June 2010	Av. t_a = 10 ; Av. t_{dp} = 10; Av. RH = 98; Partially Cloudy, midday-afternoon, drizzle
11 June 2010	Av. t_a = 12 ; Av. t_{dp} = 9; Av. RH = 81; Scattered Clouds for most of the day

5.1.1 Thermal Comfort Assessment

The sixth floor space of the Leeds Town centre house was divided into 2 Sections and 8 Zones as described in section 5.2.1 and each zone represented an occupied area (cluster of occupants) with a unique microclimate. A full day was dedicated for the preparation of equipment as explained in chapter 4 and another day was also dedicated for data collection in each section of the office. An extra day was allocated for additional tests such as the overnight logging of temperature and CO_2.

PMV values were computed for the 8 Zones in both Sections A and B using a single set of measurements obtained during the questionnaire administration period as input. A specially designed Visual Basic (VB) Thermal Comfort Program (see Appendix 1) was used to carry out the calculations. The following assumptions were made in the calculation of PMV:

- 1.2 met (58.15Wm^{-2}) to represent a standard occupant doing general sedentary office work such as typing, filing, and talking on the telephone;

- 0.6 clo to represent typical light office clothing ensembles consisting of shirt and trousers, socks and light shoes; and

- Mean radiant temperature *(t_{mrt})* was taken to be equal to air temperature *(t_a)*.

The results of the PMV calculations are summarized in Table 5.2 and they indicate thermally unfavorable conditions across the office at the time. The results also show a slight variation from one cluster (position) to another mainly due to differences in microclimatic conditions within the office.

Table 5.2 PMV Values Calculated Using the VB Thermal Comfort Program - LTCH

Section	Zone	Av. Temp.**(°*C*)**	Av. Rel Humidity ***(%)***	MRT **(°C)**	Av. Air velocity **(*m/s*)**	Clo	Met	PMV
A	1	19	47.4	19	0.03	0.6	1.2	-1.44
	2	19.3	48.7	19.3	0.03	0.6	1.2	-1.34
	3	20.5	47.1	20.5	0.03	0.6	1.2	-1.01
B	1	18.3	53.2	18.3	0.12	0.6	1.2	-1.64
	2	19.7	50.2	19.7	0.12	0.6	1.2	-1.27
	3	19.6	52	19.6	0.12	0.6	1.2	-1.24
	4	19.3	52.3	19.3	0.12	0.6	1.2	-1.37
	5	20.6	51.3	20.6	0.12	0.6	1.2	-1.02

In order to verify the results of the IEQAT, thermal comfort evaluations based on occupants' subjective opinion of their workstations were obtained from questionnaire results. A total of 28 questionnaires were handed out and 26 (93%) of them were completed. One occupant suffered from arthritis and had other health problems that rendered his responses invalid. This information was kept secret to the rest of the respondents for confidentiality purposes. Of the 28 respondents 2 (7%) were female and 26 (93%) were male.

The population distribution by age for the office was as shown in Figure 5.2 and there was no observable link between voting patterns and age of occupant.

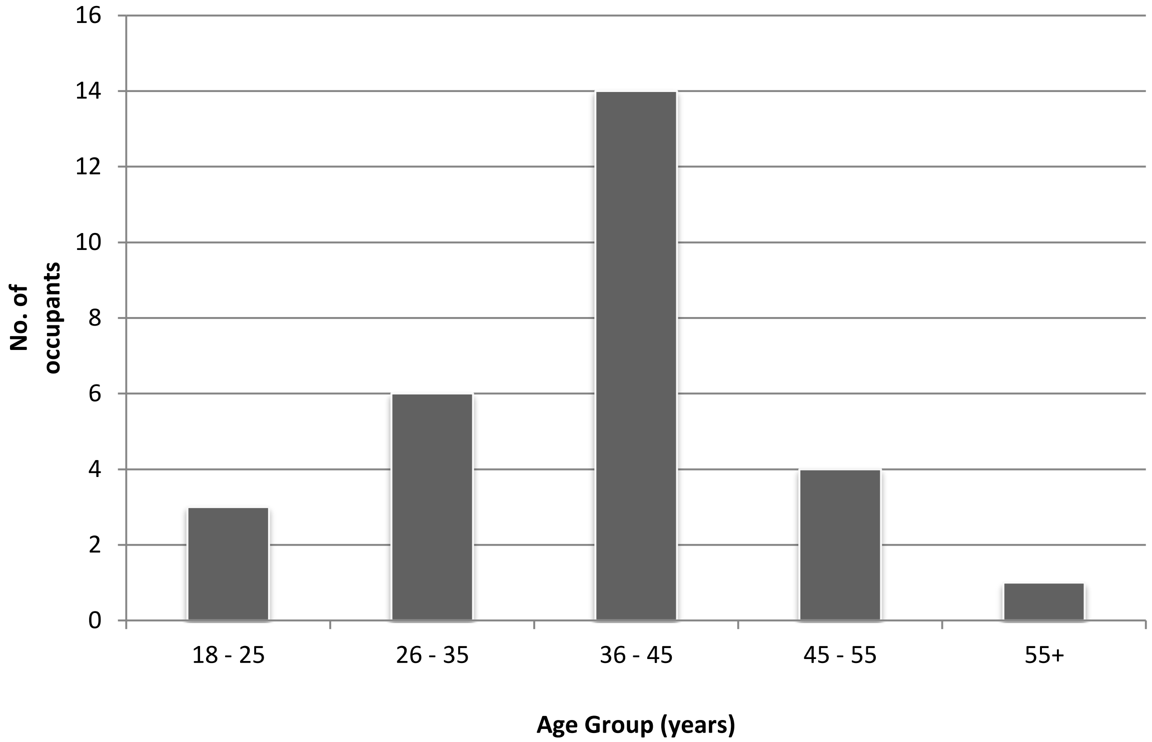


Figure 5.2 Population Distributions by Age of the Occupants of the 6th Floor Office - LTCH

Calculated thermal comfort indices agreed well with surveyed values as shown in the graph in Figure 5.3. The graph also shows that surveyed PMV votes were only slightly lower than the calculated values and more variation between individuals is observed. First this could be due to the fact that individual occupant physiology plays an important part in the perception of the thermal environment (Fiala et al, 1999; Fiala, 2008).

Secondly clothing insulation levels and metabolic heat production are quite difficult to estimate precisely (Charles, 2003) resulting in minor discrepancies between questionnaire and predicted values. On average predicted values were 0.20 more than surveyed ones indicating a slightly less precise estimation of thermal comfort variables especially metabolic rates and the failure of the PMV equation at lower temperatures. Thirdly, this could be due to different microclimates existing within the office.

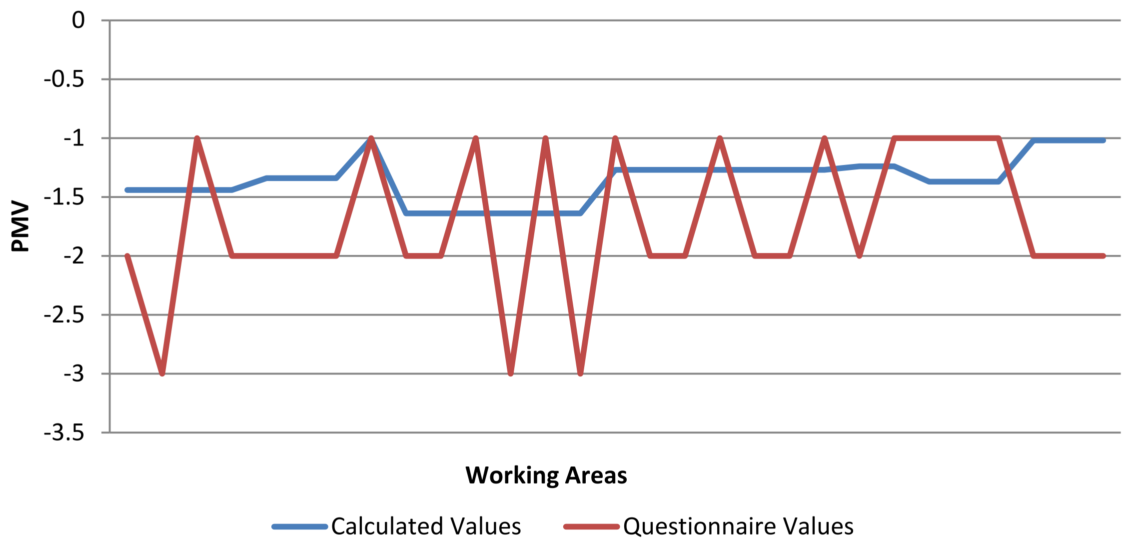


Figure 5.3 Surveyed Vs Calculated PMV Values - LTCH

The distribution of calculated and surveyed values across the office floor is shown in Figure 5.4. The distribution shows that occupants throughout the office experienced thermal discomfort with the lowest recorded value being -3 (cold) for example in Section B - Zone 1 and Section A - Zone 1, and the highest was -1 (slightly cool) recorded throughout the office space. The occupants nearer to Section B - Zone 5 and in other areas reported (observed values) slightly higher PMV values of -1 (slightly cool) compared to a calculated office average of -1.35 i.e. most occupants felt cool (see the ASHRAE assessment scale Chapter 2).

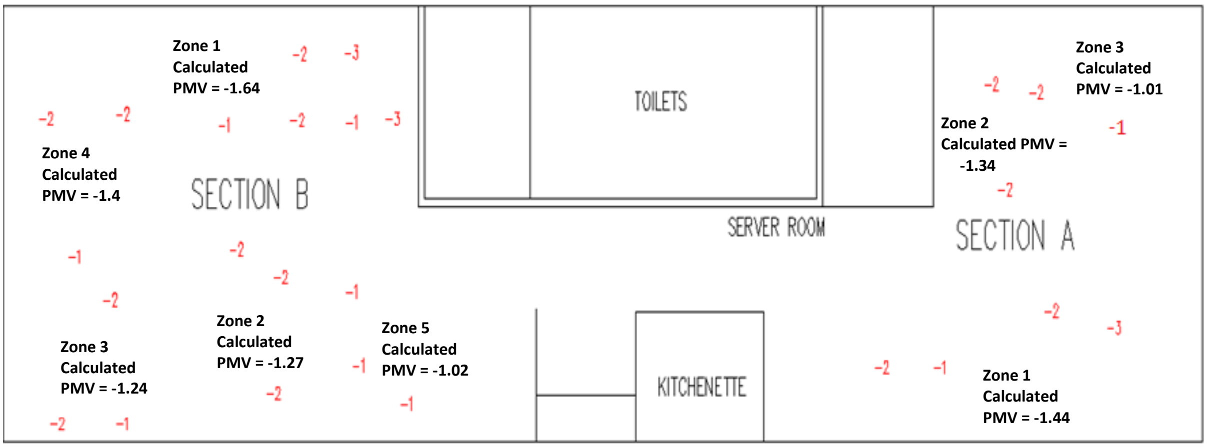


Figure 5.4 Calculated vs. Surveyed Thermal Comfort Values across Office Space - ***LTCH***

The frequency distribution of the surveyed PMV values is illustrated in Figure 5.5 and as expected, votes closer to -2 comprised the majority of the votes.

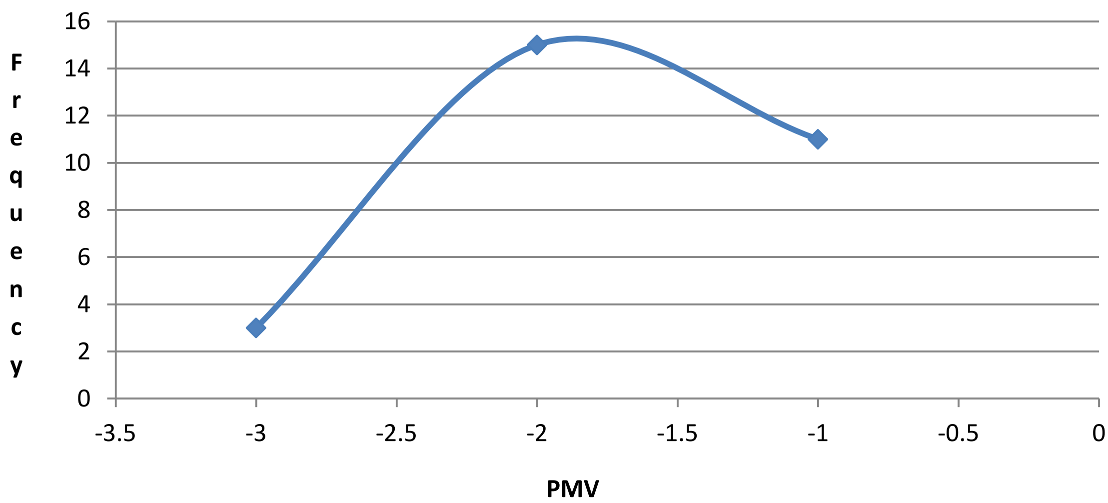


Figure 5.5 Frequency Distribution of PMV Values for Sections A and B - ***LTCH***

In order to understand thermal comfort patterns across the office temperature, air velocity and relative humidity were recorded before, during and after the questionnaire administration exercise. Temperature profiles for all zones were recorded, for example profiles for Zone 1, Section A, day 1 were recorded and they are shown in Figure 5.6. The graph shows temperatures dipping abruptly just before 11 am and again at 13:15pm. A further, yet smaller and more gradual decrease in temperature occurred after a brief period of rise and stability. This could be due to the poor positioning or poor functioning of temperature sensors in the office space. The sensors were located in the server rooms which were generally warmer than the rest of the office and which did not have any special cooling. Although sensors were set at 21°C and the fan speed was set at three, (highest) the rest of the office space recorded much lower temperatures.

The temperature recorded inside the server room was 23.8 ^{0}C at 13:10pm on the 9th of June 2010. A 2.67°C change in temperature was observed between 10:20am and 11am during day 1 and the lowest temperature recorded by the sensor positioned 0.4m above floor level was 17.07°C. Occupants expressed dissatisfaction during this period as the temperatures fell below the Building Management System´s set value of 21℃ by almost 3°C. This shows that the heating system was turned off due to sensors in the server rooms recording the correct set temperatures. As explained in Chapter 2, temperature is known to affect body heat loss by convection, conduction and radiation. As air temperature decreased body heat loss increased leading to feelings of dissatisfaction among office occupants. Mean radiant temperature was estimated to be equal to ambient air temperature in this study.

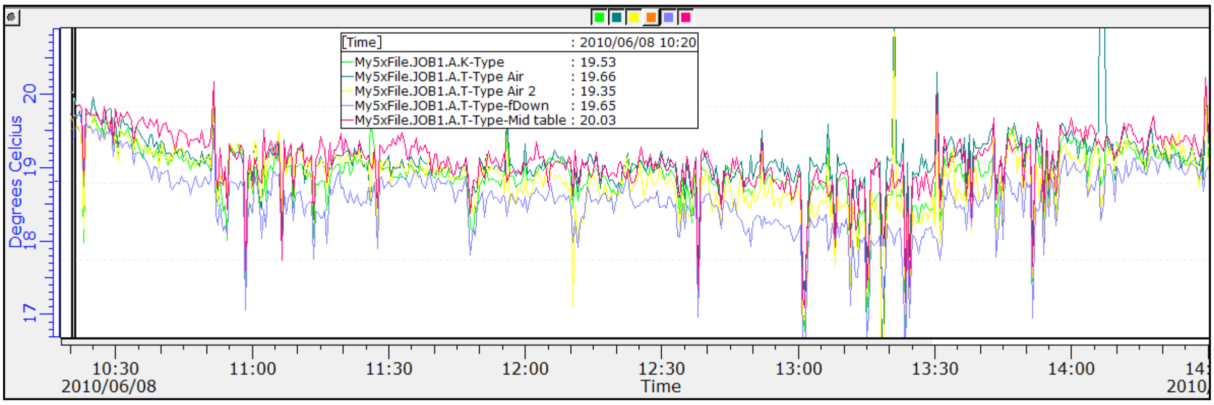


Figure 5.6 Day 1, Section A - Zone 1, Temperature Profiles (DT500) - *LTCH*

A temperature trend similar to Day 1, Section A, Zone 1 was observed in Zone 1, Section B on the second day of logging. Temperatures dropped sharply just before 11 am and continued to decrease steadily throughout the rest of the day. A 3.87 °C change in temperature was recorded between 10:30am and 11am, causing most of the occupants to adjust their levels of clothing in order to counteract the effect of the changes in the thermal environment. Transients however were not observed in Zone 3, Section B during the third day of monitoring. Temperatures remained fairly constant throughout the day with peaks around 13:00 pm.

The difference in temperatures across the office floor was thought to be the main reason for variations in thermal comfort perceived by the occupants. Average temperatures across the office were calculated and they are represented in Figure 5.7. The graph shows a general increase in temperature from zone 1 to 3 in section A. The same trend is observed as one moves from zone 1 to 5 in section B.

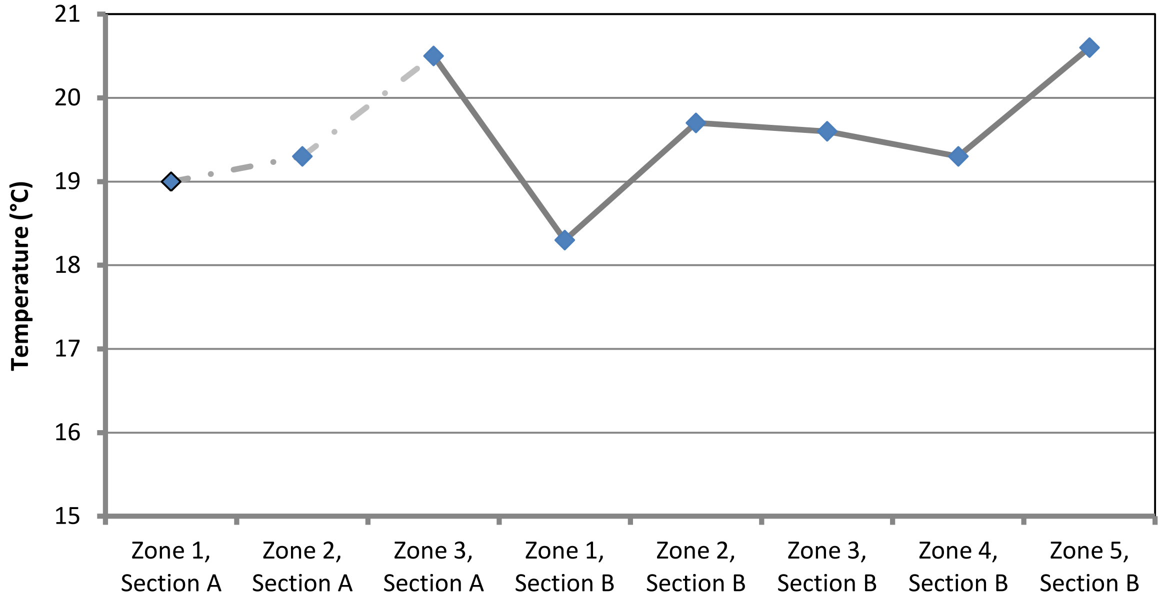


Figure 5.7 Recorded Mean Temperatures - *LTCH*

Survey results also showed that cold draughts were felt by 17 of the 26 occupants during the survey time. It has been established from literature that air movement produces a cooling effect on the skin and increased air velocities can produce a feeling of comfort even at increased temperatures (Fanger, 1973; Charles, 2003). However sudden changes in air velocities could result in feelings of draught which may lead to local discomfort especially at low temperatures. However upon investigation air velocities were only restricted to isolated peaks of less than 0.2m/s and sudden variations in temperature was thought to be the main reason why most occupants mentioned cold draughts.

Seven of the 17 occupants also recorded local discomfort due to vertical temperature differences. Vertical air temperature differences were also investigated and found to be less than 1°C. In order to check the presence of vertical temperature difference thermocouples were placed at different heights above the floor level and in section A, Zone 1 a vertical air temperature difference was observed as shown in Figure 5.8. The high number occupants dissatisfied with vertical temperature difference could be explained by the fact that the air supply grills of the VRF mixing ventilation system were positioned directly above some of the occupants, causing a cold draughty feeling (at head positions), and especially during periods of sudden drops in the temperature of supply air. This is highlighted in Figure 5.8 which shows temperature decreasing with increasing height. The difference between temperatures at 0.4 m (legs) and 1.5 metres (head, seated) was approximately 0.71 °C. People are generally less sensitive to temperatures increasing downwards compared to temperature increasing upwards (Parsons, 2008). No noticeable vertical temperature difference was observed in section B, zones 1 and 3.

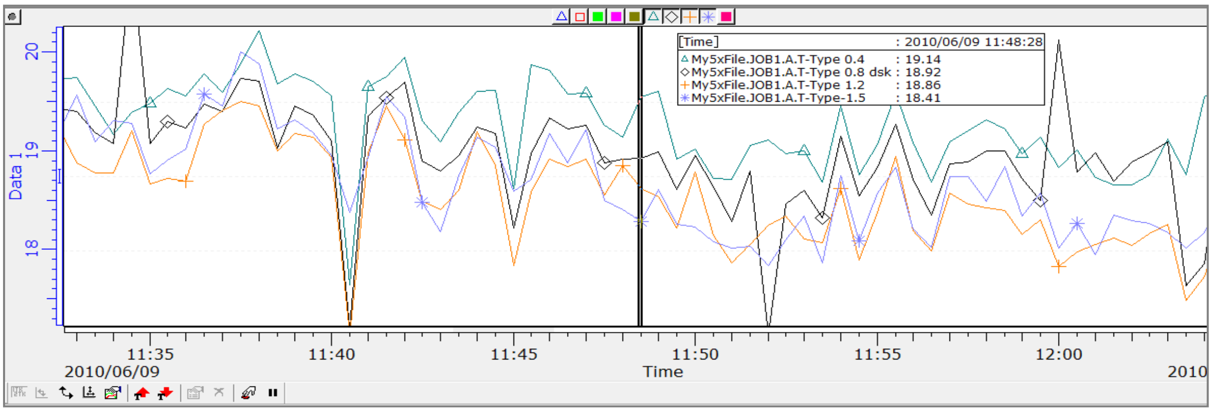


Figure 5.8 Temperature Difference with Increasing Height of Sensor above Floor Level (DT500) - *LTCH*

The average air velocities were logged and they were found to be approximately 0.03m/s in section A and 0.12 m/s in section B. This variation could only be explained either by the variation in air supply rate by the BMS program or it could be due to the positioning of the air velocity sensors relative to the air supply points and also due to the fact that the sensors were place too close to the surfaces. For example some areas such as Zone 1 in Section B lied directly below air supply grills and the areas could be susceptible even to slight changes in air flow rates.

Irregular patterns of air velocities were observed during office hours at the Town Centre House. Results for zone 1, section B (Figure 5.9) show an abrupt increase in air velocities just before 11am (survey period) and corresponding abrupt decreases in temperature as the BMS responded either to changes in the program or as a result of stimulation of sensors.

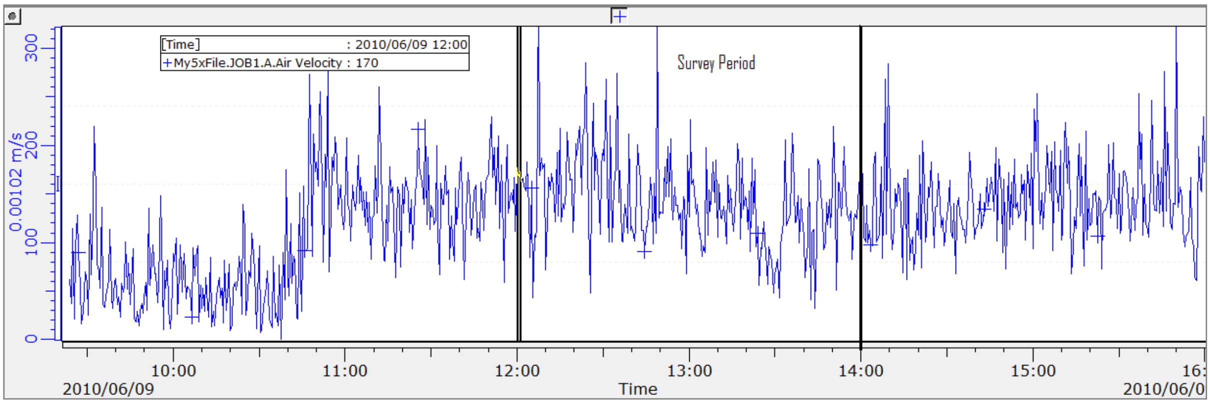


Figure 5.9 Day Two, Section B - Zone 1, Recorded Air Velocities (DT500) - LTCH

The prevalence of local discomfort factors felt by occupants are summarised in Table 5.3.

Table 5.3 Prevalence of local discomfort factors experienced by occupants

Symptom	No. of occupants experienced symptom
Draughts	17
Vertical Air Temperature Difference	7
Cold Surfaces	0
Asymmetrical radiant heat e.g. radiators or other heat emitters	0

5.1.2 Indoor Air Quality Assessment

CO_2 concentrations were used as indicators of indoor air pollution since it was assumed that bio effluents were major contributors of pollution in the indoor environment. Figure 5.10 shows a typical CO_2 concentration profile observed during the survey period.

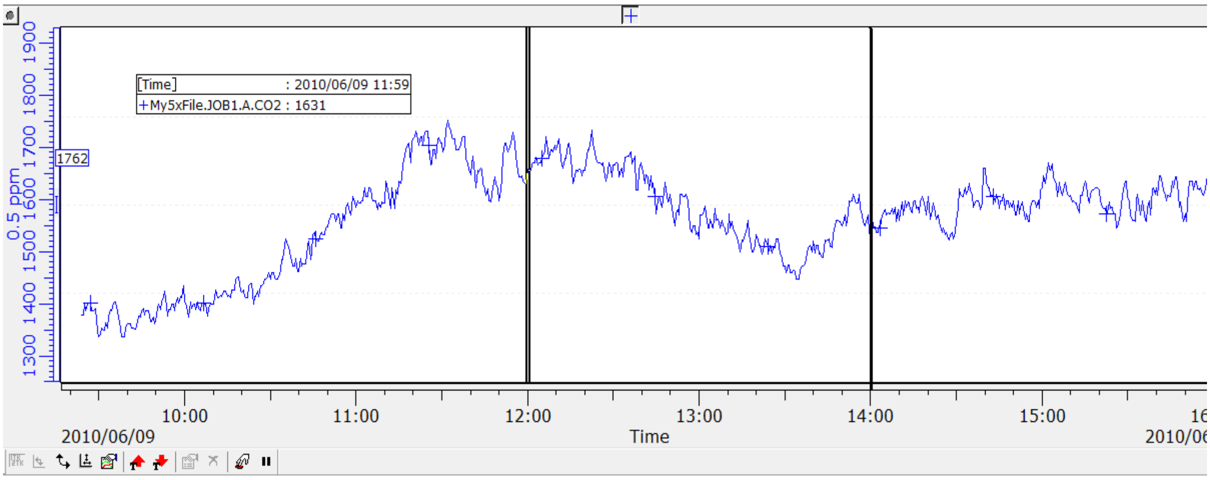


Figure 5.10 CO_2 Concentration Profile, Day 3 (DT500) - *LTCH*

During the survey period the average measured CO_2 concentration was 800ppm, 370ppm above outdoor concentration. A base level CO_2 concentration of 429 ppm was used and this value was obtained from average concentration during night time. This value was used to calculate PD_{IAQ} using *equation 3.16* (Chapter 3). The number of people satisfied (1- PD_{IAQ}) with air quality was estimated at 87.5% (*equation 3.20*). Surveyed values of number of people satisfied with IAQ were also estimated from questionnaire responses. The mean surveyed acceptance of IAQ was 84.6% (SD 13.47). The minimum value was 62.5% while the maximum was 100% (maximum acceptability). The average 84.6% is very close to the calculated value of 87.5% (Figure 5.11) hence this method could be used to calculate the quality of indoor air where bio effluents are the main pollutants.

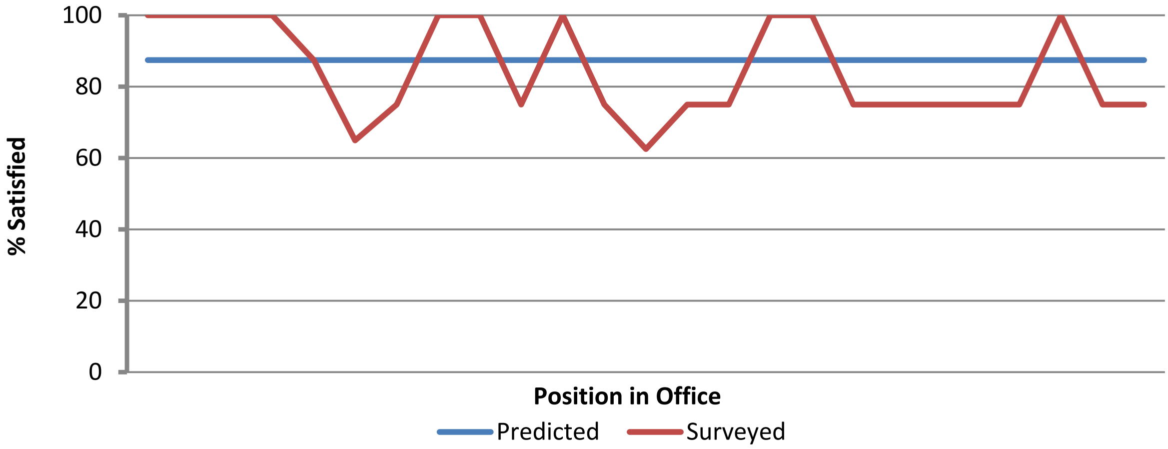


Figure 5.11 Surveyed Vs Predicted IAQ Perception in the Office - *LTCH*

The prevalence of The Sick Building Syndrome (SBS) symptoms was investigated using the questionnaire. Only five occupants expressed "blocked nose" during the survey period and their responses were about halfway on the VAS (see questionnaire) indicating that this problem was not "very serious".

5.1.3 Acoustic Comfort Assessment

Critical listening was carried out to determine the nature of background noise. Most noise was in speech related and in the form of conversations, coughing and sneezing. Walking, typing, filing, drawers opening and closing were also quite frequent. Continuous background noise from servers and HVAC equipment was approximately 65.5 dBA inside the server room. The two far ends of the office recorded about 34.5 dBA and 39.4 dBA in section A and B respectively, in the absence of conversations or any human related noise.

The level of satisfaction with the acoustic environment was calculated using *equations 3.21* to *3.24* and following the procedures recommended in Chapter 3. The calculated level of satisfaction with the acoustic environment ranged from 59.3% for those near the reception area to 96.8% for those furthest away from the reception and server room areas. Surveyed results showed a close agreement with calculated values (correlation coefficient = 0.69) as illustrated in Figure 5.12.

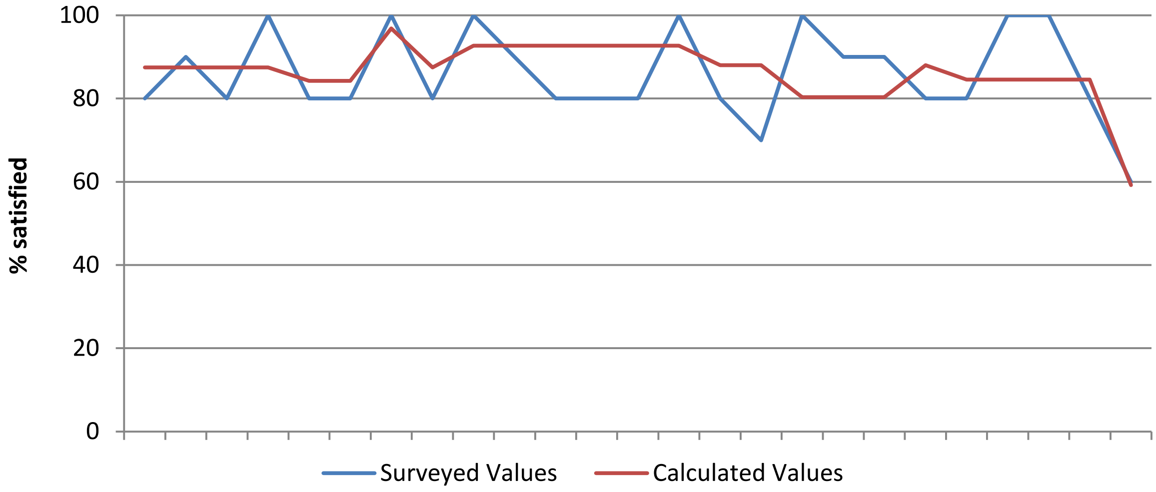


Figure 5.12 Surveyed Vs Calculated Acoustic Comfort values - *LTCH*

5.1.4 Lighting Quality Assessment

The average horizontal illumination measured on a working plane at each zone ranged from 416 to 2065 lux. These values were measured using logging apparatus and handheld instruments (see Hagner digital Lux meter, Figure 4.23). The skye lux sensor produced measurements that correlated well with handheld instruments at all illumination levels. Typical logged horizontal illumination levels are shown in Figure 5.13. The graph shows irregular patterns of illumination during the morning period (9:30 – 10:30 AM) due to cloud movement and a fairly steady and high illumination during the rest of the day (due to clearer skies). Lighting within the office was designed to adjust according to the amount of daylight received and hence the average illuminance levels were above the design value of 500 lux for most of the times.

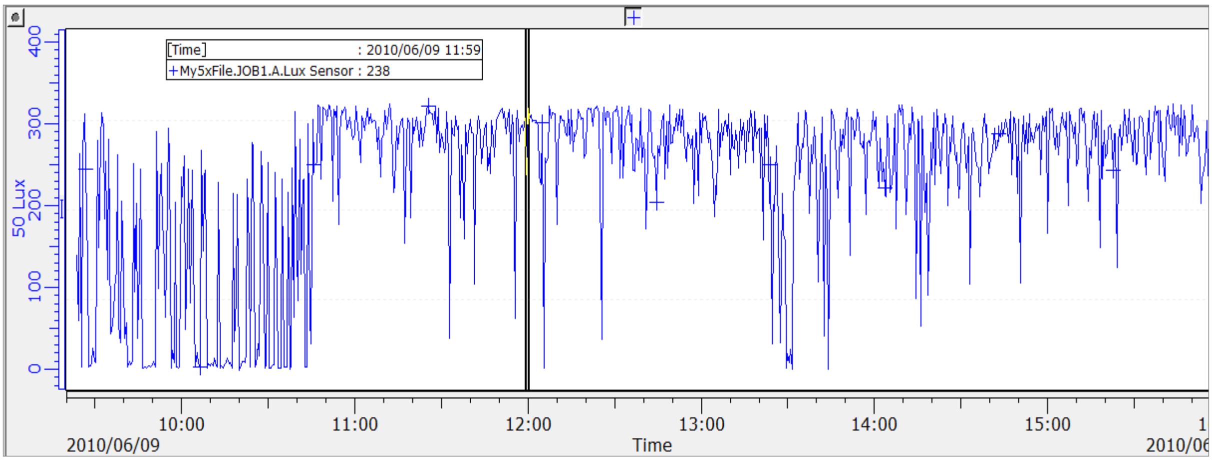


Figure 5.13 Day 2, Section A, Illuminance (DT500) - *LTCH*

Lighting quality (L_{index}) in the office was calculated using *equation 3.25* (Chapter 3). Comparison of surveyed and calculated lighting acceptance values showed that the two methods are in fairly good agreement with some observed IEQ results showing large variations between cases. The main problem associated with this is that most questions on lighting acceptance are vague hence they do not produce precise results.

This could be mainly because lighting acceptance is not necessarily proportional to the amount of light received, but rather relies on many other aspects that have not been taken into account. For example at higher illuminance levels some people may feel discomfort due to too much light for their requirements being received, or due to the presence of glare. The other problem is that VAS scales simply describe acceptability of the lighting environment but do not relate much to the "amount of light" received on a working plane. Figure 5.14 is a graph that compares model and surveyed results.

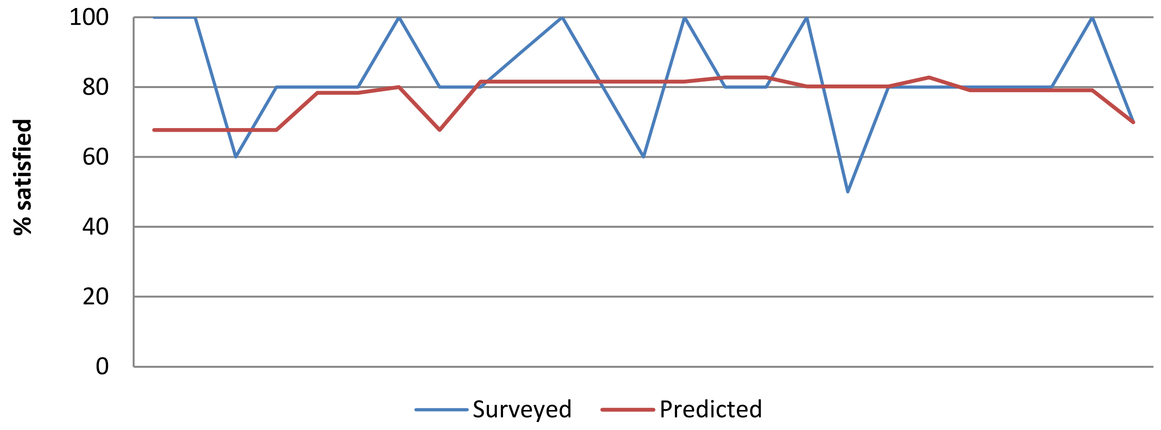


Figure 5.14 Surveyed Vs Calculated Lighting Quality Values – ***LTCH***

A comparison of the two types of scales used in the questionnaire was carried out to check the level of agreement between them. Figure 5.15 shows the level of agreement of responses obtained from the Semantic Differential and the Visual Analogue Scales (VAS). The results of the two scales are in close agreement for IAQ and acoustics, and a fairly close agreement for lighting comfort therefore both approaches could be used for subjective assessment of the indoor environment.

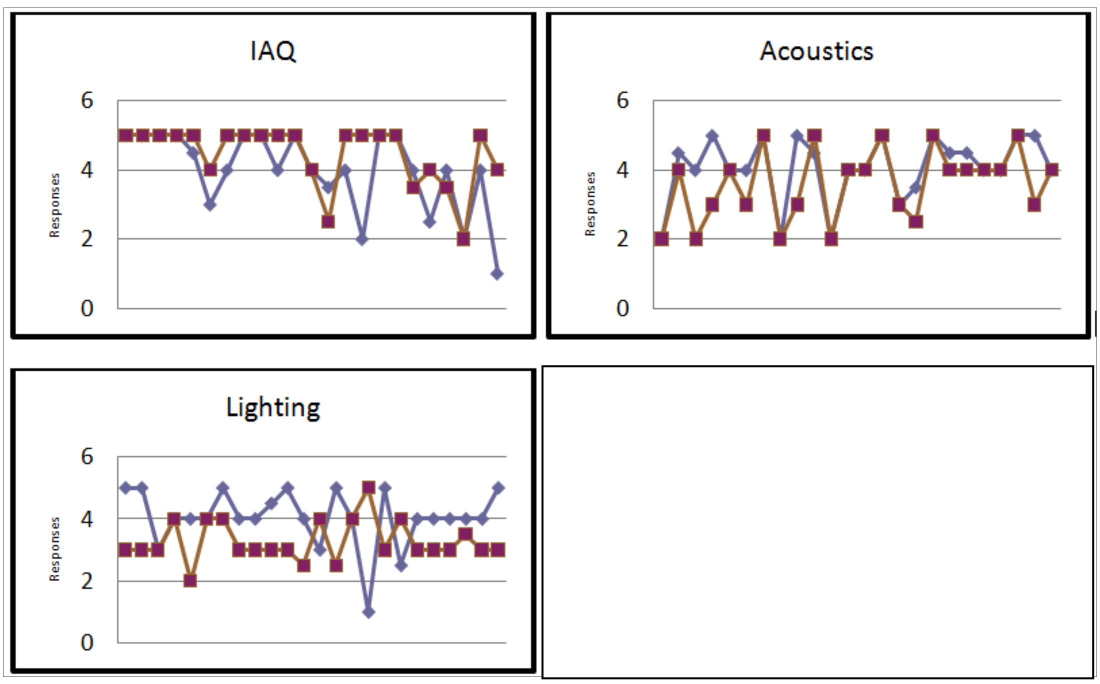


Figure 5.15 Level of Agreement of Responses Obtained from the Semantic Differential and the Visual Analogue Scales (VAS)

5.1.5 Indoor Environment Quality Assessment

A picture of the indoor environment showing the design and furniture level was taken at the end of the survey day and it is shown in Figure 5.16.

Figure 5.16 Picture of Indoor Environment - *LTCH*

Using *equation (3.30)* provisional IEQ *(IEQ_{index})* values were calculated and the results of descriptive statistics showed a standard deviation of 7.05 and a sample mean of 74.64. The minimum and maximum values were 62.92 and 85.01 respectively. The sample mean shows that occupants found the indoor environment generally "acceptable" despite variations in thermal comfort opinions across the office floor. Model calculated IEQ results were compared to questionnaire results in Figure 5.17 and they showed agreements to within 10%. The results also showed similar "general trends" across the office floor space. The AHP generated IEQ was used to check the validity of linear models as IEQ assessment tools for office buildings in the UK.

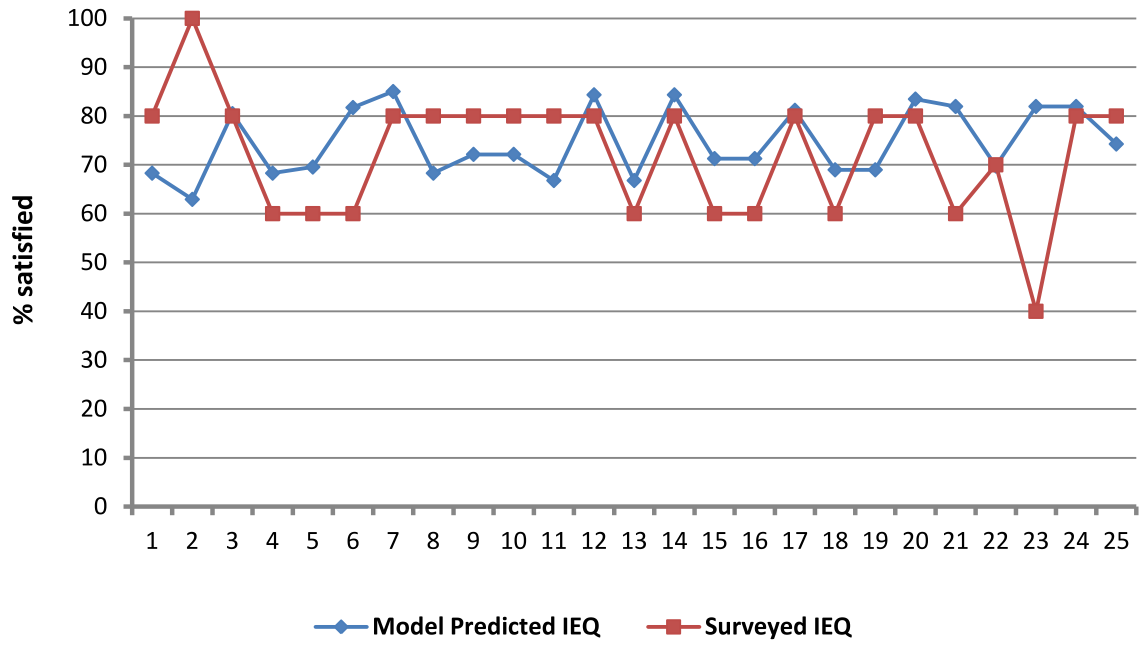


Figure 5.17 Surveyed Vs Model Calculated IEQ values - *LTCH*

5.1.6 Long Term Evaluation of IEQ – Model* performance

The applicability of the IEQ model for long term evaluation of IEQ in office buildings was tested in this case study. Using results obtained from Section A – Zone C of the office, thermal comfort, IAQ, acoustics, lighting and IEQ were calculated using appropriate equations and the results are summarised in Table 5.4.

Table 5.4 Assessment Results – Office A – *LTCH*

Time	RH	Ta (Deg.	Acoustics	10*Lux	Air velocity	MRT (D	PMV	Thermal	IAQ	Lighting	Acoustics	CO2 ab	IEQ	Model IEQ
11:00	48.9	20.6	45.1	580	0.03	20.6	-1.7	38.2	88.64	72.89	89.8	332	64	73.7979
11:30	45.5	20.7	46.2	543	0.03	20.7	-1.7	38.2	86.74	71.97	87.6	397	63	72.4684
12:00	46.9	21.3	46.2	470	0.03	21.3	-1.5	49.1	86.68	69.78	87.6	399	65	74.6563
12:30	47.3	21.5	43.9	581	0.03	21.5	-1.4	54.5	86.63	72.91	92.2	401	67	77.6082
13:00	47.1	21.4	49.4	260	0.03	21.4	-1.4	54.5	86.4	58.04	81.2	409	62	72.1315
13:30	49.5	21.3	49.4	439	0.03	21.3	-1.4	54.5	86.01	68.66	81.2	423	64	74.016
14:00	45.7	21.6	45.8	235	0.03	21.6	-1.4	54.5	84.87	55.52	88.4	465	63	72.8324
14:30	47.9	21.6	48.7	424	0.03	21.6	-1.3	59.7	84.19	68.07	82.6	491	65	74.8732
15:00	46	21.4	45	428	0.03	21.4	-1.4	54.5	84.74	68.23	90	470	65	75.5741
15:30	45.4	21.6	48	312	0.03	21.6	-1.4	54.5	85.01	62.17	84	460	63	73.1058
16:00	43.7	21.7	41.2	303	0.03	21.7	-1.3	59.7	84.85	61.54	97.6	466	67	77.3749

***Model IEQ refers to IEQ generated from the AHP**

Results can be produced for longer periods provided the input data has been collected over longer periods. Forms of results presentation have been described in Chapter 3. Figure 5.18 shows the results in graphical form (line graph) since this provides a clearer picture of the conditions likely to have been experienced during that period.

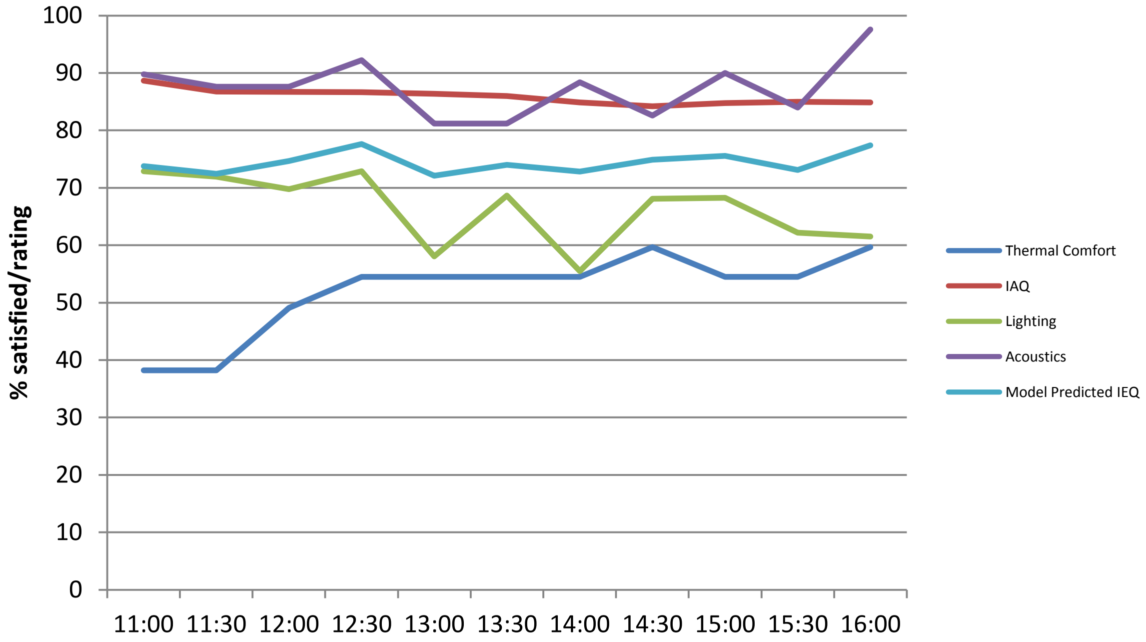
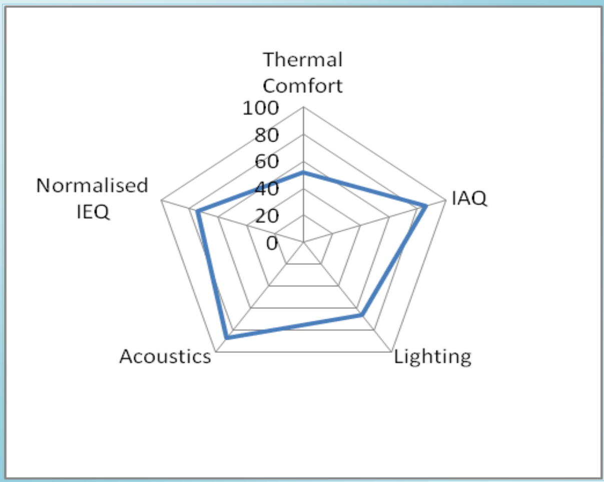


Figure 5.18 Assessment Results – Section A, Line Graph Presentation - ***LTCH***

In order to compare IEQ with building energy performance values for the duration of the year need to be averaged and presented as shown in Figure 5.21. A radar chart provides an excellent pictorial comparison between the IEQ aspects and energy performance. Energy performance of the office can be introduced into the radar chart as the sixth quantity.

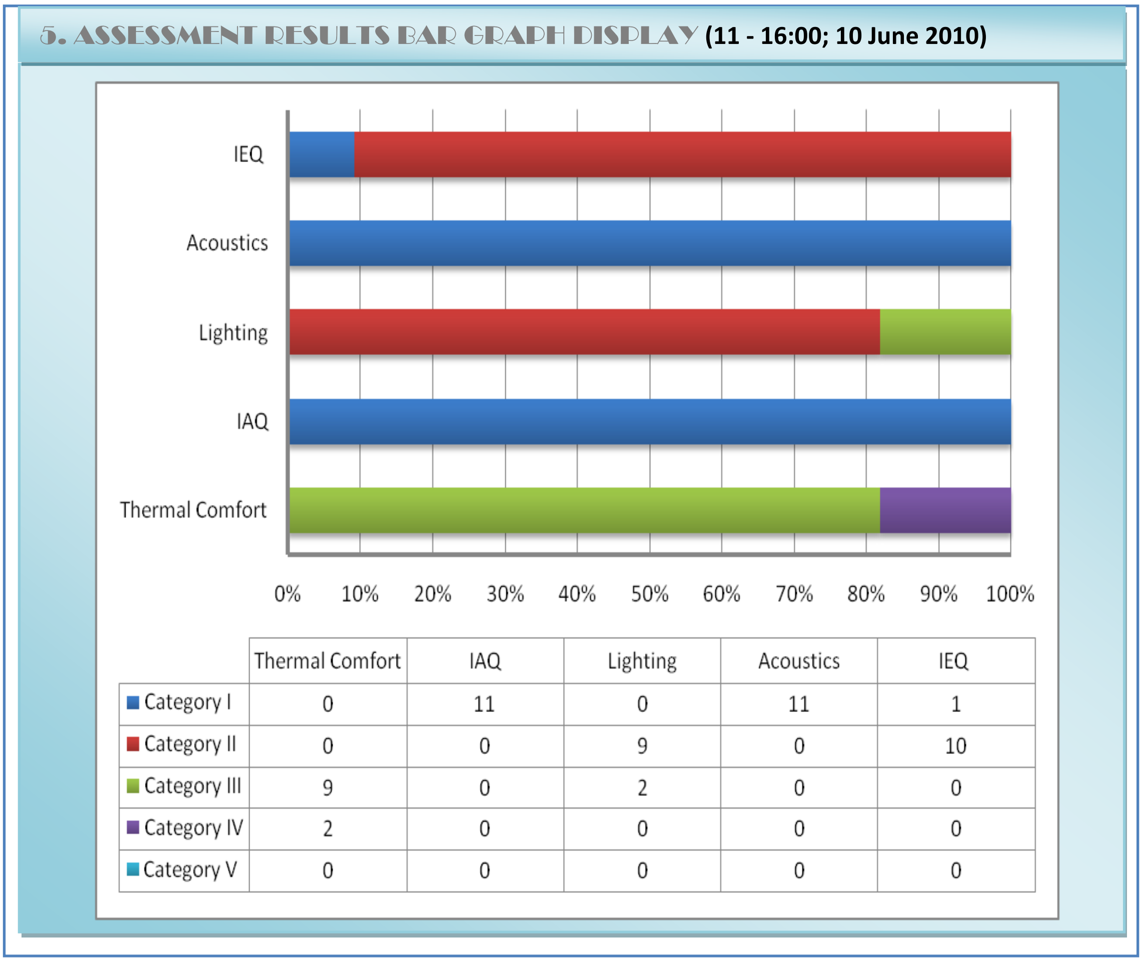


PERIOD: 11 - 16:00 10 June 2010

Thermal Comfort	51.99
IAQ	85.89
Acoustic Comfort	61.54
Lighting Comfort	87.47
IEQ	77.85
Energy Rating	XXX

Figure 5.19 Average Results for Section A of the Leeds Town Centre House 6th Floor Office Space.

In order to rate the office building or sections of buildings into categories the percentage of time the office space falls into a certain category needs to be plotted using a bar chart. Figure 5.20 shows a bar chart for Section A of the Leeds Town Centre House for a four and half hour duration. According to the information provided the section of the office can be rated into the categories described in Chapter 3 and based on the recommendations provided in section 3.28 of that Chapter. According to the information from the Leeds Town Centre building only acoustic comfort and IAQ can be rated into category I (falls into Category I for 100% of the time). Thermal comfort (81% category III), lighting (81% category II) and IEQ (91% category II) could not fall within the limits of any one category for more than 95 % of the time as described in the recommendations. Longer periods of investigation could produce clear cut categories. However the exercise provides testimony that year long evaluation of the indoor environment is possible.



	Thermal Comfort	IAQ	Lighting	Acoustics	IEQ
Category I	0	11	0	11	1
Category II	0	0	9	0	10
Category III	9	0	2	0	0
Category IV	2	0	0	0	0
Category V	0	0	0	0	0

Figure 5.20 Percentages of time Office falls inside the limits of a Category - *LTCH*

Assuming that IEQ falls within Category II (74.40) for 95% (actual value is 91%) or more of the time for section A and Category II for (74.54) for section B (> 95% of the time) and using the methodology presented in Chapter 3 *(equations 3.31 – 32)*, the IEQ rating for the Leeds office is calculated as follows:

- IEQ_{index} for section A = 74.40;
- Floor Area ratio = 1/3;
- IEQ_{index} for section B = 74.54;
- Floor Area ratio = 2/3

IEQ rating for both sections for the survey period is given as:

$IEQ\ Rating = [\left(74.40 \times \frac{1}{3}\right) + \left(74.54 \times \frac{2}{3}\right) = \mathbf{74.49}$, for the period 11AM – 4PM, on the 10th of June 2010.

5.1.7 General Considerations for the Indoor Environment

Table 5.5 Checklists for IEQ variables – Leeds Town Centre House

THE INDOOR ENVIRONMENT QUALITY ASSESSMENT TOOL (IEQAT) - 2011

GENERAL CONSIDERATIONS - THERMAL COMFORT		
Room Temperature Control		
v	Monitoring systems (thermostats, etc)	Yes
v	Room temperature setting	Yes (21°C)
v	Individual Control	No
v	Zoned control	Yes
v	Variable Loads and perimeter performance	Yes
Humidity Control		Yes
A/C System Present		Yes
GENERAL CONSIDERATIONS -IAQ		
Ventilation		
v	Ventilation System Present	Yes
v	Air Supply Schedule	Yes
v	Individual Control	No
v	Zoned control	Yes
v	Variable Loads and perimeter performance	Yes
v	Smoking	No
Pollution Source Control		
v	Chemical Pollutants Present?	None observed
v	Asbestos	None observed
v	Evidence of mould, mites, fungi, etc?	None observed
v	Legionella	None observed
v	GENERAL CONSIDERATIONS - ACOUSTICS	
Other Noise		
v	Equipment Noise	Yes (Servers), telephone
v	Outdoor Noise and Type	None Recorded
Sound Insulation		
v	Sound Insulation of Internal Walls	N/A
v	Sound Insulation of performance of floor	N/A
v	Units (impacts)	N/A

Sound insulation properties (material properties), pollutant levels, daylight and other lighting factors were not available for inclusion into the results sheet of this office building.

5.1.8 Conclusions and Lessons Learnt From the Study

The Leeds Town Centre Building case study highlights the importance of thermal comfort, IAQ, acoustics and lighting to occupants' perceptions of the quality of the indoor environment. The relative importance of each of the factors depends on prevailing microclimatic conditions hence there is need for a large number of studies to be carried out in order to determine trends associated with different sets of indoor conditions. The offices studied in the Leeds Town Centre House had a particularly unique set of indoor environment conditions as shown by the summaries of logged data. This could pave way for weightings that are based on occupant's subjective opinions and therefore less biased models can be produced.

The study also shows that the new IEQ methodology has great potential to be used as an ultimate tool that can be used to assess office buildings at any stage of the design. Special arrangements need to be made for occupants who may suffer from diseases that affect their perceptions of comfort in the office. For example occupants who suffer from Reynaud's disease and arthritis were found to be particularly susceptible to cold.

5.2 CASE STUDY 2:

MARSH, GROCHOWSKI & ASSOCIATES, NOTTINGHAM

The office studied is a naturally ventilated pre-world war II building located at Commerce Square, Lace Market, Nottingham City Centre in the United Kingdom. The building is a 1930s open plan consisting of triple height spaces. It comprises four floors with the ground floor comprising of meeting rooms and first floor comprises rest rooms and a kitchenette. The second floor consists of office space that is divided into two parts with two people occupying the first lower level section and three people occupying the second, upper level section. The higher section of the first floor is fitted with ordinary non energy efficient (incandescent) 60 watts light bulbs and the lower of the two sections has an atrium which supplies extra natural light.

The third and top floor is a standard office room which is naturally ventilated and occupied by three people. The top floor office space however has blinds fitted on all windows to prevent glare due to direct sunlight at certain times of the day. The position of the building means it is heavily shaded by other buildings hence it benefits less from daylighting. The heating needs of this building are served by isolated electric heaters and cooling in summer is assisted by plug in electric fans. This building has poor levels of insulation. The main walls consist of double brick with plaster and paint on the internal side, loose fitting single glazed windows on a metal frame. Ventilation air is supplied through supply air vents situated at various points within the building.

The total floor area of the office occupied by the 7 respondents was approximately 180 m^2. The office was occupied by mostly by white-collar workers consisting of architects and interior designers. Most of them performed sedentary work such as typing, filing, drawing, telephone conversations and they wore light office clothing. Figure 5.21 shows basic building data.

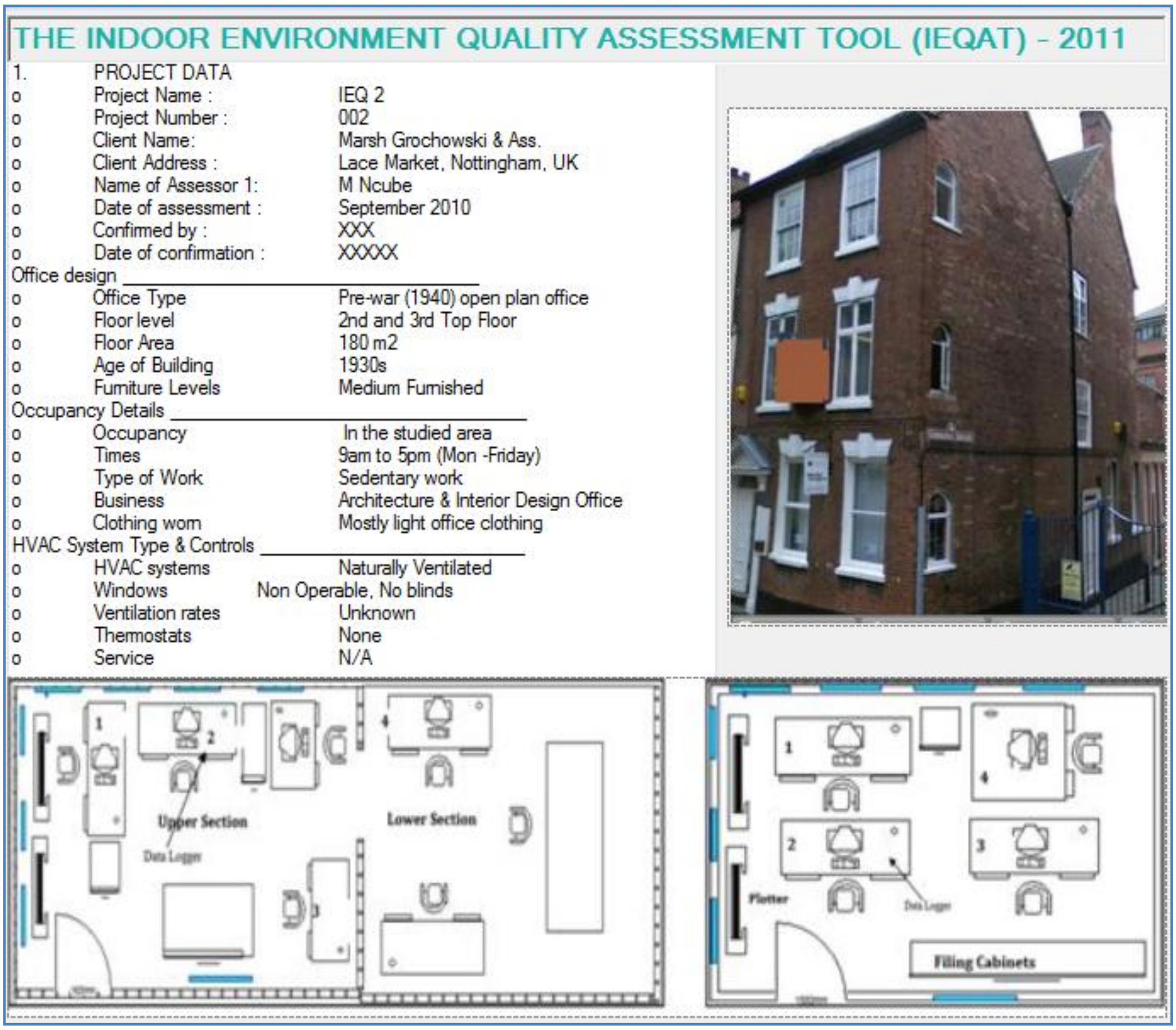


Figure 5.21 Project and Building Data – Marsh Grochowski & Associates - Nottingham

The weather conditions for the Nottingham City Centre area for the three field days were obtained from weather sources and they are summarised in Table 5.6.

Table 5.6 The weather in Nottingham during Data Collection, Source (Weather Underground, 2009)

Date	Average Outdoor Temperature, °C	Dew Point Temperature, °C	Average Relative Humidity %	Summary
14/09/10	15	11	78	Mostly Cloudy, with Light rain
15/09/10	12	8	76	Clear to scattered clouds
16/09/10	12	8	77	Partly Cloudy

5.2.1 Thermal Comfort Assessment Results

Thermal comfort assessment was carried out using the Auliciems adaptive thermal comfort model described in Chapter 3. Using the model and using the mean monthly outdoor temperature (°C) given for Nottingham City Centre, the optimum (neutrality) temperature for the office was 21.3 °C therefore 2.5 °C on either side of this temperature gives the limits of the 90% satisfied category (Category I). The higher limit for the category was calculated at 23.8 °C and the lower limit was 18.8 °C. The lower limit for the 80% satisfied category (Category II) was calculated at 17.8 °C. The average temperatures recorded in the office are shown in Table 5.7 and they were all within the 80 and 90% acceptance bands. The results were also based on the assumption that air temperature was equal to mean radiant temperature and it should be noted that this adaptive comfort standard already accounts for people's clothing adaptation and other behavioural adaptations.

Questionnaire results presented an opportunity to test the relationship between model results and occupants' evaluation of the thermal environment (the results are summarized in Figures 5.25). All healthy occupants reported feeling slightly cool as shown in Figures 5.22 and 5.23. In the second floor the occupant in position 1 indicated that they suffer from arthritis. In the top floor the occupant in position 6 voted PMV = -3 and they also indicated that they also suffered from Reynaud's disease which could have affected their perception of the indoor environment. Those two values were rendered invalid for purposes of assessing the performance of the model.

Using the assessment scale presented in the Questionnaire (Appendix 2) the votes "slightly cool" corresponded with 85% (for median values) acceptability of the indoor thermal environment. These results agree well with model calculated results for that building as shown in Figure 5.25 although the model overestimates perceived thermal comfort by 2.5% as shown in Figure 5.25. The assessment scale used in the questionnaire could however be improved to include more choices for respondents to select. This will allow for more variation in choices made by occupants and help indicate any variations in the indoor microclimate from the opinions of the individuals.

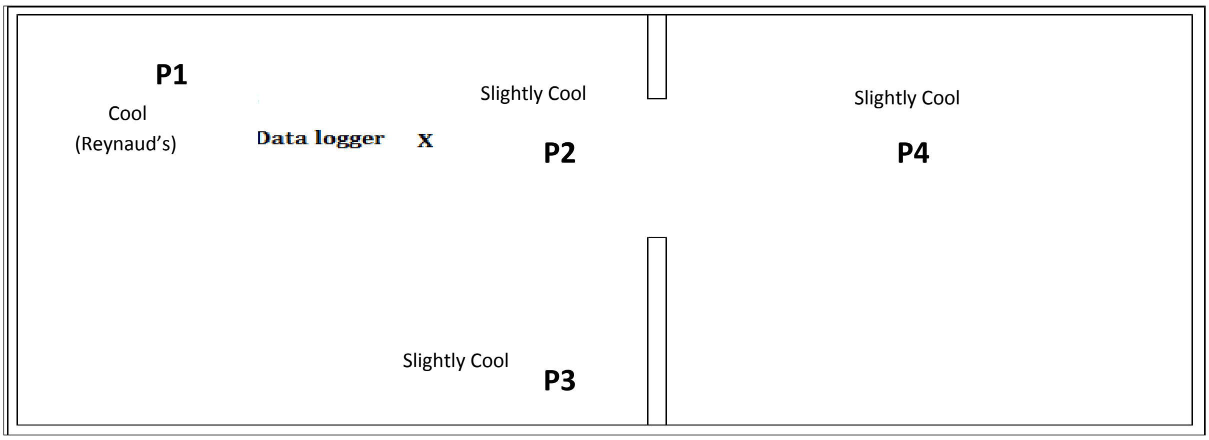


Figure 5.22 Questionnaire Results for the 2nd Floor, Marsh & Grochowski Architects, Nottingham

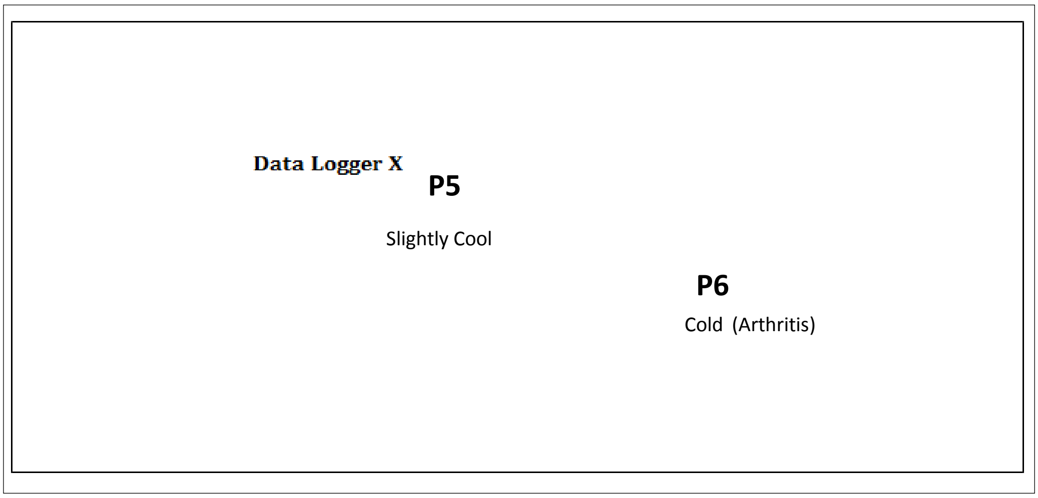


Figure 5.23 Questionnaire Results for the 3rd Floor, Marsh & Grochowski Architects – Nottingham

Table 5.7 Summary of Thermal Comfort variables and calculated PMV values – *MGA*

Floor	Position	Air Temperature Recorded	Model Predicted Acceptance	Surveyed or Questionnaire Results	Comment
2nd	1	19.5	89.5	Cool	Reject
	2	19.4	88.9	Slightly Cool	
	3	19.4	88.9	Slightly Cool	
	4	19.6	90.2	Slightly Cool	
3rd	1	19.2	87.4	Slightly Cool	
	2	19.2	87.4	Cold	Reject

It is important to note that occupants were observed as they made efforts to improve their situation by adjusting their clothing, using electric heaters and taking hot drinks regularly throughout the day. Such actions are energy intensive and they add significantly to the energy bills in naturally ventilated buildings. As explained earlier most occupants voted “slightly cool” (except those with underlying health conditions) as shown in Figure 5.24.

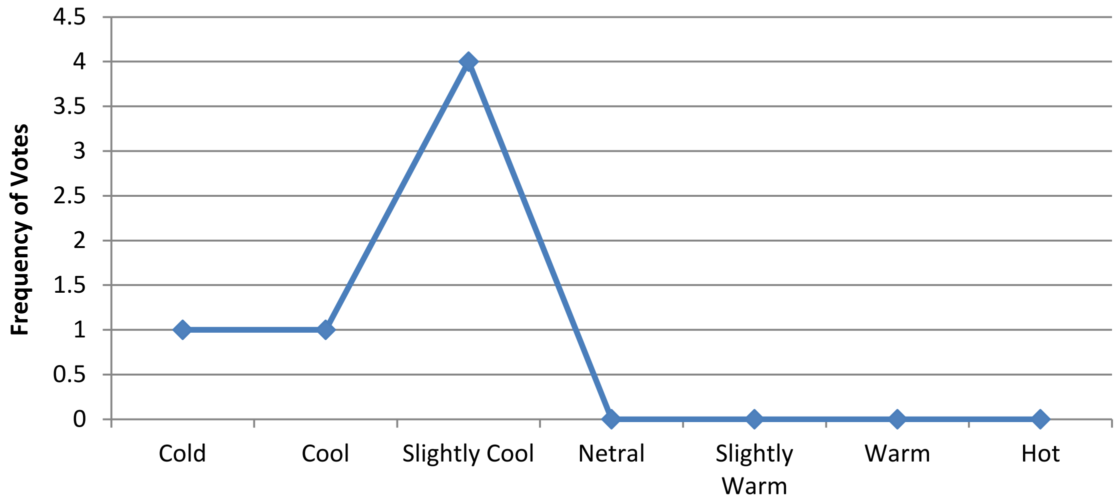


Figure 5.24 Frequency distribution of PMV values for the Marsh & Grochowski Architects, Nottingham

Figure 5.25 compares model calculated and surveyed thermal comfort results.

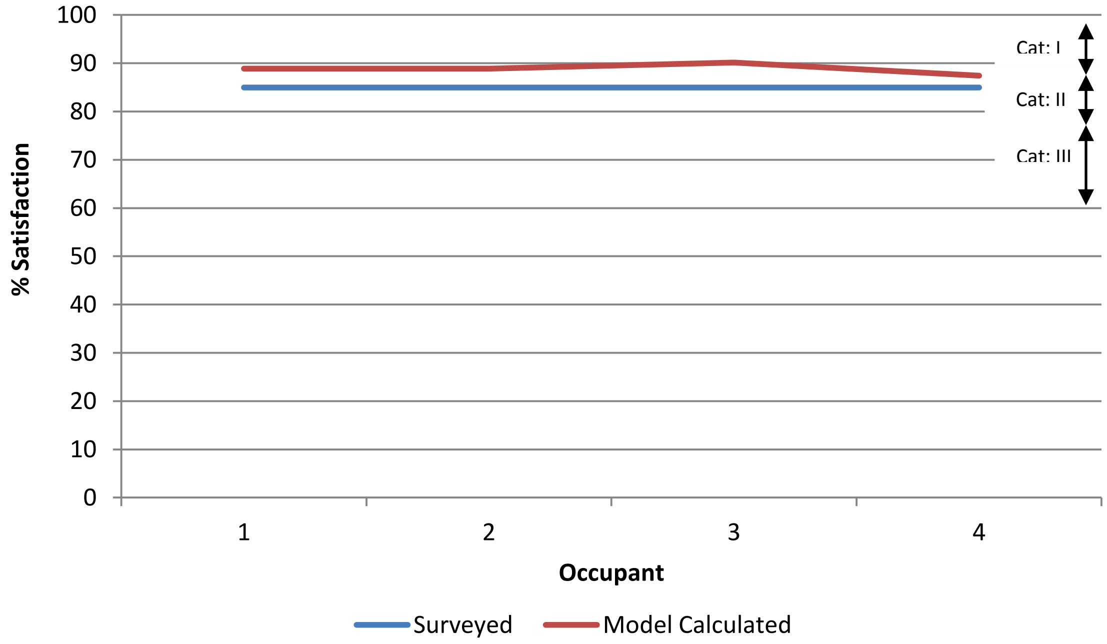


Figure 5.25 Model vs Questionnaire thermal comfort values for the Marsh, Grochowski & Associates -Nottingham

Temperature, relative humidity and air velocity were recorded throughout the survey period as done at the Leeds office and the results are explained below. The data logger was checked for its accuracy using a potentiometer sensor and the temperature profiles for the 3rd and 4th floors were recorded and an example is shown in Figures 5.26.

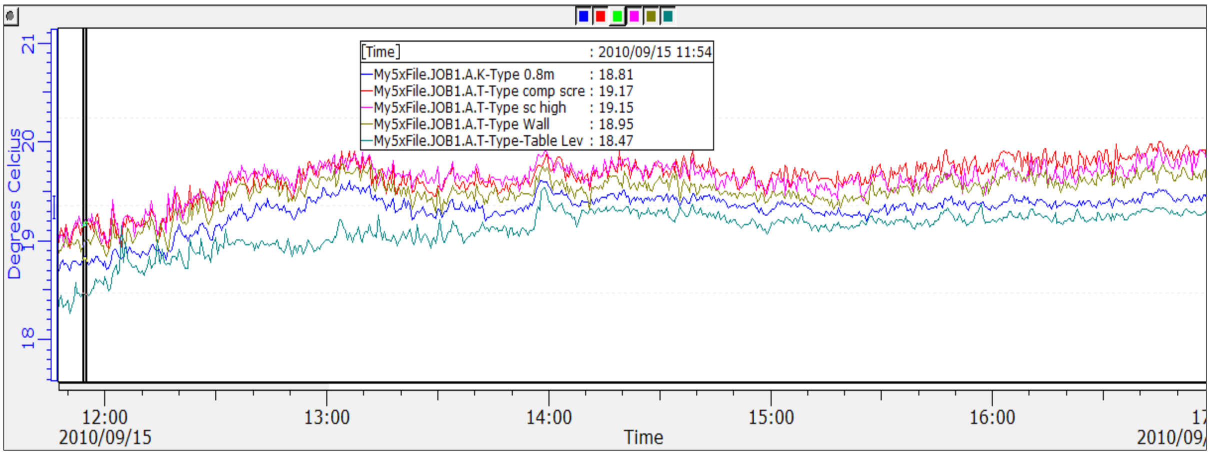


Figure 5.26 Temperature Profile for the Top (3rd) Floor Section of the Office Building (DT500) - *MGA*

Figure 5.26 show fairly constant temperatures throughout the office hours with peak daily temperatures being recorded at 19.87ºC and minimum daily temperatures recorded at 17ºC. Temperature drops after 6 PM (not shown) were observed mainly due to reduction in solar gains and occupants leaving the office. Temperatures continued to fall throughout the night as expected and gains were observed from approximately 7AM on wards as solar gains and occupancy increased. An average temperature of 19.4 and 19.0 ºC were observed between 10:30 AM and Noon (Questionnaire Period) during survey day 1 and 2 respectively. No noticeable vertical temperature differences were observed during the survey period. The average temperatures taken at various locations during questionnaire administration periods are shown in Figure 5.27. Little variation in temperatures in the 2nd floor office is observed and a difference between minimum and maximum temperatures was 0.2°C.

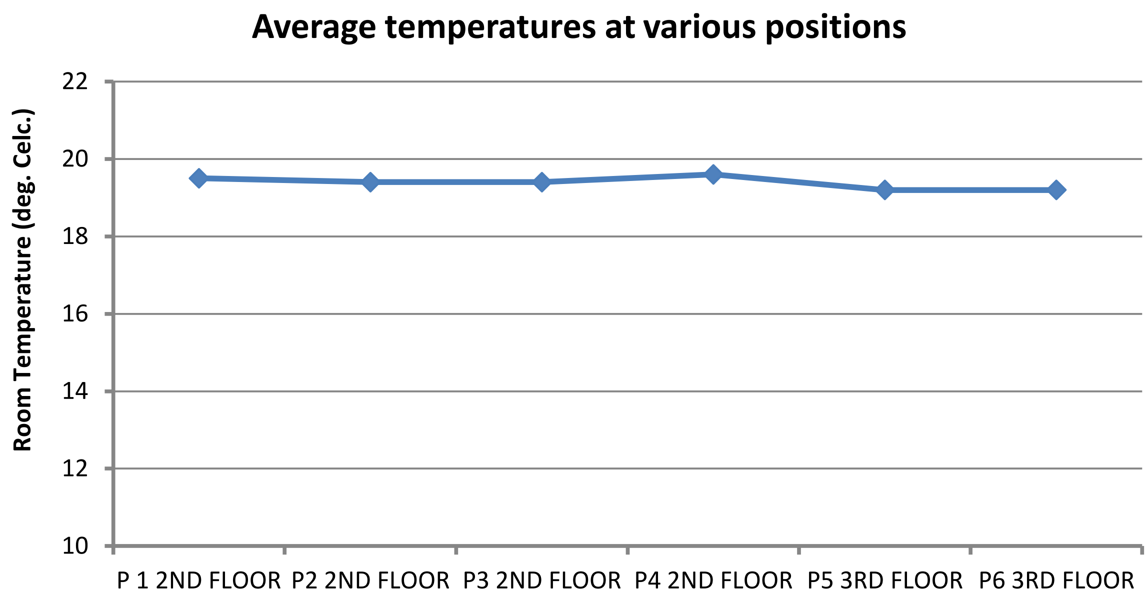


Figure 5.27 Temperature Profiles at Various Locations in the Office - *MGA*

Relative humidity (%) was recorded every 30 minutes between 10AM and 12:20PM using hand held devices and the average results are summarised in Table 5.8. Higher relative humidities were observed in the third floor probably due to the state of weather on that day.

Table 5.8 Average Relative Humidity Recorded at Various Positions in the Offices - *MGA*

Section	RH (%) Position 1	RH (%) Position 2	RH (%) Position 3	RH (%) Position 4
2^{nd} Floor	56.9	58.7	56.7	56.7
3^{rd} Floor	63.0	63.0	63.0	63.0

Average air velocities were recorded at 0.010 m/s for most of the office hours therefore they were recorded as "Not noticeable" air movement. Figure 5.28 shows air velocities remained fairly constant throughout the day and a similar trend was observed in the 3rd floor.

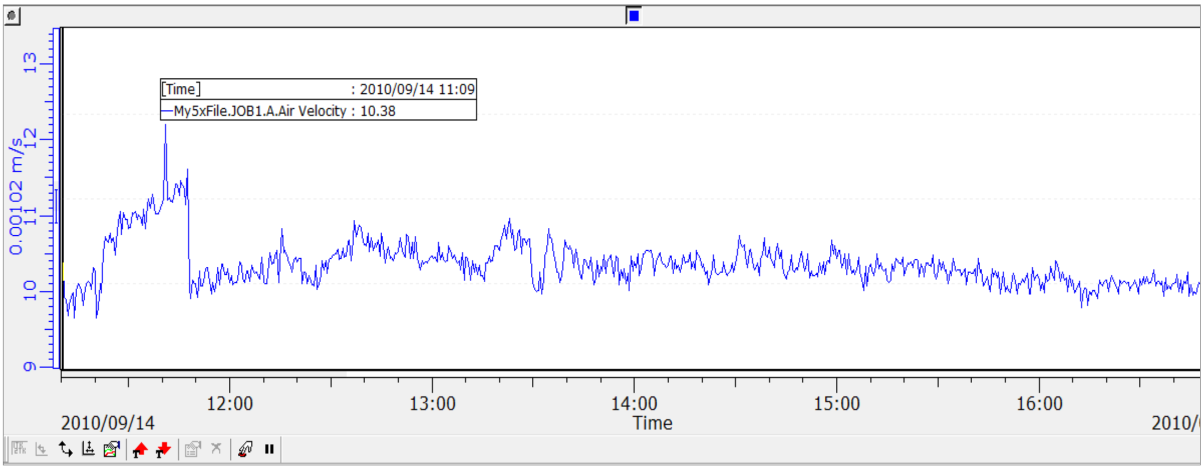


Figure 5.28 Recorded Air Velocities – Second Floor Marsh & Grochowski Architects, Nottingham (DT500)

Local discomfort factors such as draughts, vertical air temperature difference, between head and feet) and cold equipment were reported by 50 percent of occupants. All occupants who reported feeling draughty also reported vertical air temperature difference. Physical measurements suggested otherwise because the difference in measured temperature between head and ankles was approximately 0.22ºC. Local discomfort ratings were not measured in this study.

5.2.2 IAQ Assessment Results

Carbon dioxide concentrations were logged and overnight concentrations were recorded at 390 ppm in the 2nd floor office with the highest recorded concentration being 1140 ppm. During questionnaire administration the recorded average concentration was 900ppm, therefore we can assume that the concentration of CO_2 above outdoor concentration was

510ppm. The average concentration calculated from data recorded during questionnaire administration in the third floor was 1,100ppm while outdoor concentrations were 400ppm. Therefore the CO_2 concentration above outdoor was estimated at 700ppm.

A typical CO_2 profile is shown in Figure 5.29. The graph shows the concentrations of CO_2 rising steadily from around 7AM when occupancy began up to a peak around midday when the highest number of occupants were at their workstations. There was a slight drop in concentrations from between 1 and 3 PM as some occupants left for their lunch and a steady rise when they returned to their workstations. The concentrations begin to fall when occupants leave the office at the end of the day and concentrations continue to fall until they stay constant throughout the night.

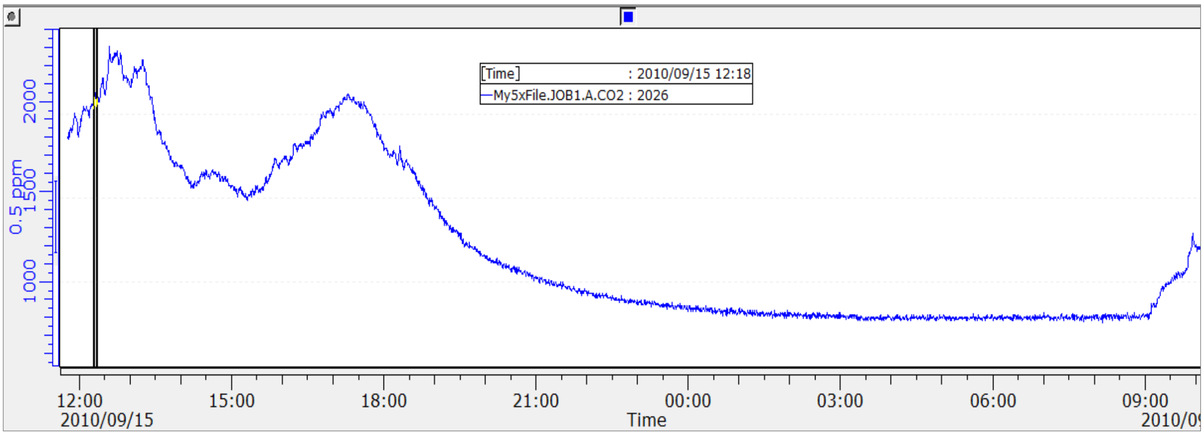


Figure 5.29 CO_2 Concentrations over a 24hr Period in the Third Floor of the Office Building (DT500) - *MGA*

The number of occupants satisfied with IAQ was calculated using *equation 3.13* and the results are summarised in Figure 5.30. The Figure shows discrepancies in the level of agreement between calculated and surveyed IAQ for different positions within the office and this could be mainly due to the fact that CO_2 was measured at only one location within the office. Again the perceived IAQ could be due to other factors such as the presence of VOCs, particulates, or other physical and biological agents. Signs of SBS were recorded in the office although all occupants expressed satisfaction with the quality of the air. Dry nose and stuffy environment was recorded by almost half of the occupants and one third expressed dissatisfaction with level of control (the fact that windows could not be opened).

This shows that the use of CO_2 concentrations to indicate the quality of the indoor environment should be limited to environments polluted due to bio effluents only. The method should however be used in conjunction with other methods such as the use of ventilation rates (the dilution of pollutants approach, or the so-called ventilation for health and comfort). The results also highlight the need to improve the precision of visual assessment scales used in the questionnaire by adding more values so that choices are more precise (smaller divisions).

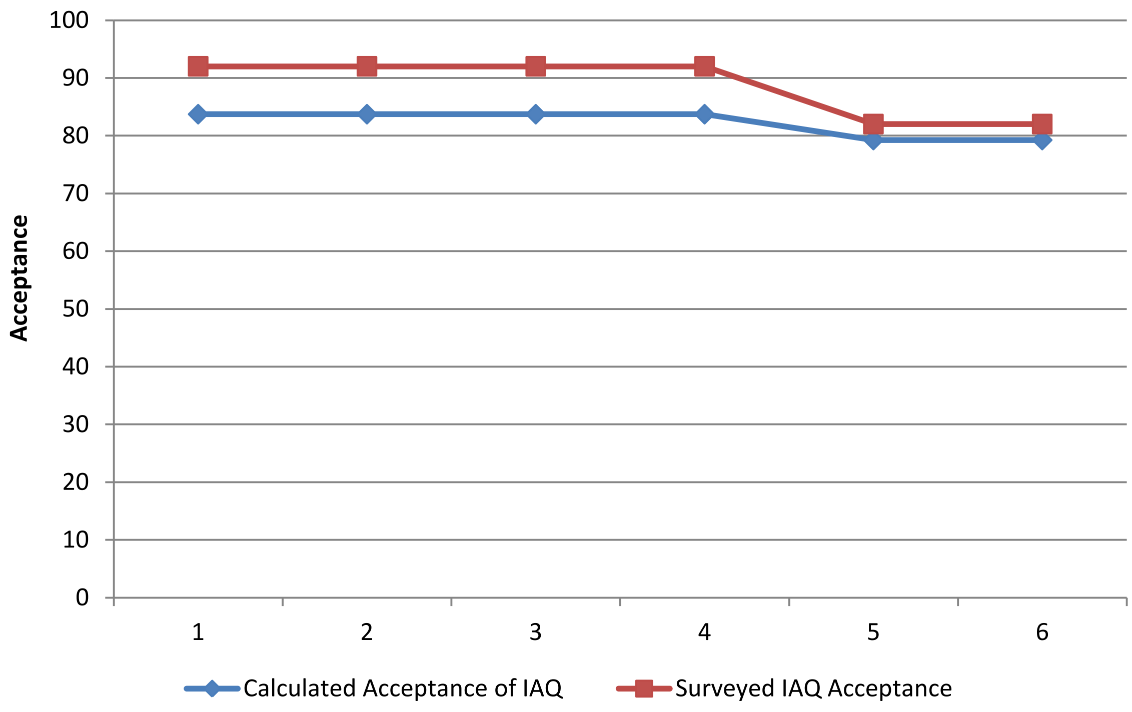


Figure 5.30 Calculated vs. Surveyed Acceptance of IAQ - *MGA*

5.23 Acoustics Comfort Assessment Results

The nature of background noise in the office was determined by critical listening. Background noise consisted on soft music playing from a portable radio, walking, typing on computers, filing, plotters, drawers, and isolated cases of conversations. The portable radio was located at position 1 and a sound level meter placed at position 2 recorded 28 dBA. The radio plus movements around the office gave a reading of 36 dBA and the highest noise levels of 66 dBA recorded included conversations between two people and a telephone ringing. Generally noise levels ranged from 24.4 – 54.8 dBA throughout the offices.

Calculated values for acceptance of the indoor acoustic environment were obtained from equations described in Chapter 3. Three of the six surveyed results showed a close match with calculated values as illustrated in Figure 5.31. It is important to note that more research is needed to verify the acoustic comfort model suggested in this thesis and to compare it with other models such as the Kjellberg et al and Nillson models explained in Chapter 3. Also in areas where higher dBA values were recorded, particularly large differences between survey and model results were observed (e.g. first two values Figure 5.31). This could also be mainly due to the fluctuating and abrupt or short lived nature of conversation and telephone noise within office buildings. Most importantly it is necessary that in future studies continuous measurement of sound pressure levels including their frequencies needs to be carried out and matched closely with times questionnaires were filled.

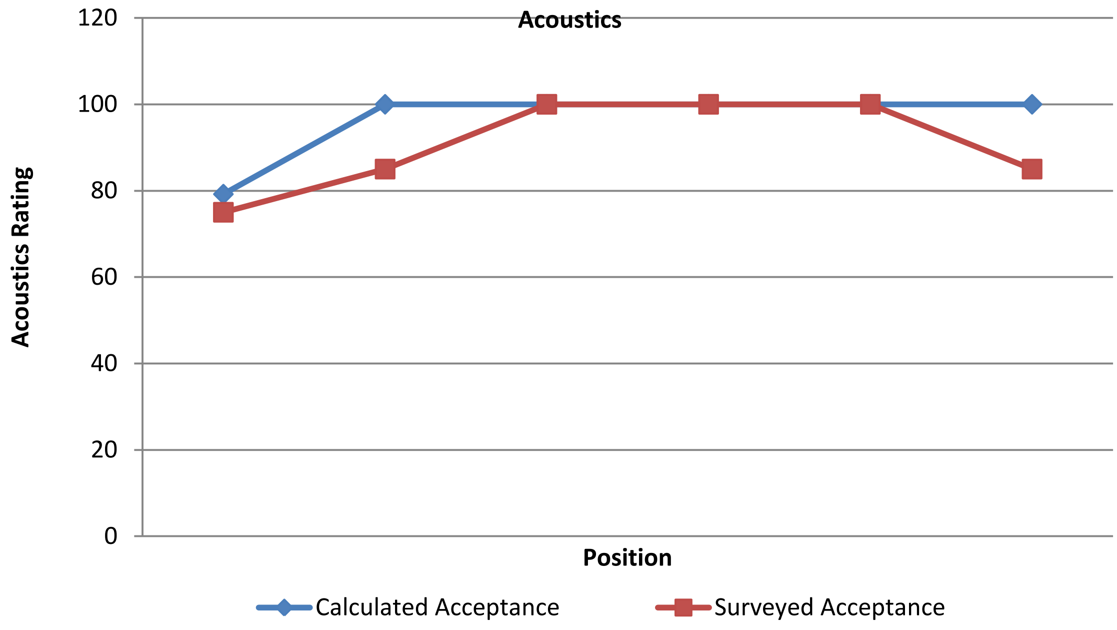


Figure 5.31 Surveyed Vs Calculated Acoustics Acceptance, 2nd & 3rd Floor - *MGA*

5.2.4 Lighting Quality Assessment Results

The average logged horizontal illumination on the working plane at data logger position in the 2nd floor ranged from 10 - 25 Klux throughout the day (Figure 5.32). The reason for high illuminance was mainly due to its location near the window and the use of additional artificial light at that point. Several peaks were observed during this partly cloudy day prompting suggestions by occupants that blinds be used to prevent too bright conditions. The 3rd Floor illuminance levels were fairly constant at around 11Klux (position 2) during the survey period (Figure 5.33). However measured illuminance varied from one position to another and although similar trends for calculated and surveyed lighting quality acceptance were observed, a relatively poor agreement between the two was observed as shown in Figure 5.34.

This could be explained by the use of less accurate spot measurement lux meters in some of the positions and the rapid variation in illumination levels for offices that rely mostly on daylighting during office hours. Overcrowding in the office also meant that some positions were shielded from direct day lighting (for example, position 3 in the 2nd floor) and hence they relied mostly on several 60W roof light bulbs hanging from the roof of the office. The presence of additional table lamps also indicates that additional lighting is often required in the office.

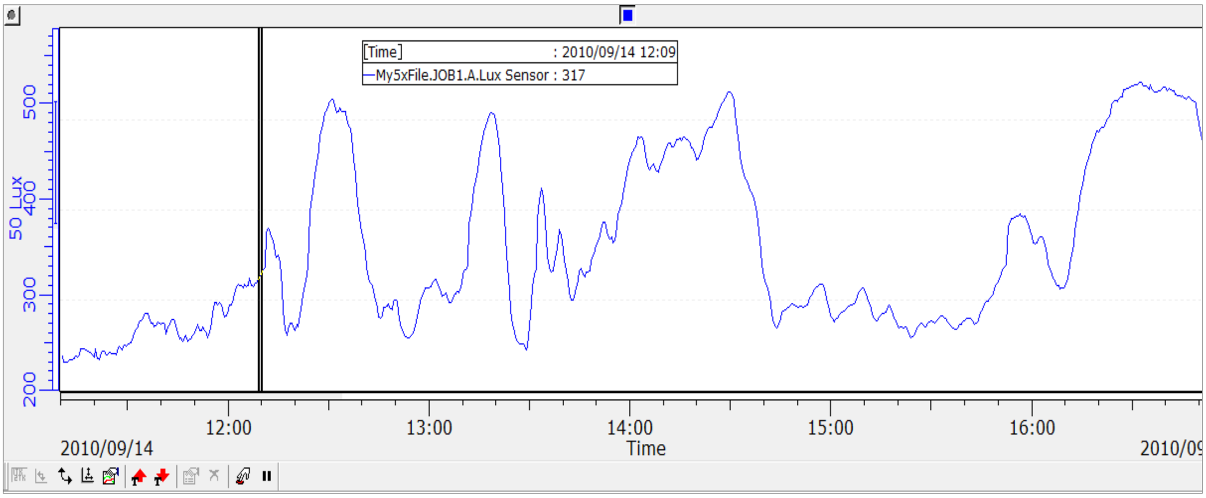


Figure 5.32 Logged Illuminance on a Working Plane Second Floor Office Space (DT500) - *MGA*

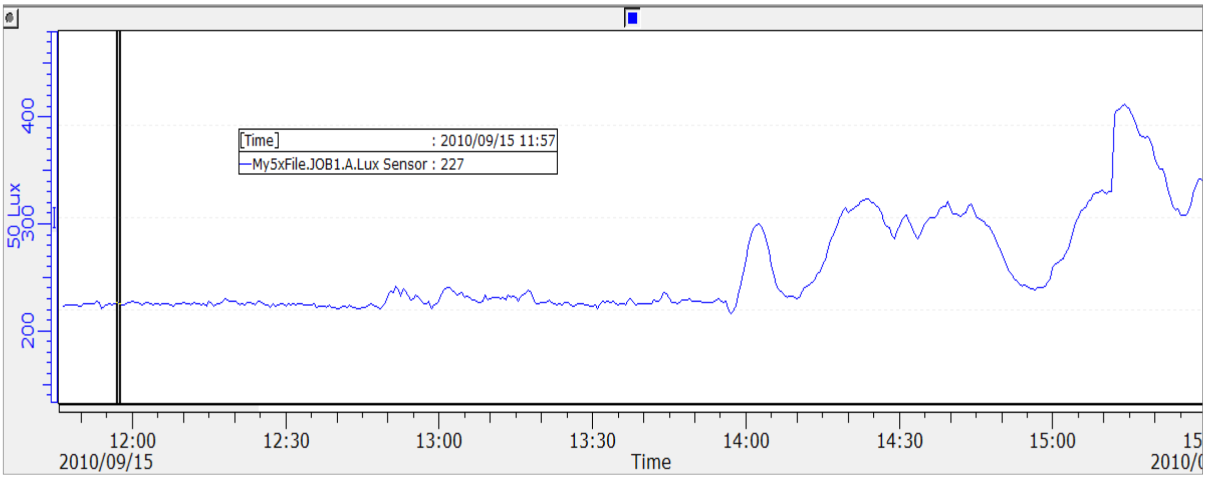


Figure 5.33 Logged Illuminance on a Working Plane Third Floor Office Space (DT500) – *MGA*

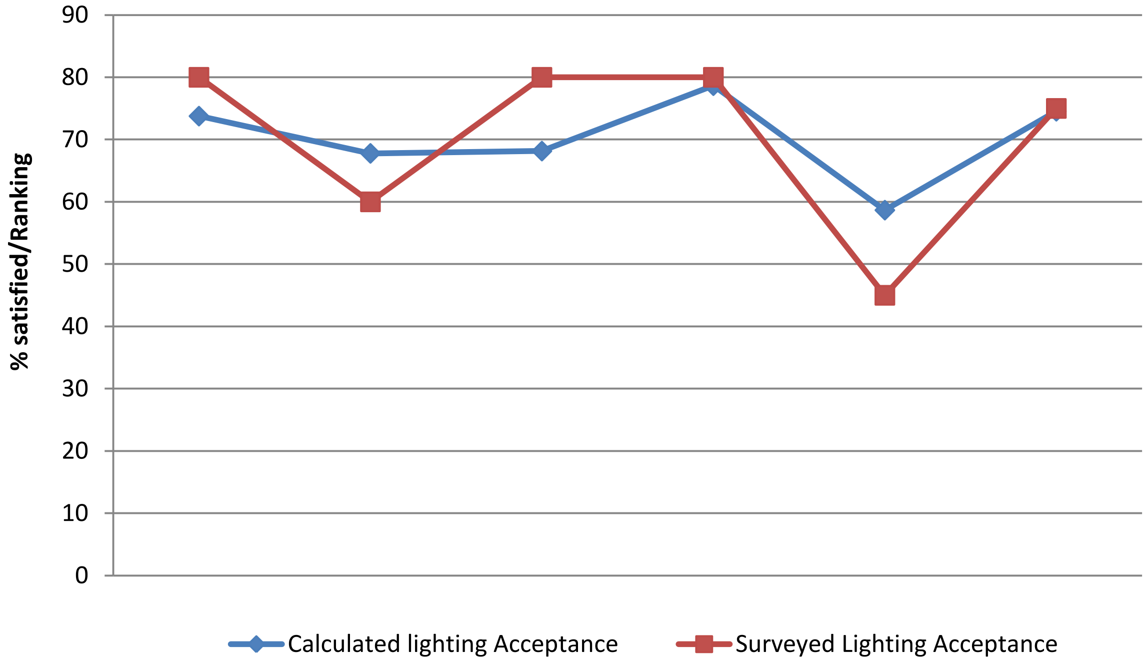


Figure 5.34 Calculated vs. Surveyed Acceptance of Lighting in the offices - *MGA*

5.2.5 Indoor Environment Quality Assessment Results

The indoor environment in the Marsh Grochowski and Associates offices could be described as a grade C office, consisting of crowded and lowly furniture levels, and less flexible designs with poor finishes. The lobbies were poorly designed and decorated while the kitchen and circulation areas were old fashioned although fairly well maintained. Some of the features of the office are highlighted in Figures 5.35.

Figure 5.35 Top Floor Office design, furniture levels, etc - *MGA*

IEQ values were calculated using the equation explained in Chapter 3 and the results showed a standard deviation of 1.94 and a sample mean of 86.7. The minimum IEQ value was 83.6 and a maximum value of 89.6 was observed. This shows a fairly uniform calculated IEQ throughout the office with most occupants thinking that the quality of the indoor environment was acceptable.

However surveyed results showed large variations from one individual to another and this could be attributed to the presence of individuals who suffer from conditions that affect their perceptions of some aspects of the indoor environment. Measurements taken at their workstations did not show much difference from the rest of the office. Calculated and surveyed IEQ values were compared and using only results from healthy occupants they showed fairly satisfactory agreements as shown in Figure 5.36. This is mainly due to the fact that the adaptive thermal comfort index is applicable to a large group of people (de Dear, 2000) and only 4 valid responses were obtained from the office.

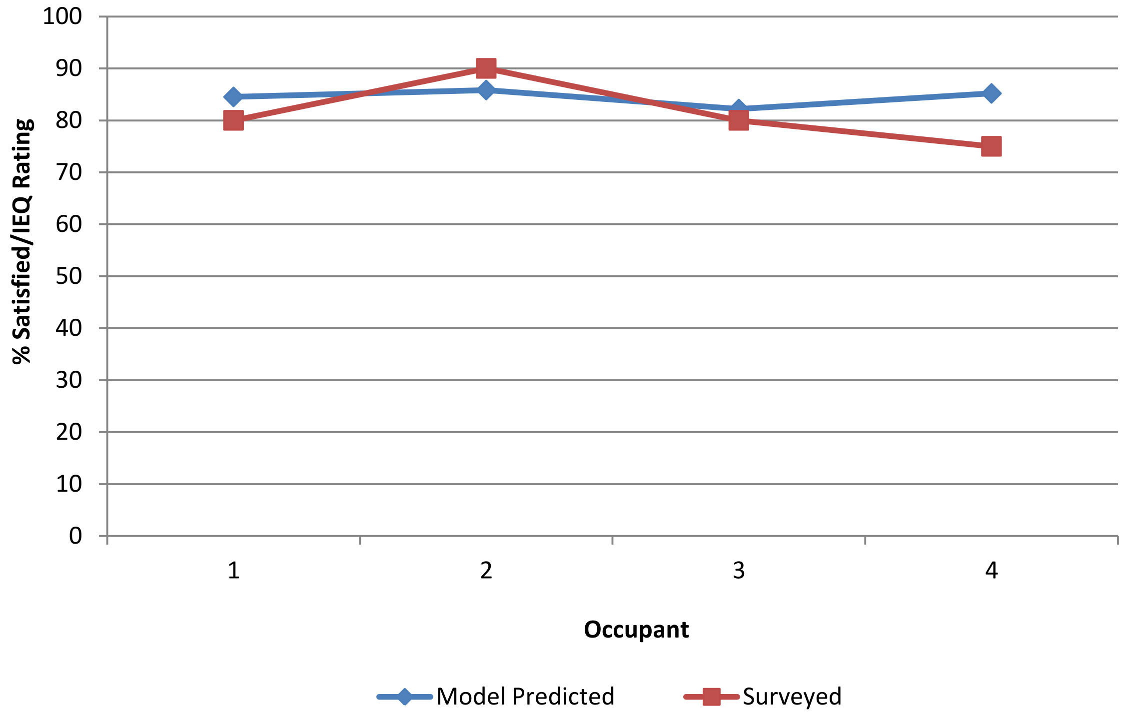


Figure 5.36 Calculated Vs. Surveyed IEQ - *MGA*

Some occupants in their evaluation of IEQ expressed disappointment with the age of the building, "the presence of single glazed windows and open triple height spaces" and overcrowding.

5.2.6 Long Term Evaluation Capabilities of the IEQ Model

A second attempt at the applicability of the IEQ model for long term evaluation of the indoor environment was tested in this case study for a period of two and half hours and the results are summarised below. Measurements taken from position 2 first floor office between 11:30 AM and 2:00PM were used to test the model and the results are summarised in Table 5.9. Results of thermal comfort, Acoustics, IAQ and IEQ are all shown in the table.

Table 5.9 Indoor environment parameters results for the period 11:30 – 14:00 – *MGA*

Time	Thermal Comfort	IAQ	Lighting	Acoustics	Model Predicted IEQ
11:00	89.5	83.7048	73.76806	89.2	84.5
11:30	88.9	83.7048	67.78457	100	85.8
12:00	88.9	83.7048	68.15401	100	85.8
12:30	90.2	83.7048	78.65293	100	88.1
13:00	87.4	79.2296	58.67069	100	82.2
13:30	87.4	79.2296	74.55237	100	85.2

The same results are shown using a line graph in Figure 5.37 and the radar chart in Figure 5.38 shows average results for the same period of time. Figure 5.39 is a bar graph showing the percentage of time the space was within limits of any category during the period under investigation.

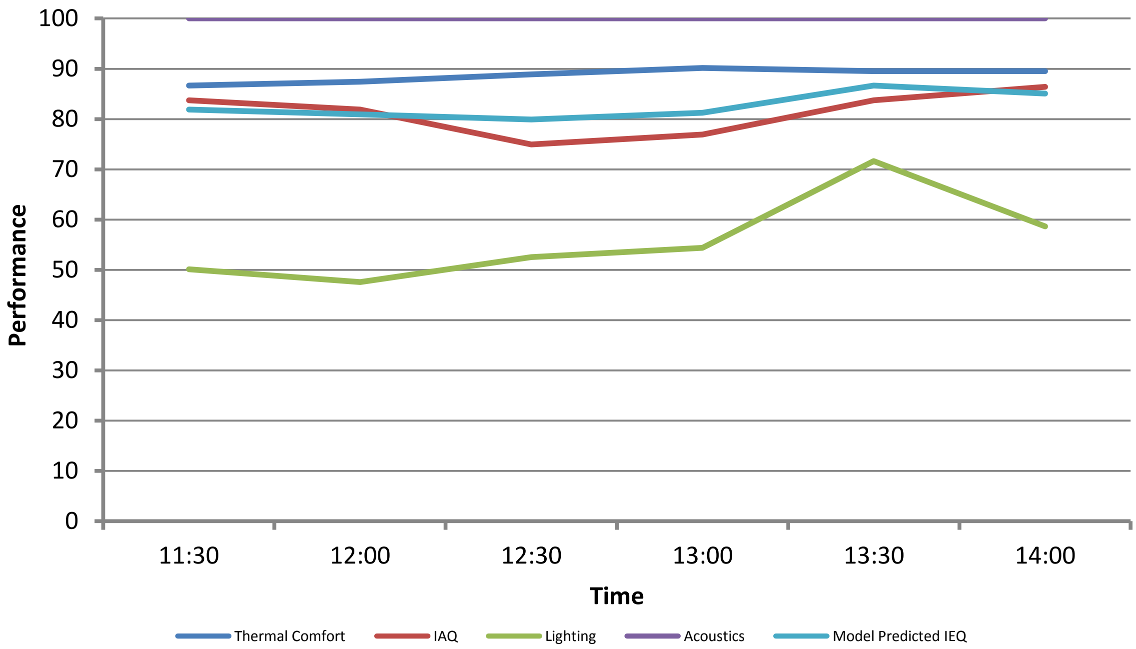


Figure 5.37 Assessment results for period 11:30 – 14:00 – Line Graph (Marsh & Growchoski)

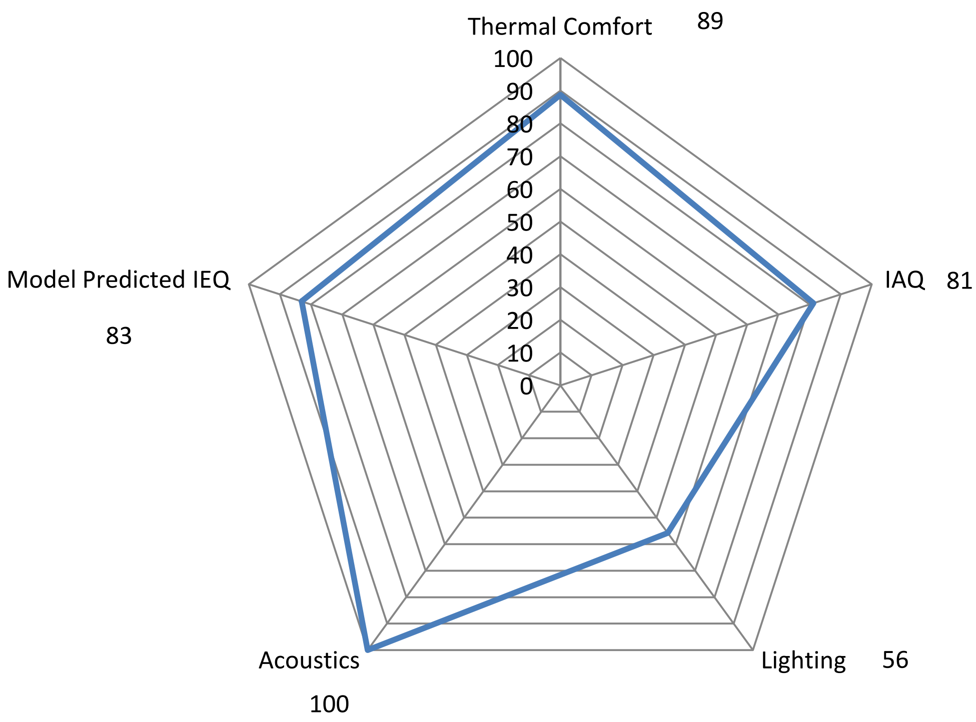
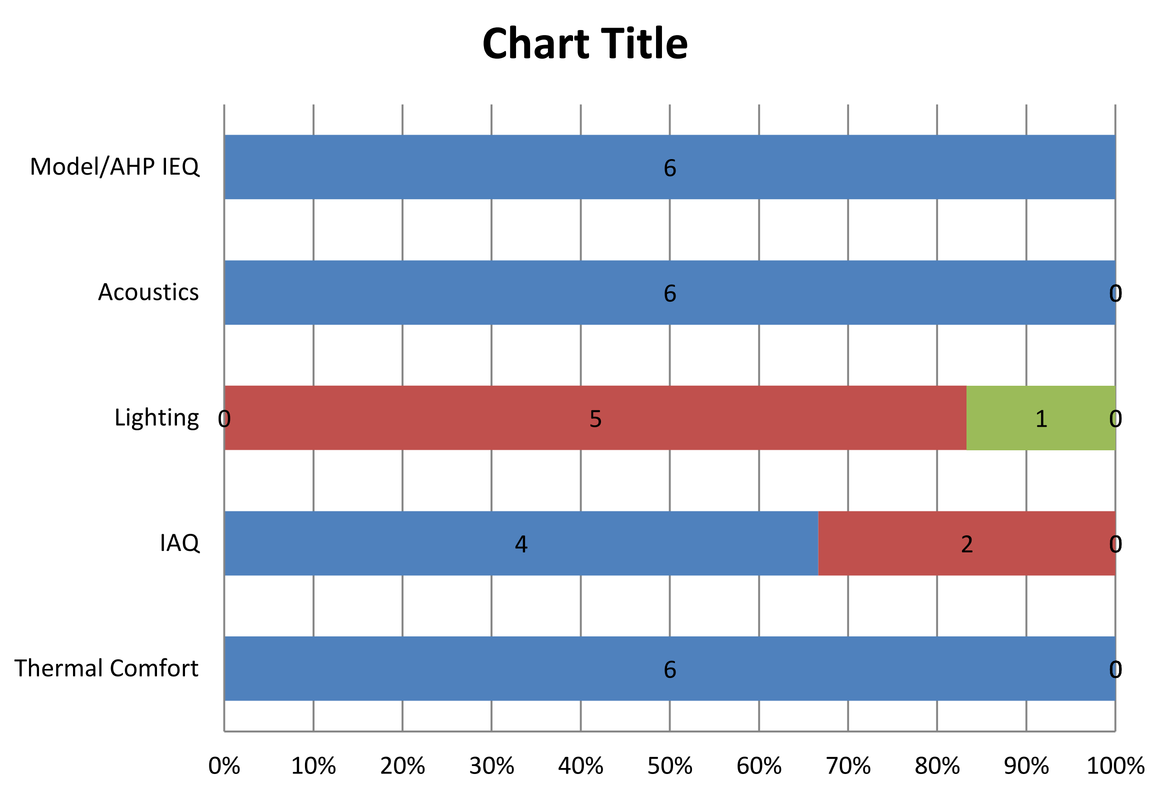


Figure 5.38 Average assessment results for the period 11:30 – 14:00 - radar chart – *MGA*

Figure 5.39 is shows that model calculated IEQ variables fell within the limits of specific categories for 100% of the time therefore we can conclude that IEQ was category II, Thermal comfort category III, Acoustics category I, Lighting category III and IAQ was category II. Using area weighted averages IEQ was calculated for the office for the period 11:30 – 14:00 and the result is summarised in Table 5.10. The result (IEQ value) is the value that should be compared to energy rating of the office for a specified period of time under investigation.



	Thermal Comfort	IAQ	Lighting	Acoustics	Model/AHP IEQ
Category 1	6	4	0	6	6
Category 2	0	2	5	0	
Category 3	0	0	1	0	
Category 4	0	0	0	0	
Category 5	0	0	0	0	

Figure 5.39 Long term assessment results – Bar graph representation – *MGA*

Table 5.10 Average IEQ Value for the Occupied Office Space (the IEQ_{index}) - *MGA*

	Positon 1	Positon 2	Positon 3	Positon 4	Positon 5	Position 6	Average value
IEQ	75	68	67	69	71	73	70.5
Area ratio	0.16666667	0.1666667	0.166667	0.1666667	0.166667	0.166667	

Table 5.10 shows that the weighted average IEQ result for the period under investigation was 70.5

5.2.7 General Considerations for the Indoor Environment

Table 5.11 General checklist for the indoor environment – *MGA*

THERMAL COMFORT - CHECKLIST		
	Room Temperature Control	
v	Monitoring systems (thermostats, etc)	No
v	Room temperature setting	No
v	Individual Control	Yes
v	Zoned control	No
v	Variable Loads and perimeter performance	No
	Humidity Control	No
A/C System Present		No
IAQ - CHECKLIST		
	Ventilation	
v	Mechanical Ventilation System Present	No
v	Air Supply Schedule	N/A
v	Individual Control	No
v	Zoned control	No
v	Variable Loads and perimeter performance	No
	Pollution Source Control	
v	Chemical Pollutants Present?	N/A
v	Asbestos	N/A
v	Evidence of mould, mites, fungi, etc?	N/A
v	Legionella	N/A
ACOUSTICS - CHECKLIST		
	Other Noise	
v	Equipment Noise	Telephone ringing
v	Outdoor Noise and Type	None
	Sound Insulation	
v	Sound Insulation of Internal Walls	N/A
v	Sound Insulation of performance of floor	N/A
v	Units (impacts)	N/A
v	Sound Insulation of openings	N/A
v	Reverberation time of sound	N/A
LIGHTING - CHECKLIST		
	Daylighting	
v	Daylight factor	N/A
v	Orientation of windows or openings	NE/SE/NW
	Antiglare installed	
v	Blinds, curtains for daylight control	Blinds in some areas
v	Anti glare for artificial lighting	No
	Illuminance level	
v	Uniformity of illuminance	N/A
v	Colour of light	N/A
v	Colour rendering Index	N/A
	Light controls accessible	Yes
Other Checklists		N/A

5.2.8 Conclusions and lessons learnt from the study

The study showed that naturally ventilated office buildings provide a greater challenge for building owners to provide a consistently uniform indoor environment. The study showed that occupants of naturally ventilated office tended to take individual action to improve conditions in their work areas. Extra lamps, fans, portable electric heaters and selection of clothing were evidence of the need to adjust to conditions in their workspaces. Decisions to take “matters into their own hands” may prove very costly in terms of energy bills at the end of the year as occupants use any method to keep themselves comfortable with little regards for energy conservation.

5.3 CASE STUDY 3: GRANBY HOUSE, NOTTINGHAM CITY CENTRE, UK

Case study 3 consists of offices situated on the first floor offices of Granby House on Friar Lane in the centre of Nottingham City, United Kingdom. The office is a large open plan type that has been split into several sections that include two general office spaces, a meeting room, one cellular office space, a kitchenette, a store room, toilets and no reception area. This property has been comprehensively refurbished including the common areas and the two office suites. The open plan floor plates are rented by Hestia Managed Services on behalf of the Energy Saving Trust and they are used as walk in advisory (and call centre) and consultancy offices.

The office was occupied by white collar workers consisting of energy advisors, project managers and consultants. Only the call centre area was studied and the occupants performed sedentary activities such as typing, telephone conversations, filing, sorting of mail. Most wore light office clothing consisting of trousers, shirt, tie and light shoes and in some cases light office suites that included jackets. The level of furniture was medium with work stations consisting of drawer desks, filing cabinets, printers and a medium size server placed openly within the office space (bottom corner – marked S).

The HVAC system was mechanical with air supply grills located at the ceiling and a series of radiators (unused) indicating the office was initially designed as a naturally ventilated one. A small conventional gas boiler supplying hot water to the office was located in one of the cabinets and almost all used in the office equipment was Grade A - energy efficient and fitting the service provided by the business. A room thermostat was located in a centrally located pillar and a remote control was available for adjusting temperature and air fan speed as required by the occupants. The main features of the office building are summarised in the Figure 5.40.

THE INDOOR ENVIRONMENT QUALITY ASSESSMENT TOOL (IEQAT) - 2011

1. PROJECT DATA

o	Project Name :	IEQ 3
o	Project Number :	003
o	Client Name :	Energy Saving Trust
o	Client Address :	Granby House, Nottingham
o	Name of Assessor 1:	M Ncube
o	Date of assessment :	09/12/2009
o	Confirmed by :	XXX
o	Date of confirmation :	XXXXX

Office design

o	Office Type	Standard Open Plan
o	Floor level	1st Floor in a three floor building
o	Floor Area	159 m2
o	Age of Building	Floor renovated extensively in 2009
o	Furniture Levels	Medium Furnished

Occupancy Details

o	Occupancy	10 In the studied area (5 female and 5 male)
o	Times	9am to 5pm (Mon -Friday)
o	Type of Work conversations, etc	Sedentary work e.g. typing, telephone
o	Business	Call Centre and Consultancy Office
o	Clothing worn	Mainly light office clothing

HVAC System Type & Controls

o	HVAC systems	Mechanically Ventilated (mixing)
o	Windows	Operable, blinds
o	Ventilation rates	Standard (per m2)
o	Thermostats	Set at 22 Degrees Celsius
o	Service	Every three months

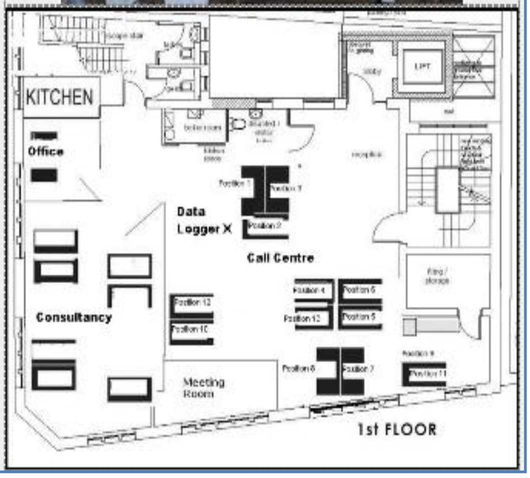


Figure 5.40 Project and building data – Granby House – Nottingham City Centre

The weather for the Nottingham City Centre area on the survey day (06/12/2009) was obtained from weather underground (Weather Underground, 2009). The day was mostly clear with a few cases of scattered clouds and an average relative humidity of 89%. The mean outside air temperature was 8°C and the minimum and maximum temperatures were 7 and 10°C respectively.

5.3.1 Thermal Comfort, IAQ, Lighting and Acoustic Comfort Assessment Results

Following methodologies used in case studies 1 and 2, questionnaires were handed out to occupants between 11:00 and 11:45AM during the survey day and measurement of variables of interest was carried out before, during and after the questionnaire administration exercise. Thermal comfort calculations were carried out using the VB program. The metabolic heat production was estimated at 1.2 met and clothing levels were estimated at 1 clo based on tables presented in Chapter 3. Model calculated PMV (all -0.1) values perfectly matched surveyed ones (0) in an otherwise uniform thermal environment. IAQ, acoustic and lighting comfort ratings were also computed using equations already described in Chapter 3 and the results are summarised in Figure 5.42. The graphs show good agreement between model calculated and survey results for IAQ, thermal comfort and acoustic comfort.

For lighting Model calculated results differed slightly from survey results for positions 8 – 10 while the rest of the positions showed very close agreement indicating that window locations are generally associated with better satisfaction with the lighting environment. These positions were closest to the windows and blinds were drawn during the survey period. Figure 5.43 also shows that thermal comfort and IAQ were uniform throughout the office floor suggesting that the mixing ventilation system was effective. Only one occupant (position 10) expressed feelings of dry nose and they attributed this to the quality of indoor air. As expected acoustic comfort rating fluctuated from one position to another since background noise consisted mainly of abrupt, non continuous telephone conversations, filing, drawers, telephones ringing and interpersonal conversations.

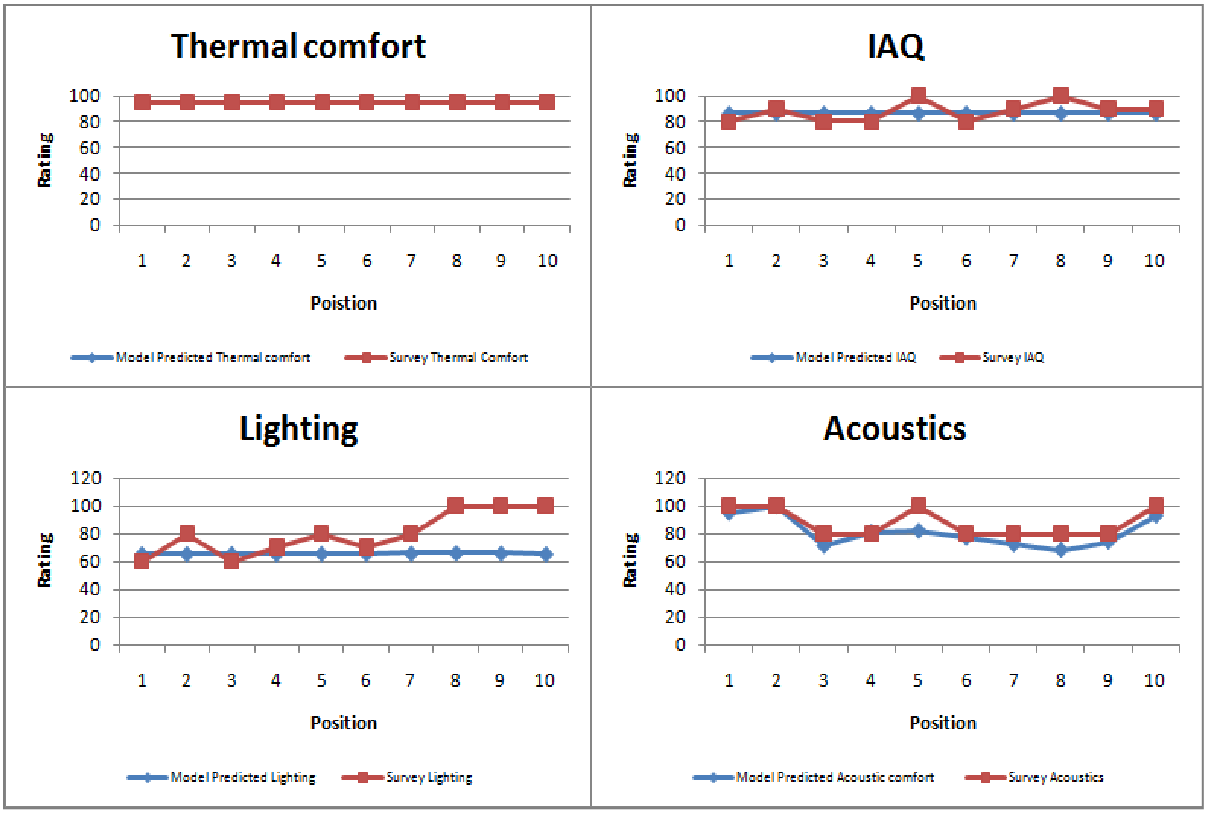


Figure 5.41 Comparison between Model calculated and Survey results - Case study 3 - GH

Model calculated and surveyed (observed) IEQ results also showed very close agreement (Figure 5.42) and as expected survey results showed more variation between occupants compared to model calculated results. The mean model calculated IEQ value was 83.4 and the minimum and maximum values were 80.3 and 87.7 respectively. The standard deviation was only 2.6 suggesting that IEQ was uniform throughout the office as suggested by the contributing parameters.

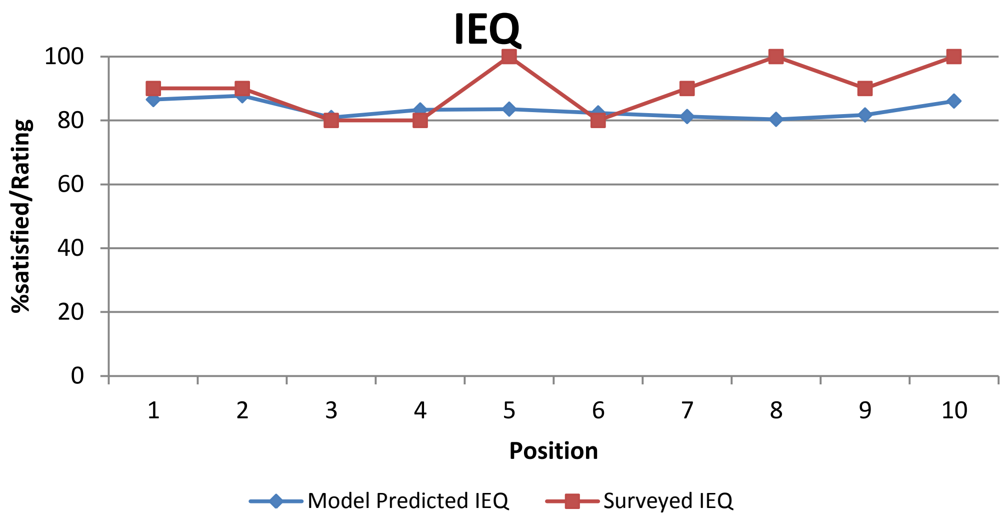


Figure 5.42 Comparison between Model calculated and Survey IEQ results - Case study 3 - *GH*

5.3.2 IEQ Assessment Results for the Granby House

The assessment of the Granby house general office space was carried out for a period of seven hours. The variables of interest were collected every hour (hourly data) and used to calculate IEQ parameters as shown in Figure 5.43 and 5.44.

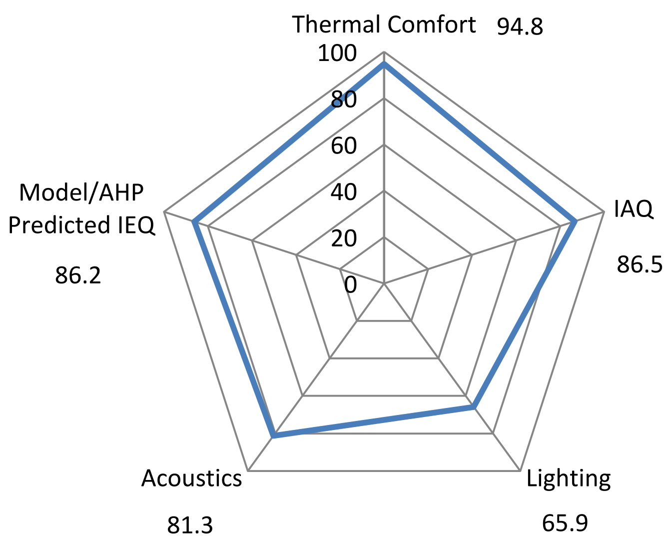
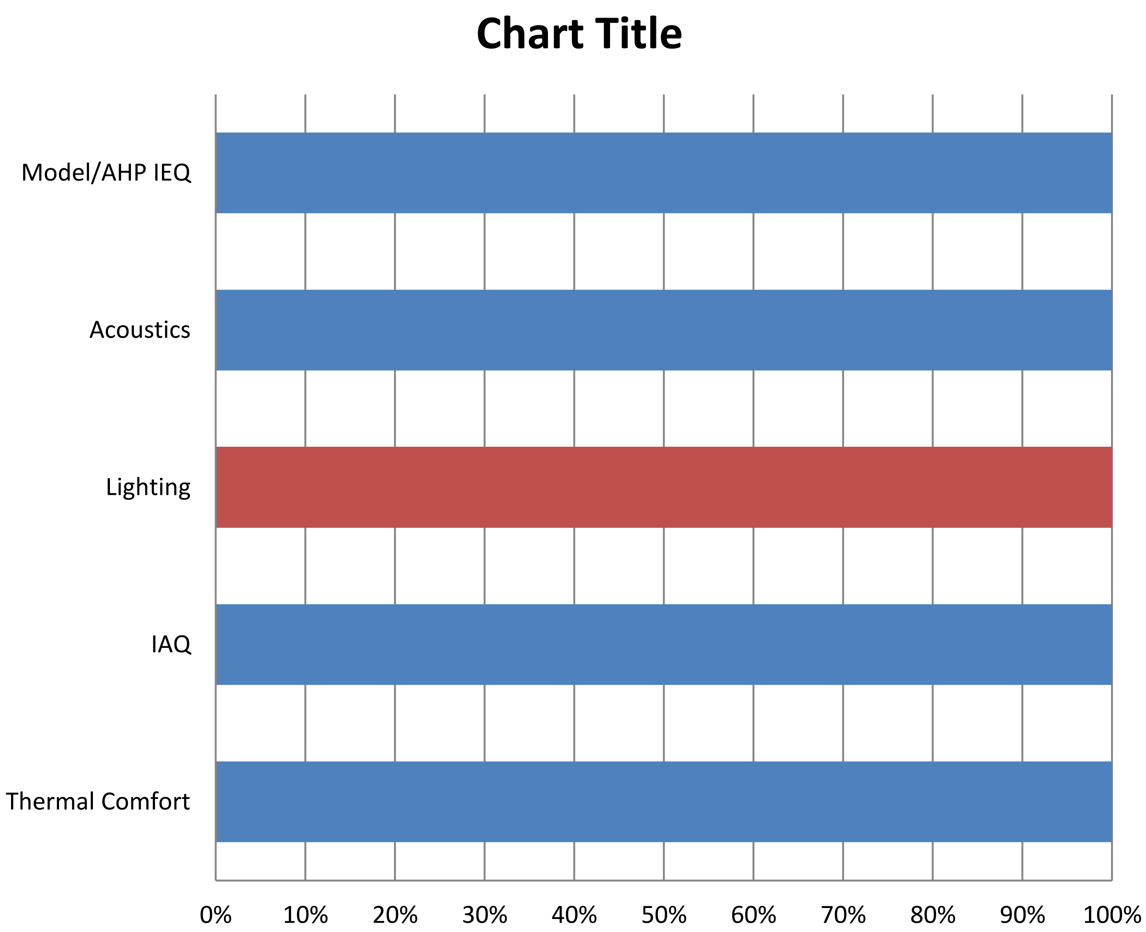


Figure 5.43 Radar Chart – Thermal, Acoustic, IAQ and lighting comfort rating Granby House



	Thermal Comfort	IAQ	Lighting	Acoustics	Model/AHP IEQ
Category 1	7	7	0	7	7
Category 2	0	0	7	0	
Category 3	0	0	0	0	
Category 4	0	0	0	0	
Category 5	0	0	0	0	

Figure 5.44 Bar Graph - Overall IEQ rating of the Granby House office

Classifying IEQ parameters into categories was straight forward for all IEQ parameters. However during the data collection period the average rating for Lighting was about 65.9% (for most of the time) implying that the office received less light during that period. This was mainly due to the partly cloudy sky and the lights were off during that brief period. Based on the information shown in the results the office was category I for that period.

5.3.3 General Checklist of the Granby House Office Space

A general checklist for the office was completed and the results showed that thermal comfort data was readily available during the assessment unlike IAQ, acoustics and lighting which either required more time or specialist knowledge and equipment to complete. The results of the assessment are summarised in Table 5.12.

Table 5.12 General checklist for the indoor environment – Granby House

THERMAL COMFORT - CHECKLIST		
	Room Temperature Control	
v	Monitoring systems (thermostats, etc)	Yes
v	Room temperature setting	Yes
v	Individual Control	Yes
v	Zoned control	Yes
v	Variable Loads and perimeter performance	Yes
	Humidity Control	Yes
A/C System Present		Yes
IAQ - CHECKLIST		
	Ventilation	
v	Mechanical Ventilation System Present	Yes
v	Air Supply Schedule	Yes
v	Individual Control	Yes, windows operable
v	Zoned control	No
v	Variable Loads and perimeter performance	No
	Smoking*	
	Pollution Source Control	
v	Chemical Pollutants Present?	N/A
v	Asbestos	N/A
v	Evidence of mould, mites, fungi, etc?	N/A
v	Legionella	N/A
ACOUSTICS - CHECKLIST		
	Other Noise	
v	Equipment Noise	telephone ringing
v	Outdoor Noise and Type	vehicular traffic
	Sound Insulation	
v	Sound Insulation of Internal Walls	N/A
v	Sound Insulation of performance of floor	N/A
v	Units (impacts)	N/A
v	Sound Insulation of openings	N/A
v	Reverberation time of sound	N/A
LIGHTING - CHECKLIST		
	Daylighting	
v	Daylight factor	N/A
v	Orientation of windows or openings	SE/SW
	Antiglare installed	
v	Blinds, curtains for daylight control	Blinds in all windows
v	Anti glare for artificial lighting	Yes
	Illuminance level	
v	Uniformity of illuminance	N/A
v	Colour of light	N/A
v	Colour rendering Index	N/A
	Light controls accessible	Yes
	Other Checklists	N/A

5.3.4 Conclusions and lessons learnt from the case study

The study was a perfect example of good indoor environment quality with less variation in microclimates across office space and time. Rating of the office using the proposed IEQ Model is less challenging in offices with homogeneous microclimatic conditions compared to rating naturally ventilated offices. Typical IEQAT generated assessment summaries for the three case study buildings are shown in appendix 3.

5.4 MULTIVARIATE REGRESSION ANALYSIS

Regression analysis was carried out to get a better picture of the relative importance of each of the parameters contributing to perceived IEQ for each office buildings. The SPSS statistical software was used to carry out regression analysis and questionnaire data was stored for later use in MLWiN multilevel modelling. Although the use of statistical methods to determine the relative weightings of each of the contributing factors is relatively easy, extreme care needs to be taken to avoid violation of certain rules. One of the basic assumptions in most statistical procedures is that observations are independent, i.e., that information about the scores of any one of the observed cases does not help to predict the scores of any other observation (Lowe, 2009; Kahane, 2008). This assumption is only met if particular selection methods such as the simple random sample are used to select case studies as is in the case in this study. Analysing offices individually (or as groups of similar types) does not lead to the violation of this assumption through clustered observations (dependence caused by physical, geographical or social proximity), instead analysing them separately has the obvious advantage associated with establishing any behaviour typical of those types of offices. This is one of the important reasons why this study is carried out, to establish any patterns that may be associated with certain types of offices.

Regression analysis of the Leeds Town Centre House gives an adjusted R^2 = 0.92 and a significance F value of 1.86*e $^{(-14)}$ suggesting that the model has a lot to say about the behaviour of the dependent variable. Thermal comfort (β = 0.23, p=*0.35*), IAQ (β = 0.35, p=*0.002*), Acoustics (β = 0.13, p=*0.43*) and Lighting (β = 0.29, p=*0.01*). In this case we reject the null hypothesis (Kahane, 2008) based on the significance value F. The constant has been excluded from the regression analysis because firstly, and as expected, a case where all independent variables are equal to zero must produce and IEQ rating of 0 (intercept on the x-axis). Secondly regression results with a constant show a very poor association between the contributors and IEQ (R^2 = 0.42) and the model has a very poor p value for the constant (0.82). The interpretation of the weightings for the Leeds Town Centre House is that, for example, for a unit increase or decrease in thermal comfort the IEQ_{index} increases or decreases by 0.23 respectively, all else being equal. In terms of energy use any energy efficiency measure that increases perceived thermal comfort by 1 unit will add 0.3 to the expected perceived IEQ value. The same explanation applies to the coefficients derived below. The results of this analysis are particular to this office and cannot therefore be generalised to other naturally ventilated office buildings without the advantage of studying several similar offices to establish pattern that may exist those types of offices.

Regression analysis of the MGA office showed that the resultant model explained the behaviour of the dependent variable (adjusted R^2 = 0.91). The model Significance, F is 4.07*e $^{(-50)}$ meaning that the model as a whole has a lot to say about perceived IEQ in that office. Thermal comfort contributes the most to perceived IEQ with a β coefficient of 0.39 (*p=0.02*), followed by IAQ (β = 0.30, p=*0.05*), followed by lighting (β = 0.18, p=*0.02*) and finally acoustics (β = 0.13, p=*0.003*).

The Granby House regression produced adjusted R^2 = 0.92, significance F = 1.6*e $^{(-27),}$ and the weightings for contributors were thermal comfort (β = 0.28, p=*0.06*), IAQ (β = 0.32, p=*0.06*), Acoustics (β = 0.23, p=*0.085*) and lighting (β = 0.16, p=*0.008*). The way coefficients bounce about the weightings also varied from office to office with the highest variance observed at the Leeds Town Centre House and the least at the Granby House. Offices with IEQ conditions "typical" of natural, mechanical and mixed mode ventilation need to be considered in order to get typical patterns for different office types. "Typical" conditions are those conditions which are consistent with median values of data expected in office buildings in the UK (BRECSU, 2000). Weightings need to be generated for all office grades for both the heating and cooling seasons and recommendations for future research are discussed in Chapter 6.

Table 5.13 compares regression coefficients derived from case studies and those from the AHP. The Table suggests that different equations or models are required for different types of offices and fitting questionnaire data to proposed models at occupant level (so called level 1) does not necessarily produce resultant models that can be applicable to all offices. For example the resultant weightings could work well for the Granby house and not for the Marsh-Grochowski Associates and the Leeds Town Centre House. The coefficients also vary from building to building for example the thermal comfort coefficient for the MGA office is very high compared to the rest of the studies while the lighting coefficient for the Leeds Town Centre House is higher than that of the other offices suggesting that different buildings need to be accounted for using different models. It is also possible for variations to exist between buildings of similar types and this can only be determined through extensive studies.

Carrying out regression analysis at occupant level, i.e. taking observations as if they come from one office resulted in coefficients that are a little biased towards the Leeds office as shown in Table 5.13. This trend could be explained by the fact that the Leeds Town Centre House office contributed about 60 percent of the total number of respondents. Although the importance of the weightings towards perceived IEQ is trivial since all weightings have been deliberately made to add up to 1 (the error term is ignored), weightings still play a very important role when deciding which energy efficiency initiatives most affect human comfort. The weightings of the AHP indicate that they may be more relevant to air conditioned buildings with homogeneous conditions and not for the naturally ventilated or heterogeneous office environments.

Table 5.13 Comparison of adjusted relative weightings produced by the AHP and the regression processes

Process	Thermal comfort	IAQ	Acoustics	Lighting
AHP	0.24	0.34	0.19	0.23
Leeds	0.20	0.38	0.13	0.29
MGA	0.35	0.31	0.16	0.18
Granby H.	0.28	0.32	0.16	0.23
Regression (All)	0.24	0.35	0.14	0.26

5.5 Conclusions

Multivariate analysis shows that different types of offices environments need to be accounted for using different models and that the AHP could be more suitable for air conditioned homogeneous conditions. The exercise also shows that results cannot be generalised to all office buildings in the UK since a very small number of offices have been used in this thesis. More offices need to be investigated and any patterns that exist between different types of offices need to be highlighted in the models. This highlights the importance of the multilevel analysis approach to IEQ assessment which will be discussed further in the next chapter, and which is a subject of future studies.

6. Discussions, Suggestions for Future Work and Conclusions

6.1 GENERAL DISCUSSION AND SUGGESTED IMPROVEMENTS

The IEQAT is a promising novel tool that can be used for assessing the quality of the indoor environment in office buildings in the UK. As explained earlier in Chapter 3 the IEQ model was developed from proposed contributing factors using weighting of factors suggested by Chiang and Lai (2002) AHP. The weightings were verified by fitting a regression model to questionnaire results obtained from the occupants of three office buildings in the UK. It was hoped that the relative weightings derived from regression would provide information which would be more relevant to the UK situation since the case study buildings which were selected for that purpose were located within that region.

The relative weightings shown in Table 5.11 suggest that AHP and regression model (correlation) generated results are in close agreement for the Granby House and less so for the other two buildings. As a universal index (taken at occupant level) the regression generated model showed good correlation with observed IEQ results (Figure 5.47) with an R^2 value of 0.94 and a significance (*F)* value of 3.91exp (-27). However looking at results at a higher level (at office level) presents a different picture as offices that exhibited less favourable indoor environment conditions agreed less with the AHP. This aspect needs to be investigated further and more case studies need to be carried out to establish trends associated with different IEQ conditions. Some researchers suggest that a number of subjective observations greater than 500 are needed in order to minimise the errors in weightings (Nemes et al, 2009).

The IEQ index would be more powerful if cause and effect relationships could be established between IEQ and contributing factors. Unfortunately the study was not been able to establish important mechanisms of the relationships to be able to justify the study of the cause and effect dimensions of this model. Studies have confirmed that it is difficult to isolate causes from effects in buildings (Leaman and Bordass, 1999) and even if this was done an ideal IEQ index would still require extensive knowledge on how human systems perceive IEQ and how this relates to the risk of negative health outcome.

Perception of IEQ would be based on knowledge of how the human body reacts to stimuli (IEQ variables) coming in via respective sensory organs (skin, ears, eyes, nose), how it processes or screens the information and how the final perception of the indoor environment is reached. This process needs to be explained physiologically; otherwise continued reliance on predictive correlative studies will remain in place. The development of a thorough IEQ model needs to take this study deeper into extensive experimentation involving human subjects.

The accuracy of the IEQAT tool depends on the accuracy of the data used as input in the calculations, for example the accuracy of measured data depends on the accuracy of the data collection procedures and the equipment used. Similarly, the relative accuracy of simulation data depends on the accuracy and quality of the simulation exercise. The accuracy of the IEQAT also depends largely on the methodology used for its development. The assumptions made in the development of assessment tools for thermal comfort, IAQ, acoustic comfort, lighting and IEQ will influence the results and therefore influence the decision making processes relating to energy use, comfort and even cost.

6.1.1 Thermal Comfort Index

Thermal comfort calculation in air conditioned and mechanically ventilated office buildings using ISO 7730 is the industry standard worldwide. The use of the PMV model to determine perceived thermal comfort however has its limitations. Studies by Humphreys (Humphreys, 1994), noted that the PMV model was accurate (when compared with observed PMV) in laboratory studies where occupants wore light clothing and carried out sedentary work but was less accurate for heavier clothing and higher activity levels. Model calculated PMV values were approximately 0.2 more than observed values in the Leeds Town Centre House, and 0.1 less for the Granby House.

The Lace Market (Marsh Grochowski & Associates) building used the adaptive comfort model and calculated % satisfaction results differed from observed ones by as much as 18% and the reasons have already been explained in Chapter 5. Charles (Charles, 2003) summarised studies by several researchers and concluded that the predicted and actual thermal sensations differed for non neutral conditions and got larger the further away from thermal neutrality one moved, and that occupants were more sensitive especially to changes in temperature than the PMV model could predict under those conditions.

This conclusion was observed at the Leeds office where there was a slight difference between predicted and observed PMV, and this could be due to the fact that questionnaires were completed soon after sudden changes in temperature. Changes in temperature still had an effect on the perceptions of thermal comfort for tens of minutes after the initial change was recorded as indicated in the questionnaire responses. The results of the two mechanically ventilated buildings show that PMVs are better estimated in uniform offices than in heterogeneous office environments, therefore the TC_{index} (Thermal Comfort index) should be used for offices where steady state conditions prevail.

The last statement is a very "uncomfortable" one because it limits the use of the PMV index to homogeneous offices leaving poor performing offices (non steady state) at the mercy of a long wait for new indices to be developed. It is important to note that the reliance on the PMV model means we have to accept the errors that model brings until such a time that better models or improvements on the existing model are available. Two main types of errors to be expected in field settings were identified by Charles (2003) and they are listed below:

- Measurement errors associated with estimations of physical and personal variables and
- Contextual errors associated with differences in participants' races, gender, age, physiology, adaptation, building differences and the influence of the outdoor climate.

The model also is not suitable for situations where local thermal discomfort exists, meaning that different models need to be used, e.g. the draught model, PPD due to vertical temperature differences, cold floors, etc. new equations for calculating PD due to the above conditions are found in Chapter 3, *equations* 3.11 -13. Discomfort caused by radiant temperature asymmetry can also be calculated and the methodology is found in the EN ISO7730 (EN-ISO7730, 2005). In Figure 6.1 the percentage of people dissatisfied with radiant temperature asymmetry caused by warm ceiling, cool wall, cool ceiling and warm wall is shown graphically.

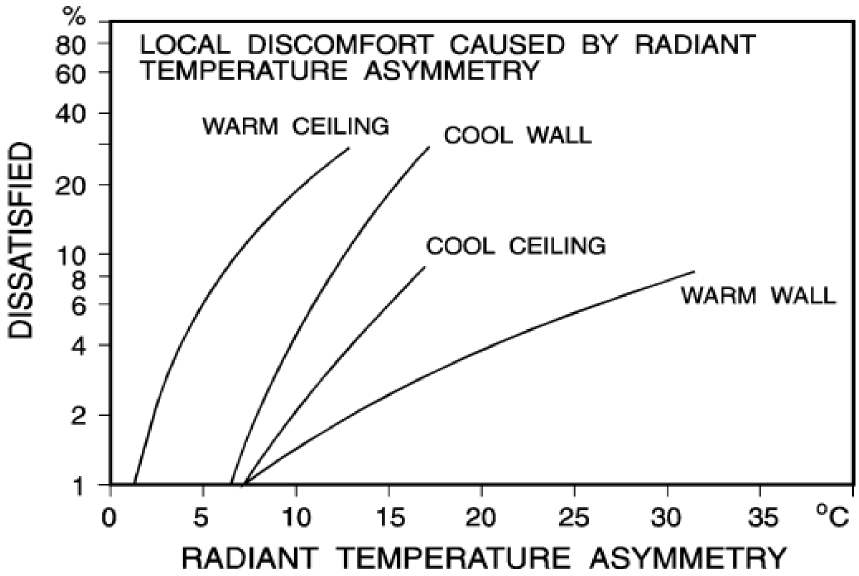


Figure 6.1 The Percentage of those dissatisfied as a function of radiant temperature asymmetry caused by warm ceiling, a cool wall, cool ceiling and warm wall (Olesen and Parsons, 2002)

Figure 6.1 shows that people are more sensitive to radiant asymmetry caused by warm ceilings and cool walls than radiant asymmetry caused by cool ceilings and warm walls. The graph shows that occupants can tolerate asymmetries of only up to 5°C from warm ceilings (5% Dissatisfied) but up to 14°C for cool ceilings (5% Dissatisfied). Occupants can also tolerate asymmetries of up to 10°C and 23°C for cool and warm walls respectively (for 5% Dissatisfied). Olesen and Parsons (2002) argues that radiant asymmetry is less common in mechanically ventilated and air conditioned spaces except in offices with high illumination levels and large window areas. Large windows are associated with direct solar radiation (radiant asymmetry) and lighting problems such as glare therefore it should be avoided (Olesen and Parsons, 2002).

Combining the PMV index with models explained above presents a problem similar to that of the single index based IEQ models (a vicious cycle) simply because little is known about how the indices can be added to produce one representative value and that PPD values overlap i.e. those dissatisfied with draughts could also be dissatisfied with temperature, and so on. The equations discussed above need to be added to the IEQAT to improve its performance. Naturally ventilated offices use different criteria for thermal comfort as explained in Chapters 2, 3 and 5.

The effects of physical variables affecting thermal comfort on perceived IEQ is important for purposes of establishing the link between energy use and occupant comfort. It is essential for example, to get an idea of how much influence a change in temperature can bring to perceived IEQ for purposes of programming the tool. To investigate the effects of each of the variables at all possible conditions (various office microclimates) would require too many equations and this would be time consuming and nearly impossible to complete. However the problem could be easily solved using a computer program (Computer Code) therefore the formulations could be included in the IEQAT's modelling capabilities. Example Equations linking variables to IEQ are derived in the next paragraphs.

The Effects of Air and Mean Radiant Temperature on Thermal Comfort

Figure 6.2 shows the relationship between Thermal comfort rating and, air and mean radiant temperature. By showing the effects of temperatures on thermal comfort we can demonstrate their impact on occupant comfort since thermal comfort forms part of IEQ acceptance. The turning point of the curve is the set point (neutrality temperature). The graphs were produced by varying air and mean radiant temperature and keeping all other variables constant. For offices where mean radiant temperature differs from air temperature individual equations can be produced and added into the computer code to cater for the effects of each of the parameters. For example air temperature/mean radiant temperature were plotted against IEQ at 1°C increments from 18 to 28°C while keeping air velocity at 0.05m/s, relative humidity at 50%, Clothing level at 1 clo and metabolic heat production at 1 met.

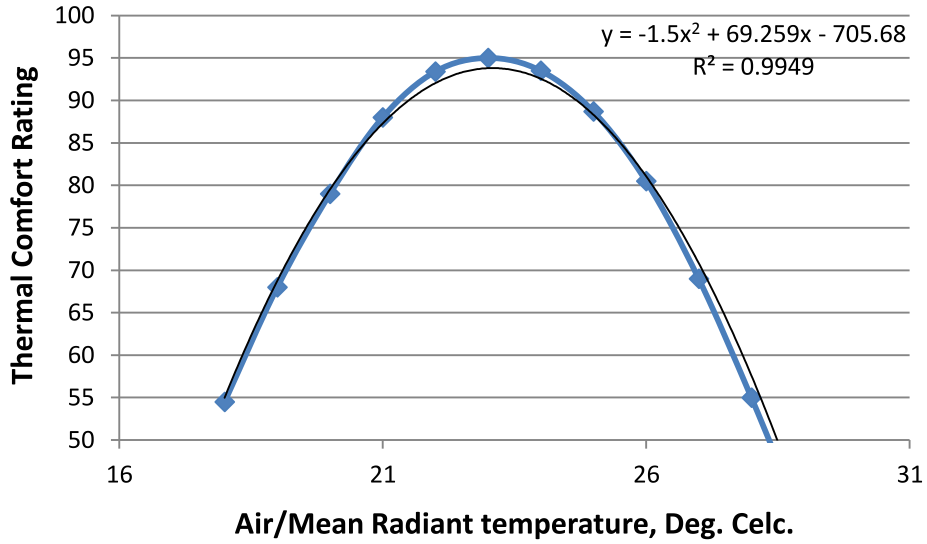


Figure 6.2 Effects of changes in air and mean radiant temperature on IEQ ratings

Adding a polynomial trend line to the graph produces an equation (R^2 value = 0.9949) that can be used to improve the decision making process because the impacts of changing the variables on thermal comfort (and hence IEQ) and energy can be made. The Effects of air /mean radiant temperature on perceived thermal comfort when all other variables are held at constant is shown by the relationship:

$$T - Effect\ on\ Thermal\ Comfort = -1.5t^2 + 69.26t - 705.68 \qquad \mathbf{6.1}$$

An energy efficiency programme that changes air temperature will have a greater effect on perceived IEQ and increasing or decreasing the design value or operational value of the variables has implications in terms of the amount of energy used in the office.

The Effects of Air Velocity on Thermal comfort

The effects of air velocity (including its temperature dependence) on perceived thermal comfort is illustrated in Figure 6.3. Plots of varying v (above and below a temperature set point, e.g. 23°C) against thermal comfort rating at various temperatures are illustrated. For example at 22°C increasing air velocity has a negative effect on thermal comfort whereas at 26°C it has a positive effect. The relationships between air velocity and thermal comfort at 22°C and 26°C are shown by equations 6.2 and 6.3 respectively.

$$Tc\ rating = 95.78 * e^{-0.387x} \qquad \mathbf{6.2}$$

$$TC\ rating = 4.897\ln(v) + 94.72 \qquad \mathbf{6.3}$$

Increasing air velocity means more energy is used to pump the air at higher flow rates and the effects on thermal comfort and IEQ need to be programmed accurately if comparisons are to be made.

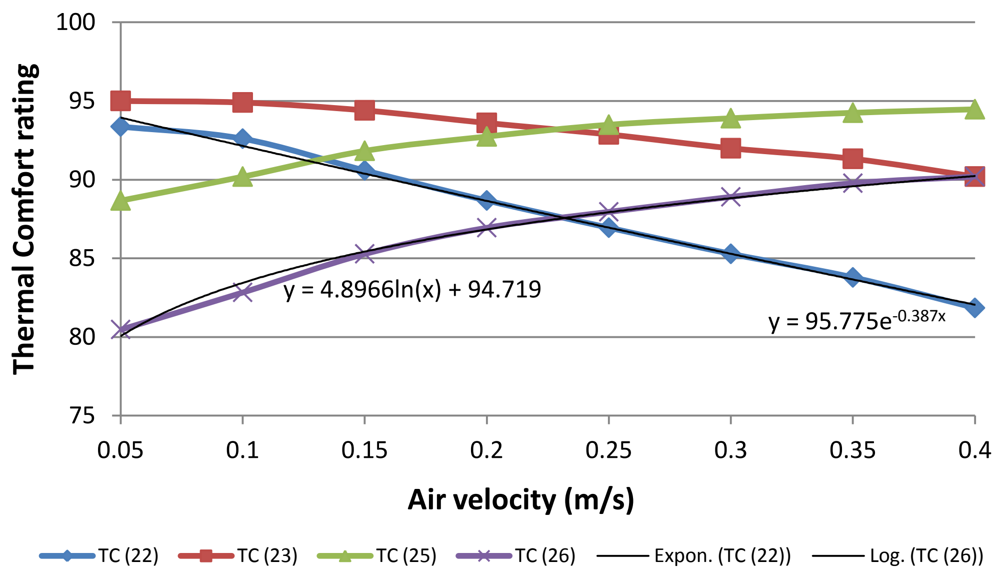


Figure 6.3 Effects of Air Velocity on Thermal Comfort

The Effects of Relative Humidity on IEQ

A plot of relative humidity against IEQ is shown in Figure 6.4 and the graph shows that the effects of relative humidity are highest nearer to RH value of 50%. The trend line produced in the graph has an R^2 value of 0.95 suggesting a strong association between the two variables of equation 6.4.

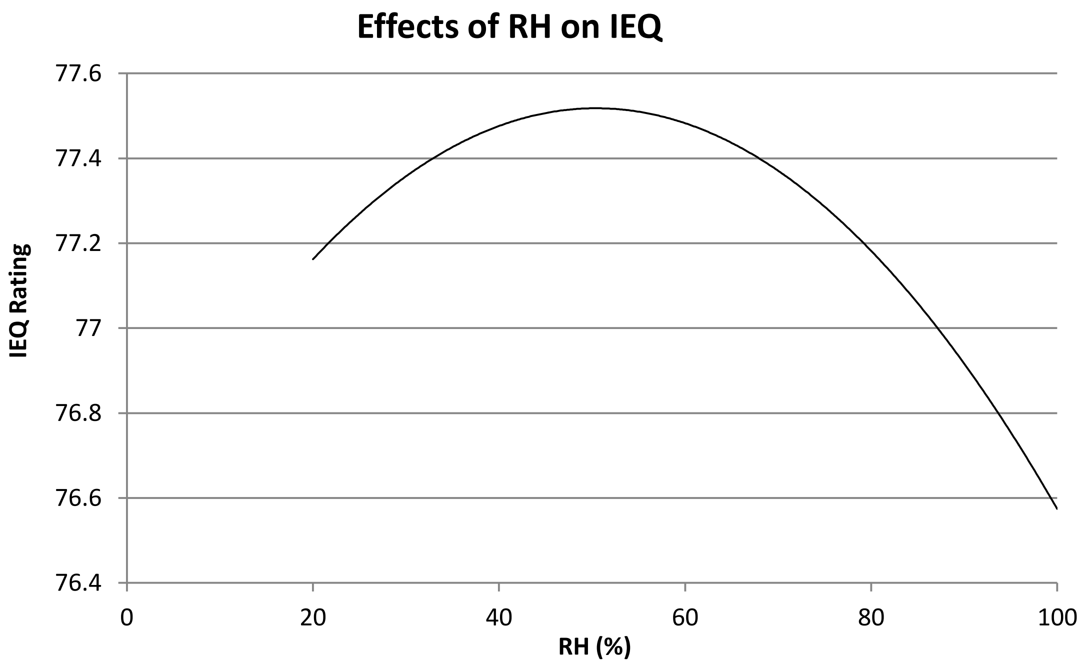


Figure 6.4 Effects of Relative Humidity on IEQ

Humidification and dehumidification processes are energy intensive hence the effects of changing humidity levels in supply air on perceived IEQ need to be known to office designers. The Effects of Relative Humidity on perceived IEQ when all other variables are constant is shown by the relationship:

$$IEQ\ rating = -0.0004(RH)^2 + 0.00387(RH) + 76.541 \qquad \mathbf{6.4}$$

6.1.2 The IAQ Index

The IAQ assessment model presented in this thesis only uses three forms of input namely CO_2 concentration, air pollution level in decipol and ventilation rates to calculate perceived IEQ. In this thesis only the CO_2 route was investigated leaving the other two open to further investigation although these methods are generally accepted as correlating well with perceived IAQ. The results of IAQ assessment of office buildings showed a good agreement, as explained in Chapter 5, with observed values bouncing about the model calculated ones in the Leeds Town Centre House study, and the model overestimating perceived IAQ in the Lace Market office study. The model was almost perfect for the Granby House - again indicating (as in thermal comfort assessment) that IEQ models tend to do better in air conditioned homogeneous environments. The model's performance depends on the quality of input data hence data collection methods and equipment needs to be of the required standard in order to reduce the size of error in calculation.

A comprehensive approach to IAQ assessment has been urged on by researchers (Moschandreas and Sofuoglu, 2003) although there is still a long way before an index that takes into account all parameters relevant to IAQ assessment is developed. An ideal model, which at present is beyond the realms of a PhD study, should include a database of all known factors that cause dissatisfaction with the quality of indoor air including all factors known to cause negative health effects. This should include the sources of pollution, source strengths and the kinetics of release of pollutants. Exposure – effect relationships for all pollutants listed in the database needs to be documented and a formula or model that shows the additive or combined effects of combinations of pollutants needs to be developed. Kinetics should express both health and comfort (satisfaction) effects of relative quantities of known pollutants. Equation 6.4 shows a hypothetical IAQ expressed as a function of known pollutants (summation of pollutant concentrations multiplied by their relative weightings).

$$IAQ \approx \left(\sum_{i=1}^{n} P_i W_i\right) \qquad \mathbf{6.5}$$

Unfortunately such expressions would take a long time to develop hence for the time being calculations will have to depend on information available in literature, whilst urging research forward.

A graph that shows the relationship between IAQ and IEQ is shown in Figure 6.5 and an equation showing the same relationship is shown by equation 6.6. The equation can be used to make choices on which variables to manipulate in order to improve energy efficiency in the office. For example, Changing CO_2 concentrations could involve increasing ventilation rates, a decision that could increase electrical power consumed by the pumps and fans.

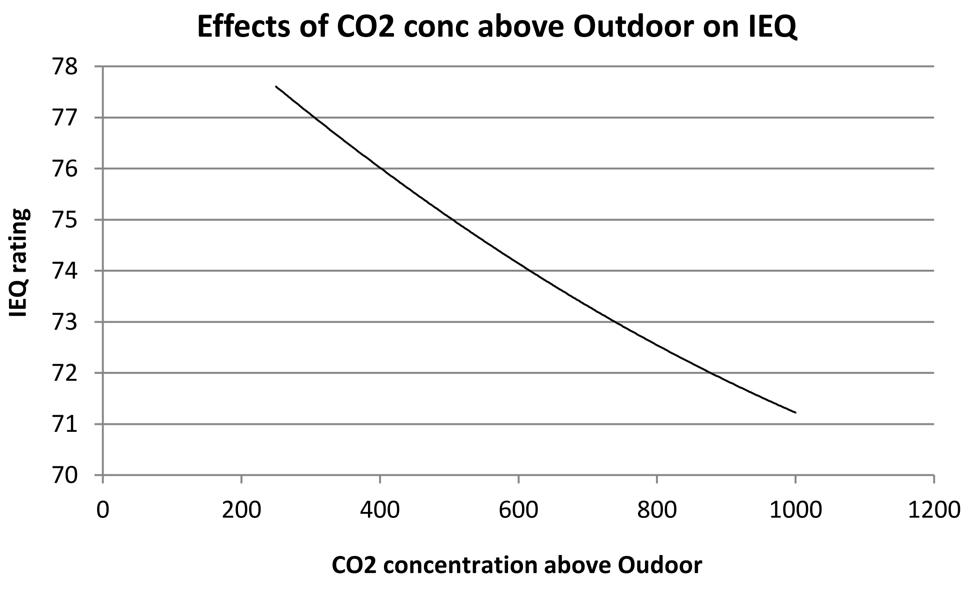


Figure 6.5 Effects of Indoor CO_2 Concentrations on IEQ

The Effects of CO_2 on perceived IEQ when all other variables are constant is shown by the relationship:

$$IEQ\ rating = 3 \times 10^{-6} \times conc.CO_2{}^2 - 0.0128 conc.CO_2 + 80.597 \quad \mathbf{6.6}$$

In offices where PVS are used a new equation for estimating perceived air quality can be utilized. The equation was developed by Zeng and Zhao (2005). Dissatisfaction due to a personalized ventilation system supplying isothermal fresh air can be calculated using *equation* 6.7.

$$PD_{PVS(Q)} = e^{[(1-\varepsilon_p)^{-0.25} \times (\ln(100 \times PD_{MVS(Q)}) - 5.98) + 5.98]} \quad \mathbf{6.7}$$

Where PD_{MVS} is PD with air pollution level as given in equation 3.14 and ε_p is the personal exposure effectiveness defined as:

$$\varepsilon_p = \frac{(C_{I,O} - C_I)}{(C_{I,O})} \quad \mathbf{6.8}$$

6.1.3 Lighting Quality Index

A new office lighting rating index was developed for the IEQAT based on the amount of illumination received on a working plane. Illumination level is an excellent indicator of the amount of both natural and artificial light in an office building. This approach is based on findings by early researchers (Saunders, 1969) who found that this parameter correlated very well with perceived visual comfort and its performance in this study was satisfactory. This was confirmed in this study where there were good agreements between the amount of illuminance measured and occupants' evaluation of the lighting environment. However lighting quality or visual comfort in much more than just illuminance, more parameters are involved in visual comfort. Other factors need to be brought into the index if the "dream" to produce comprehensive lighting indices is to be realised.

These factors include the following glare, colour of light (artificial lighting), daylight factors, the colour rendering index, uniformity of illuminance, etc. The factors that are not included IEQAT calculation methodology are however considered using checklists provided. Even though this is done it is most ideal for lighting comfort indices to be based on how the human eye reacts to various visual parameters and how the information is processed into visual perception and comfort. This would need extensive experimentation with variables and the involvement of human subjects. The effects of increasing illuminance levels on perceived IEQ with all other variables constant is shown in the plot in Figure 6.6.

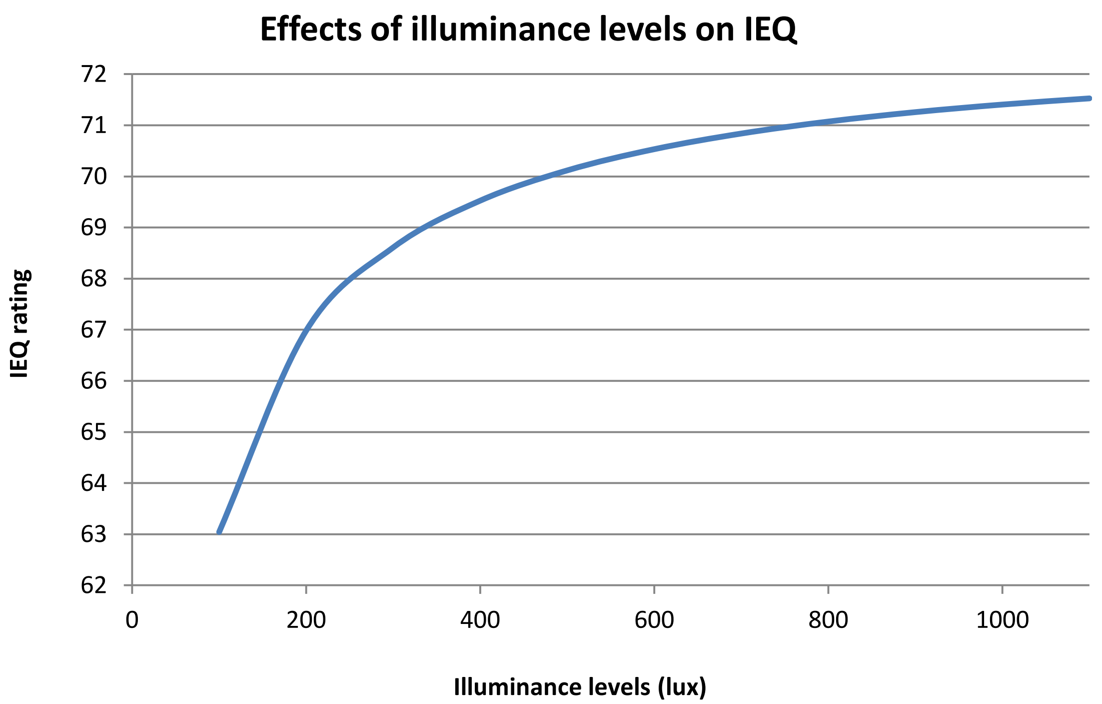


Figure 6.6 Effects of illuminance on IEQ

The equation linking illuminance to IEQ can be produced by substituting equation 3.25 into equation 3.30 (Chapter 3) and the equation produced is:

$$IEQ\ rating = 0.30 \times TC_{index} + 0.36 \times IAQ_{index} + 0.16 \times (-1.76X^2 + 738X - 690.29 + 0.18 \times ACcindex \qquad \textbf{6.9}$$

$$IEQ\ rating = 0.30 \times TC_{index} + 0.36 \times IAQ_{index} + 0.16 \times (-1.76[\ln(lnx)]^2 + 738lnx - 690.29 + 0.18 \times ACcindex \qquad \textbf{6.10}$$

Simplifying the equation for purposes of programming it becomes:

$$G = 0.176\ [\ln(lnx)] - 738lnx, \qquad \textbf{6.11}$$

$$where\ G = -\left(\frac{(IEQrating - 0.30TC_{index} - 0.36IAQ_{index} - 0.18ACc_{index})}{0.16}\right)$$

The equation is used to plot illuminance against IEQ for purposes of energy use comparisons when all other variables are held constant.

6.1.4 Acoustic Comfort

In this thesis a new index for rating acoustic comfort in offices provided an opportunity to link background noise level with satisfaction with the acoustic environment. The equation providing that link is shown below while a plot of background noise against IEQ with all other variables constant is shown in Figure 6.7.

$$IEQ\ rating = -0.36 \times Background\ noise\ level + 89.8 \qquad \textbf{6.12}$$

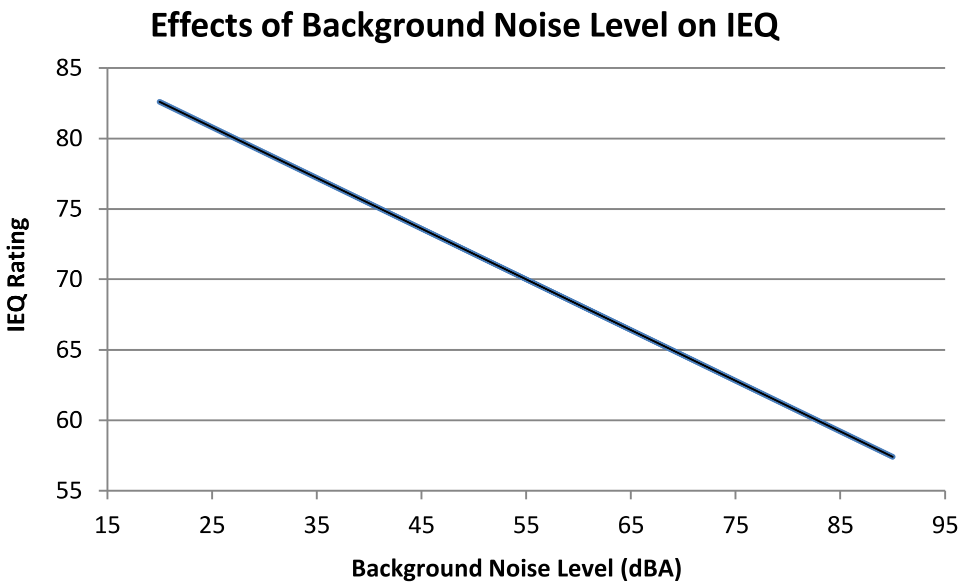


Figure 6.7 Effects of Background noise level on IEQ

The index performed very well for all case studies despite complications associated with sudden fluctuations in sound pressure levels caused by abrupt speech and the untimely ringing of the telephone, etc. The Lace market office (naturally ventilated office) showed more variation in observed acoustic comfort ratings than the Town Centre House and the Granby House.

This could be due to the location of the office and its poor sound proofing walls and windows that allowed noise from outside to be heard by the occupants. However the acoustic comfort index still needs to be improved so that it takes into account all other factors that may be relevant to occupant’s perception of the acoustic environment. Important factors such as sound frequency, power, etc need to be weighted in when considering future acoustic comfort indices.

6.1.5 Important features of the IEQAT

The IEQAT methodology developed in this thesis allows the calculation of thermal comfort, IAQ, acoustic, lighting comfort and perceived IEQ using the same variables used for building energy performance evaluation. This approach allows comparisons to be made between the two aspects of building performance and encourages decisions that provide the best balance between occupant comfort and energy use. This tool is designed to be used for assessment of all types of offices and similar buildings in the UK using the following types of data as input:

- Design;
- Calculated;
- Measured; and
- Questionnaire (survey) data.

The results of the assessments (quantities) can be calculated on any one of the following basis depending on the amount of data that has been collected:

- Instantaneous (real time);
- Hourly;
- Daily;
- Weekly;
- Monthly;
- Seasonal; and
- Annual.

Using this tool it is possible to compute IEQ and other results for any part of an office building space i.e. assessments can be carried out for the following:

- Whole buildings; and
- Parts of buildings.

Tenants within the same building could chose to have different IEQ assessment certificates / ratings based on the performance of the tenanted area. This is particularly important in buildings that have a degree of variation in microclimates due to factors such as tenant location, poor design of the HVAC systems, etc. The tool also makes it possible to assess buildings at any stage of construction, i.e. from design stages right up to post occupancy evaluation stages hence it has potential to be used as a design tool that sets sustainable design priorities for engineers and determines which energy efficiency measures provide a good balance between environmental performance and occupant comfort. It can also be used as a management tool to organise and control variables that affect energy use and cost without sacrificing human comfort and productivity. It helps with identifying problem areas that should be given priority when considering improving the quality of the Indoor environment. The office rating system is also important for the following reasons:

- it provides market recognition for high performing buildings
- it can be used to negotiate tenancies
- it gives a competitive advantage to better quality offices
- encourages best practice in commercial buildings

The IEQAT therefore can either be used for voluntary assessment of office spaces or enforced in the form of legislation should the need arise. It can be used to improve current assessment tools by incorporating it into comprehensive Building Environment Performance tools.

6.2 GENERAL CONCLUSIONS

This thesis demonstrates the need to develop IEQ assessment methodologies that can be used in office buildings in the UK and worldwide. The European directive on the energy performance of buildings has challenged researchers to develop energy assessment tools and these have been developed successfully. Some of the tools are currently being used to produce energy performance certificates for domestic and commercial buildings. Most of these tools have calculated energy performance based on criteria used for the indoor environment. However a declaration of energy use without declarations of IEQ does not make sense simply because it is possible to design energy efficient buildings that are uninhabitable.

Energy performance certificates do not provide much information, if any, on the quality of the indoor environment hence the need to develop this tool. Current buildings assessment tools are biased towards comprehensive assessment of the environment performance of buildings and with less focus on building IEQ assessment tools that reflect the occupant’s perception of the indoor environment.

6.2.1 IEQ Indices

Early indices on thermal comfort, IAQ, Acoustics and lighting were derived from literature review. Thermal comfort assessment indices proved to be the most developed of the four indices and hence the ISO 7730 thermal comfort assessment standard which is based on the PMV model was adopted. PMV and PPD indices allow office spaces to be rated according to the ratio of people dissatisfied with the thermal environment.

This approach provided a foundation on which other indices were developed in this study. Studies on the performance of the PMV model have been carried out on different types of buildings across the globe and recommendations have been put forward to the wider public. A computer program based on based on Fanger's thermal comfort model was developed quite easily using the VB program and the full program code is found in the Appendix.

IAQ indices proved more difficult to produce mainly due to the large (hundreds) numbers and the complex nature of parameters contributing to IAQ acceptance. The parameters include particulates, gases, organic compounds, chemicals, and biological agents which are very difficult to quantify in indoor air. Their effects on health and well being of occupants depend on the complex kinetics that are not well understood and need several years of further investigation. A few assessment methods suggested in literature included those based on the IAQ guidelines hence ventilation rates, CO_2 concentrations and air pollution levels in decipol were adopted for this index.

Acoustic comfort indices which reflected satisfaction with the indoor environment could not be established from literature. Most noise rating techniques were useful for design and dimensioning of office buildings but they neither reflected satisfaction with the acoustic environment nor reflected on correlation to productivity. A new acoustic comfort index was developed based on the results of research studies that compared noise levels with satisfaction with the indoor noise levels. The lack of information on assessment approaches that reflect or correlate with human evaluation echoed problems that were encountered with all other indices.

Lighting indices were no exception. Lighting guides have been produced by regulatory bodies and standards associations and a few reflect occupant satisfaction, or lack of, with their internal environment. In this thesis a lighting quality index based on the findings of research carried out by Saunders (Saunders, 1969) was developed and this finally paved way for the development of the IEQ index. The IEQ assessment methodology is based on the IEQ model, a linear relationship between IEQ and contributing parameters explained above. The relative weightings of each of the contributors were obtained from AHP studies carried out by Chiang et al (Chiang and Lai, 2002) and the weightings were verified using the study of three selected case study buildings.

6.2.2 The Case study Buildings

Case study buildings were selected from a list of office buildings in the UK. Offices which were different from each other in a variety of ways were selected in order to allow for better generalisation of results. These included a naturally ventilated - pre war office building situated in an urban location, a mixed mode - post 1996 refurbished - urban office building and a modern mechanically ventilated office building located in a city centre.

The case study buildings were used largely for two purposes:

- To verify the IEQ model developed in Chapter 3 and
- To derive relative weightings of each of the contributing factors.

Model based IEQ assessments were carried out using data collected from the case study buildings as input. Measurement of variables necessary for the calculation of IEQ was carried out using specialised equipment which included a data logger and several sensors. Extreme care was exercised in the selection of the equipment and therefore only high precision and relevant equipment was used. In order to verify the performance of the model its results were compared to the results of subjective assessment of the indoor environment.

Subjective assessment results were also required for purposes of deriving coefficients therefore a study design was developed. Questionnaires were used to collect subjective evaluations of the offices and they were administered at a time when measurements were taken in order to get a better understanding of the patterns that prevailed within the buildings. It was concluded that the weightings (coefficients) compared well with those from the AHP and that regression coefficients were better suited to the UK situation since case study buildings were all within the UK.

Model calculated results compared well with subjective evaluations hence it was concluded that the IEQAT methodology was appropriate for rapid assessment of IEQ in office buildings in the UK. However in order to generate weightings that can be generalised to all office buildings in the UK a study that is longer than a normal PhD period may be required.

6.2.3 The IEQ Model

The conclusions on the final IEQ model developed in this work include the following:

- The development a model that reflects the opinion of the occupant;
- The use of variables that are used in the calculation of building energy performance for the calculation of IEQ;
- The potential of the IEQAT to be used as a design, management and compliance tool;
- The potential of the tool to be incorporated into the BMS and into comprehensive building environmental assessment tools; and
- The development of a tool which is more applicable to air conditioned office buildings with uniform conditions.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The work produced in this study represents the first attempt at using weightings derived from subjective evaluation of indoor environments to develop a methodology for assessment of IEQ in occupied office spaces in the UK. It needs to be followed up by rigorous evaluation of the IEQ Model by studying a number of selected office building and in some cases continuously for a period of more than a year. During this time questionnaires need to be administered to capture occupants' long term evaluation of the indoor environment and standard questionnaires such as the BUS occupant surveys could be administered periodically in conjunction with the IEQ assessment questionnaire presented in this thesis (Appendix 2) for verification purposes where possible.

The exercise allows the following types of data to be captured for comparative analysis:

- Design data (as designed),
- Measured data some of which may be captured via the BMS and through the use of a data logger connected to remote sensors that are located strategically across the office space.
- Modelling data which can be obtained from extensive simulation of the indoor environment using validated models. Examples of variables collected this way may include lighting data, thermal comfort variables, selected IAQ data such as pollutant distribution over time (CFD analysis), and sound pressure level estimation using relevant equations (Rasmussen, 1999). Simulations should include energy performance analyses using approved software such as the Bentley HEVACOMP software (described in Chapter 3).

In order to improve on the accuracy of relative weightings of the parameters contributing to IEQ multi level analysis needs to be carried out to investigate the effects of clustering at other (or higher) levels of investigation. For example the relative weightings may vary depending on age or gender of occupants, geographic location of office, type of office building, or social class of the occupants.

More studies need to be carried out in order to establish the trends across different types of environments and groups. Continued study of different types of office buildings could also lead to the establishment of benchmarks for performance and the setting of minimum standards below which office buildings are considered to have failed the IEQ test. Multi level analysis can be complex and time consuming and a more viable alternative would be to carry out physiological studies on office occupants. Such studies could include climate chamber studies where occupants are subjected to varying stimuli (pure experiments) and their subjective assessment of the microclimates are captured using questionnaires. Physiology based studies would strongly back predictive models.

Finally a computer program based on the IEQ model needs to be developed. The tool needs to incorporate an energy performance assessment methodology so that both IEQ and energy performance analysis can be carried out at once and results can be compared (using dynamic simulation capabilities of the tool). A cost analysis section that gives a third dimension to the tool could also be a welcome addition. Costs of energy saving or comfort enhancement actions could help decide whether these initiatives are economically viable or not. For example replacing an incandescent bulb with a fluorescent one may be productive in terms of lighting comfort and energy saving but it could cost more. Economic appraisal of energy systems adds a good dimension to the tool.

A database of building construction materials, their polluting power and sound propagation characteristics, weather data, lighting ensembles, air pollution levels, typical outside air CO_2 levels in the UK could be added to the tool. The addition of CAD capabilities into the tool allows the construction of model buildings by specifying materials and plans hence energy and IEQ analyses could be carried out from the same project.

7. References

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7. Appendices

Appendix 1 - The VB Code for Thermal Comfort calculation

```
Partial Class _Default

    Inherits System.Web.UI.Page




    Protected Sub PMV_TextChanged(ByVal sender As Object, ByVal e As
System.EventArgs) Handles txtPMV.TextChanged



    End Sub



    Private Sub PredictedMeanVote()

        Dim Clo As Decimal

        Dim decPa As Decimal

        Dim decPsat As Decimal

        Dim Icl As Decimal

        Dim fcl As Decimal

        Dim hc As Decimal

        Dim Celcius As Decimal

        Dim tr As Decimal

        Dim decPMV As Decimal

        Dim tcl As Decimal

        Dim M As Decimal

        Dim PPD As Decimal
```

```
        Dim celciusK As Decimal 'Temp Kelvin

        Dim trK As Decimal 'Radiant temp in Kelvin

        Dim SDL As Decimal 'Skin Differential Loss

        Dim SL As Decimal 'Sweat Loss

        Dim LRL As Decimal 'Latent Respiration Loss

        Dim DRL As Decimal 'Dry Respiration Loss

        Dim RL As Decimal  'Radiation Loss

        Dim CL As Decimal  'Convection Loss

        Dim TSSTC As Decimal ' Thermal sensation to skin transfer
coeffficient

        Dim P1 As Decimal

        Dim P2 As Decimal

        Dim P3 As Decimal

        Dim P4 As Decimal

        Dim P5 As Decimal

        Dim XN As Decimal

        Dim XF As Decimal

        Dim N As Decimal

        Dim EPS As Decimal

        Dim v As Decimal 'Air Velocity

        Dim HCF As Decimal

        Dim HCN As Decimal

        Dim TPO As Decimal

        Dim tclK As Decimal


        Clo = txtClothingLevel.Text


        Icl = Clo * (1 / 6.45)
```

```
        fcl = IIf(Icl < 0.078, 1.0 + 1.29 * Icl, 1.05 + 0.645 * Icl)


        Celcius =
ConvertToCelcius(cboTemperature.SelectedItem.Text.ToString,
CDec(txtAirTemperature.Text.ToString))

        tr =
ConvertToCelcius(cboMeanRadiantTemperature.SelectedItem.Text.ToString,
CDec(txtMeanRadiantTemperature.Text.ToString))

        v = ConvertToMetersPerSecond()

        M = txtActivityLevel.Text * 58.15

        HCF = 12.1 * v ^ 0.5

        celciusK = Celcius + 273

        trK = tr + 273

        decPsat = Math.Exp(16.6536 - 4030.183 / (Celcius + 235))

        decPa = decPsat * CDec(txtRelativeHumidity.Text.ToString) * 10


        tclK = celciusK + (35.5 - Celcius) / (3.5 * (6.45 * Icl +
0.1))

        P1 = Icl * fcl

        P2 = P1 * 3.96

        P3 = P1 * 100

        P4 = P1 * celciusK

        P5 = 308.7 - 0.028 * M + P2 * (trK / 100) ^ 4

        XN = tclK / 100

        XF = tclK / 50

        N = 0

        EPS = 0.0015

        While Math.Abs(XN - XF) > EPS
```

```
            XF = (XF + XN) / 2
            HCF = 12.1 * v ^ 0.5
            HCN = 2.38 * Math.Abs(100 * XF - celciusK) ^ 0.25

            If HCF > HCN Then
                hc = HCF
            Else
                hc = HCN
            End If

            XN = (P5 + P4 * hc - P2 * (XF ^ 4)) / (100 + P3 * hc)
            N = N + 1
        End While

        tcl = 100 * XN - 273

        SDL = 3.05 * 0.001 * (5733 - 6.99 * M - decPa)
        TSSTC = 0.303 * Math.Exp(-0.036 * M) + 0.028
       DRL =   0.0014 * M * (34 - TA)
       LRL = 1.7 * 0.00001 * M * (5867 - decPa)
        CL = fcl * hc * (tcl - Celcius)
        RL = 3.96 * fcl * (XN ^ 4 - (trK / 100) ^ 4)
        SL = IIf(M > 58.15, 0.42 * (M - 58.15), 0)

        If v < 0.2 Then
            TPO = 0.5 * Celcius + 0.5 * tr
        Else
```

```
            If v < 0.6 Then

                TPO = 0.6 * Celcius + 0.4 * tr

            Else

                TPO = 0.7 * Celcius + 0.3 * tr

            End If

        End If




        decPMV = Math.Round((TSSTC * (M - SDL - SL - LRL - DRL - RL -
CL)), 2)


        PPD = 100 - 95 * Math.Exp(-0.03353 * decPMV ^ 4 - 0.2179 *
decPMV ^ 2)


        txtPMV.Text = decPMV

        txtPredictedPercentageDisatisfied.Text = Math.Round(PPD, 2)

        txtOperativeTemperature.Text = TPO


    End Sub

    Private Function ConvertToMetersPerSecond() As Decimal

        Dim decMetersPerSec As Decimal

        If cboAirVelocity.SelectedValue.ToString = "ft/s" Then

            decMetersPerSec = CDec(txtAirVelocity.Text.ToString) *
0.3048

        Else

            decMetersPerSec = CDec(txtAirVelocity.Text.ToString)

        End If

        Return decMetersPerSec
```

```
    End Function

    Private Function ConvertToCelcius(ByVal Fahrenheit As String,
                                      ByVal Temp As Decimal) As
Decimal
        Dim decFahrenheit As Decimal
        If Fahrenheit = "°F" Then
            decFahrenheit = (Temp - 32) * 5 / 9
        Else
            decFahrenheit = Temp
        End If
        Return decFahrenheit

    End Function

    Protected Sub Button1_Click(ByVal sender As Object, ByVal e As
System.EventArgs) Handles Button1.Click

        PredictedMeanVote()

    End Sub

End Class
```

Appendix 2 – The Indoor Environment Questionnaire

The Indoor Environment Quality Questionnaire

September

20--

The Indoor Environment Quality Questionnaire

Background

Five main parameters that affect the quality of the indoor environment have been proposed. They are Thermal comfort, Indoor Air Quality, Acoustic comfort, Lighting, and workplace design. The purpose of this questionnaire is to try and determine how much influence each of the five parameters has on perceived Indoor Environment Quality (IEQ) in offices or related buildings. This will help develop a weighted ranking of the parameters and provide an insight into the complex way in which they combine to dictate perceived IEQ in offices in the UK.

The Questionnaire is divided into two sections:

Section 1 tries to assess, instantaneously, the influence of perceived thermal comfort, indoor air quality, acoustic, visual & workplace design on the overall IEQ during a particular season of the year. [Heating season (November - April) and Cooling season (May - October)]

Section 2 contains personal factors such as age, gender or any underlying problems that could affect your level of satisfaction with the indoor environment. You are not obliged to answer these questions but they may help to explain any discrepancies between field measurements and your subjective opinion.

NB: A guide to answering all questions in section A is provided on a separate sheet, questions in section B are fairly self explanatory. You may use extra space provided for additional comments. Space has been provided at the end of Section 2 if you wish to elaborate on any of the answers you may have given in this questionnaire.

Section 1 - Building Comfort

Please note all the answers should be subjective. For questions in Section 1 please use the assessment scales given and fill in your responses in the spaces provided.

Question 1 - Building characteristics – Please state

Building Name	Floor	Date	Time

Question 2 – The Indoor Environment

(a) Is the Quality of the Indoor Environmental (i.e. IEQ) in this building **AT THIS MOMENT** acceptable to you? (Please use the assessment scale below):

1 = YES, **0 = NO**

Question 2 – The Indoor Environment

2 (b) How would you rate the quality of Indoor Environment in your work area **AT THIS MOMENT**? (Please mark anywhere on the assessment scales below; from 1 to 5)

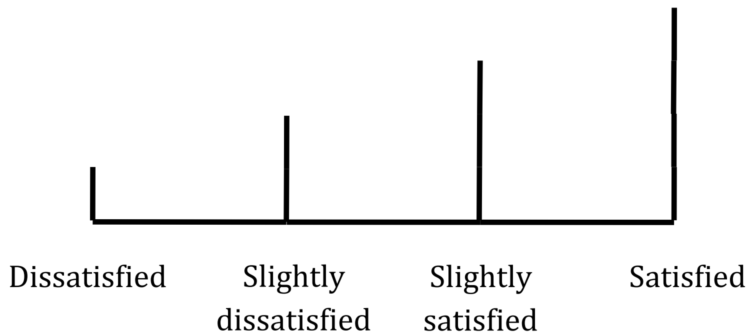
Question 3 – Thermal Environment

How would you rate your thermal sensation in your work area **AT THIS MOMENT**? (Please mark your answer on the assessment scale below)

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	+1	+2	+3

Question 4 – Level of Environment Control

How satisfied are you with your level of control of comfort parameters at your workspace **AT THIS MOMENT**? E.g. opening or closing a window or a door to the outside, adjusting a thermostat, drapes or blinds, space heater, turning local fan on or off? (Please mark anywhere on the assessment scale below)



Question 5 – Acoustics

(a) How would you perceive the background noise levels in your work environment right **AT THIS MOMENT**? (Please mark anywhere on the assessment scale below; from 1 to 5)

Not Acceptable (1) : : : : : : : :2 : : : : : : : : ::3 : : : : : : : : : : :4 : : : : : : : : : : : (5): **Acceptable**

(b) How would you describe your levels of background noise in your work environment **AT THIS MOMENT**? (Please mark your answer on the assessment scale below From 1 = VERY QUIET to 5 = VERY NOISY)

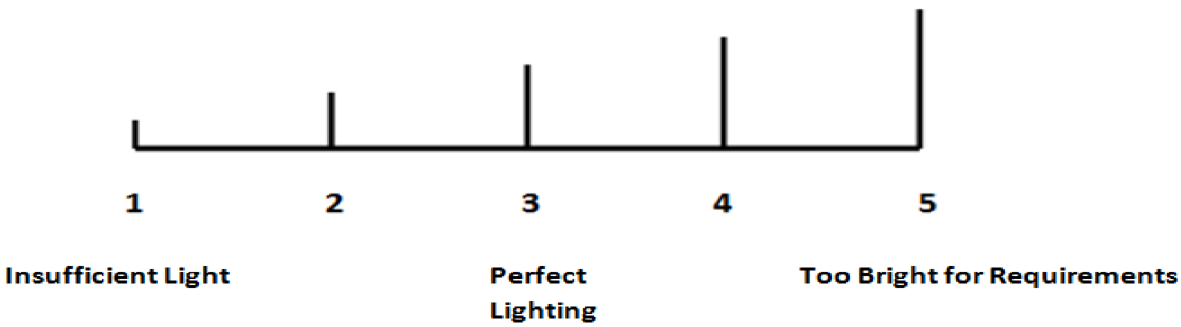
Question 6 - Lighting

(a) How would you perceive the quality of lighting in your work area **AT THIS MOMENT**? (Please mark anywhere on the assessment scale below; from 1 to 5)

Not Acceptable (1) : : : : : : : :2 : : : : : : : : ::3 : : : : : : : : : : :4 : : : : : : : : : : : : (5) **Acceptable**

Your answer...

(b) How would you describe the amount of light received on your working plane **AT THIS MOMENT**? (Please mark on the assessment scale, 1 = Insufficient Lighting, 3 = Perfect Lighting 5 = Too bright for requirements)

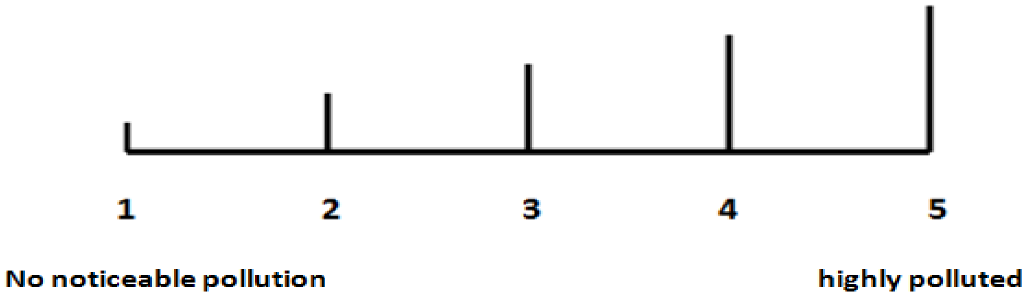


Question 7 - Indoor Air Quality

(a) How would you perceive the air quality in your work environment **AT THIS MOMENT**? (Please mark anywhere on the assessment scale below; from 1 to 5)

Not Acceptable (1) : : : : : : : :2 : : : : : : : ::3 : : : : : : : : : :4 : : : : : : : : : : : (5) **Acceptable**

(b) How would you describe the levels of air pollution you perceive in your work environment right now? (Please mark your answer on the assessment scale given):



(c) Are you experiencing any of the following symptoms **AT THIS MOMENT?** (Please tick the scales below at the place that best represents how you feel at this moment)

Blocked nose **Clear nose**

Dry nose **Runny nose**

Dry throat **Not dry throat**

Dry mouth **Not dry mouth**

Question 8 - Local Discomfort factors

AT THIS MOMENT do you feel any discomfort caused by any of the following in your work area? Please tick where applicable.

Draughts – cold or warm draughts	
Cold floors	
Cold equipment	
Vertical Air Temperature Varies (e.g. from head to heels)	
Discomfort due to differences in radiant heat? e.g. radiators or other heat emitters or surfaces	

Section 2 - Personal Factors

Q1. Please state whether you are Male / Female (circle as appropriate):

Q2. Please state your age category below.

18 – 25 ________

26 – 35 ________

36 – 45 ________

45 – 55 ________

+ 55 ________

Q3. Do you suffer from any physical ailment that might increase your sensitivity to your surrounding environment? For example if you suffer from Reynaud's disease you may be more sensitive to drops in temperature.

YES / NO

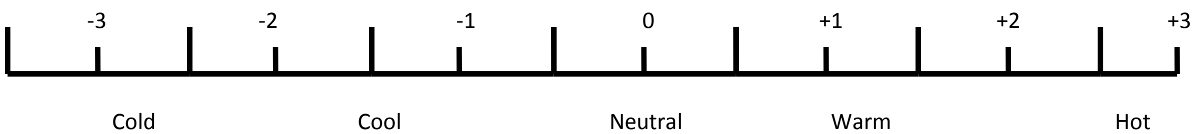
If you have answered yes and are willing to elaborate then please do so in the box below.

Q4. Further comments on the building's comfort level are welcomed in the box below. If you wish to elaborate on any of the issues raised in this questionnaire then please refer to the section and question number.

Additional Information:

End of Questionnaire! Thank You for your participation.

NB: Question 3 for Naturally Ventilated Buildings



Appendix 3 – IEQAT Results - Town Centre; Lace Market & Granby Houses.

CASE 1 – LEEDS TOWN CENTRE HOUSE

PERIOD: 11 - 16:00 10 June 2010

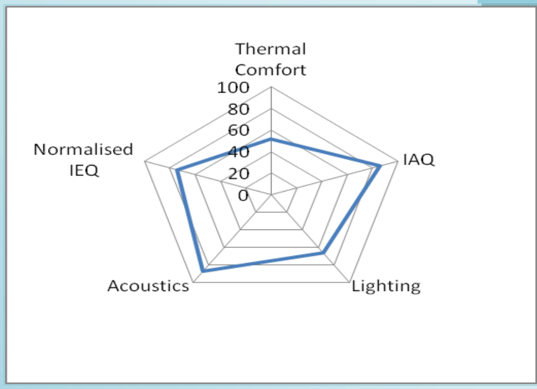
Thermal Comfort 51.99,

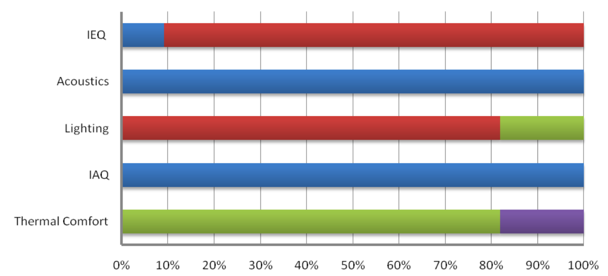
IAQ 85.89

BUILDING DATA SUMMARY

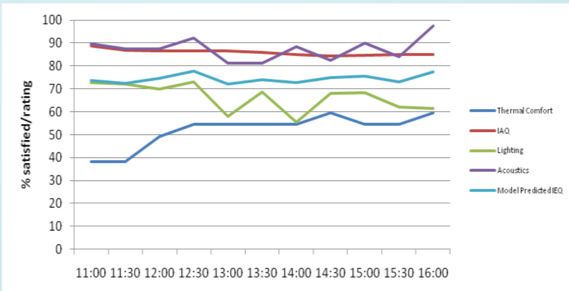
- Project Name : IEQ 3
- Project Number : 003
- Client Name : Hoare Lea & Partners
- Client Address : Town Centre House
- Name of Assessor 1: M Ncube
- Date of assessment : 09/12/2009 &
- Confirmed by : XXX
- Date of confirmation : XXXXX

Office design ___________________________
Office Type Standard Open Plan
Floor level 1st Floor in a three floor building
Floor Area 159 m^2
Age of Building Floor renovated extensively in 2009
Furniture Levels Medium Furnished (Normal office equipment, servers)
Occupancy Details ___________________________
Occupancy 10 In the studied area (5 female and 5 male)
Times 9am to 5pm (Mon –Friday)
Type of Work Sedentary work e.g. typing, telephone conversations, etc
Business Engineering Consultancy Office
Clothing worn Mainly light office clothing
HVAC System Type & Controls ___________________
HVAC systems Mechanically Ventilated (mixing)
Windows Non Operable, blinds
Ventilation rates Standard (10 l/s)
Thermostats Set at 21 Degrees Celsius
Service Every three months





	Thermal Comfort	IAQ	Lighting	Acoustics	IEQ
Category I	0	11	0	11	1
Category II	0	0	9	0	10
Category III	9	0	2	0	0
Category IV	2	0	0	0	0
Category V	0	0	0	0	0



GENRAL CONSIDERATIONS

THERMAL COMFORT

- Room Temperature Control
  - Monitoring systems (thermostats, etc) Yes
  - Room temperature setting Yes (21°C)
  - Individual Control No
  - Zoned control Yes
  - Variable Loads & perimeter performance Yes
- Humidity Control Yes
- A/C System Present Yes

IAQ

- Ventilation
  - Ventilation System Present Yes
  - Air Supply Schedule Yes
  - Individual Control No
  - Zoned control Yes
  - Variable Loads & perimeter performance Yes
- Smoking No
- Pollution Source Control
  - Chemical Pollutants Present? None observed
  - Asbestos None observed
  - Evidence of mould, mites, fungi, etc? None observed
  - Legionella None observed

ACOUSTICS

- Other Noise
  - Equipment Noise Servers, phone
  - Outdoor Noise and Type None Recorded
- Sound Insulation
  - Sound Insulation of Internal Walls N/A
  - Sound Insulation performance of floor N/A
  - Sound Insulation of openings N/A
  - Reverberation time of sound N/A

LIGHTING

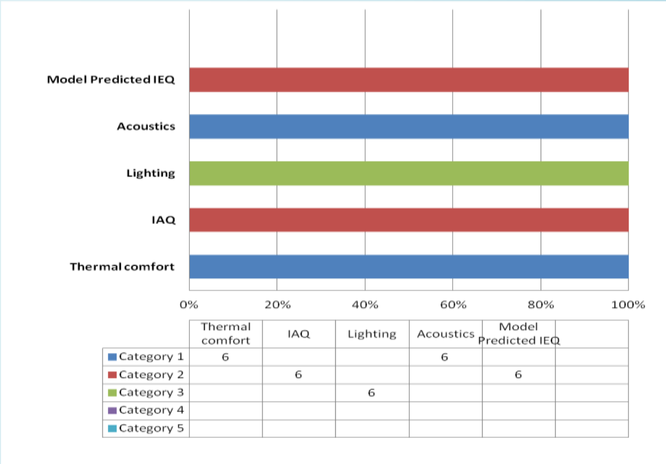
- Daylighting
  - Daylight factor N/A
  - Orientation of windows or openings E/W/N/S
- Antiglare installed
  - Blinds, curtains for daylight control: Blinds all round
  - Anti glare for artificial lighting Yes
- Illuminance level
  - Uniformity of illuminance N/A
  - Colour of light N/A
  - Colour rendering Index N/A
- Light controls accessible Yes

CASE 1 – MARSH GROCHOWSKI & A

PERIOD: 11 - 16:00 10 June 2010
Thermal Comfort = 57.1
IAQ = 81.3
Lighting = 55.8
Acoustics = 100
IEQ = 75.0 IEQ CATEGORY = II

BUILDING DATA SUMMARY

Project Name :	IEQ 2
Project Number :	002
Client Name :	Marsh Grochowski & Associates
Client Address :	Commerce Square, Lace Market
Name of Assessor 1:	M Ncube
Date of assessment :	September 2010
Confirmed by :	XXX
Date of confirmation :	XXXXX
Office design	
Office Type	Pre-war (1940) open plan office building
Floor level	2nd and 3rd Top Floor
Floor Area	180 m^2
Age of Building	1930s
Furniture Levels	Medium Furnished (office equipment, servers)
Occupancy Details	
Occupancy	In studied area (1 female and 3 male on 1st Fl
Times	9am to 5pm (Mon –Friday)
Type of Work	Sedentary work e.g. typing, telephone
Business	Architecture & Interior Design Office
Clothing worn	Mostly light office clothing
HVAC System Type & Controls	
HVAC systems	Naturally Ventilated
Windows	Non Operable, No blinds
Ventilation rates	Unknown
Thermostats	None
Service	N/A



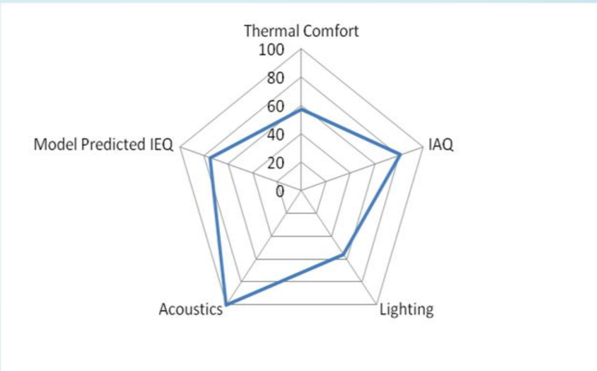
GENRAL CONSIDERATIONS

THERMAL COMFORT - CHECKLIST

Room Temperature Control	
Monitoring systems (thermostats, etc)	No
Room temperature setting	No
Individual Control	Yes
Zoned control	No
Variable Loads and perimeter performance	No
Humidity Control	No
A/C System Present	No

IAQ - CHECKLIST

Ventilation	
Mechanical Ventilation System Present	No
Air Supply Schedule	N/A
Individual Control	No
Zoned control	No
Variable Loads and perimeter performance	No
Pollution Source Control	
Chemical Pollutants Present?	N/A
Asbestos	N/A
Evidence of mould, mites, fungi, etc?	N/A
Legionella	

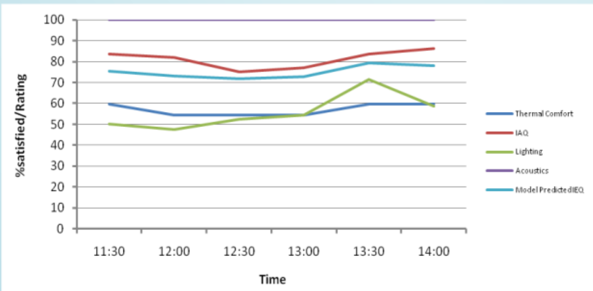


ACOUSTICS - CHECKLIST

Other Noise	
Equipment Noise	Telephone ringing
Outdoor Noise and Type	None
Sound Insulation	
Sound Insulation of Internal Walls	N/A
Sound Insulation of performance of floor	N/A
Units (impacts)	N/A
Sound Insulation of openings	N/A
Reverberation time of sound	N/A

LIGHTING - CHECKLIST

Daylighting	
Daylight factor	N/A
Orientation of windows or openings	NE/SE/NW
Antiglare installed	
Blinds, curtains for daylight control	Blinds in some areas
Anti glare for artificial lighting	No
Illuminance level	
Uniformity of illuminance	N/A
Colour of light	N/A
Colour rendering Index	N/A
Light controls accessible	Yes
Other Checklists	N/A
UGR	N/A
R_a	N/A



CASE 1 - GRANBY HOUSE

BUILDING DATA SUMMARY

- Project Name : IEQ 3
- Project Number : 003
- Client Name : Energy Saving Trust
- Client Address : Granby House,
- Name of Assessor 1: M Ncube
- Date of assessment : 09/12/2009 & 20/07/2009
- Confirmed by : XXX
- Date of confirmation : XXXXX
- Office design ___________________________
- Office Type: Standard Open Plan
- Floor level: 1st Floor in a three floor building
- Floor Area: 159 m^2
- Age of Building: Floor renovated extensively in 2009
- Furniture Levels: Medium Furnished (office equipment, servers)
- Occupancy Details ___________________________
- Occupancy: 10 In the studied area (5 female and 5 male)
- Times: 9am to 5pm (Mon –Friday)
- Type of Work: Sedentary work e.g. typing, telephone
- Business: Call Centre and Consultancy Office
- Clothing worn: Mainly light office clothing
- HVAC System Type & Controls ____________________
- HVAC systems: Mechanically Ventilated (mixing)
- Windows: Operable, blinds
- Ventilation rates: Standard (per m^2)
- Thermostats: Set at 22 Degrees Celsius
- Service: Every three months

GENRAL CONSIDERATIONS SUMMARY

THERMAL COMFORT - CHECKLIST

- Room Temperature Control
  - Monitoring systems (thermostats, etc) — Yes
  - Room temperature setting — Yes
  - Individual Control — Yes
  - Zoned control — Yes
  - Variable Loads and perimeter performance — Yes
- Humidity Control — Yes
  - A/C System Present — Yes

IAQ - CHECKLIST

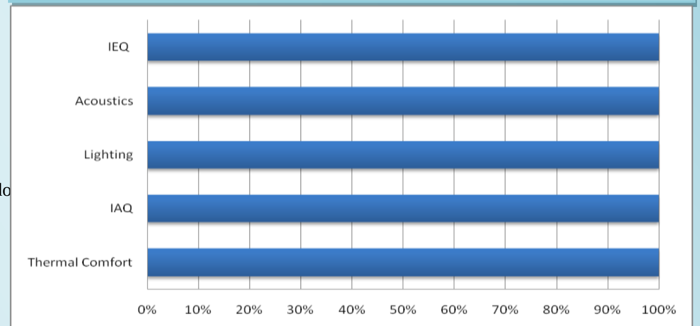
- Ventilation
  - Mechanical Ventilation System Present — Yes
  - Air Supply Schedule — Yes
  - Individual Control — Yes, windo
  - Zoned control — No
  - Variable Loads and perimeter performance — No
- Smoking*
- Pollution Source Control
  - Chemical Pollutants Present? — N/A
  - Asbestos — N/
  - Evidence of mould, mites, fungi, etc? — N/A
  - Legionella — N/A

ACOUSTICS - CHECKLIST

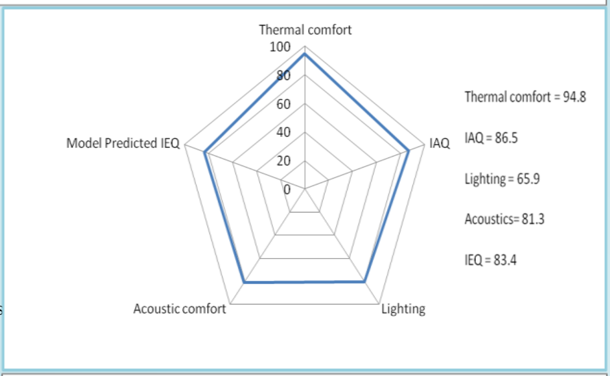
- Other Noise
  - Equipment Noise — telephone r
  - Outdoor Noise and Type — vehicular traffic
- Sound Insulation
  - Sound Insulation of Internal Walls — N/A
  - Sound Insulation of performance of floor — N/A
  - Units (impacts) — N/A
  - Sound Insulation of openings — N/A
  - Reverberation time of sound — N/A

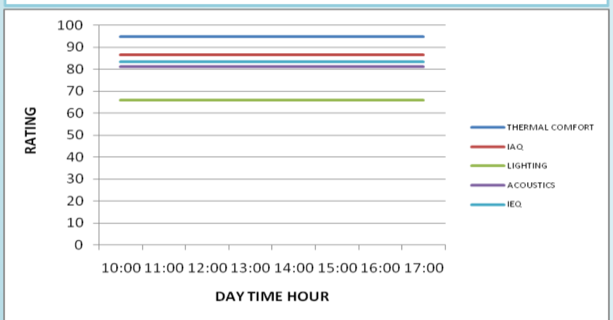
LIGHTING - CHECKLIST

- Daylighting
  - Daylight factor — N/A
  - Orientation of windows or openings — SE/SW
- Antiglare installed
  - Blinds, curtains for daylight control — Blinds in all windows
  - Anti glare for artificial lighting — Yes
- Illuminance level
  - Uniformity of illuminance — N/A
  - Colour of light — N/A
  - Colour rendering Index — N/A
- Light controls accessible — Yes
- Other Checklists — N/A
  - UGR
  - R_a



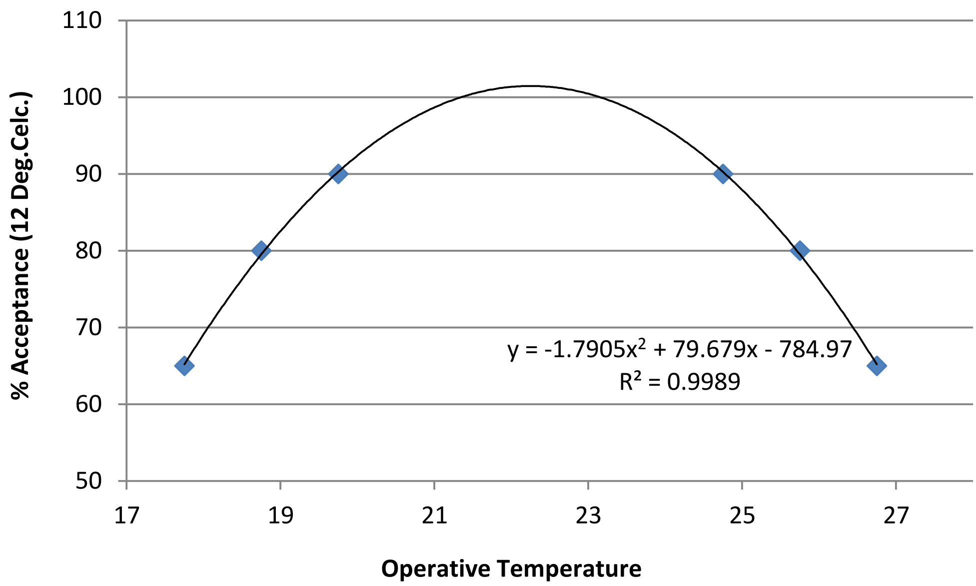
	Thermal Comfort	IAQ	Lighting	Acoustics	IEQ
Category 1	7	7	7	7	7
Category 2	0	0	0	0	0
Category 3	0	0	0	0	0
Category 4	0	0	0	0	0
Category 5	0	0	0	0	0





IEQ Category = I

Appendix 4 A plot of % acceptance against operative temperatures (Exponentially weighted running mean of the daily outdoor temperature of the plot = 12°C). The graph shifts to the left or right depending on the mean outdoor temperature for the month in question.



Appendix 5 List of Work Published in Journals & Conference Proceedings

1. Ncube, M and Riffat, S. B., 2012, Developing an Indoor Environment Quality Tool for Assessment of Mechanically ventilated Office Buildings in the UK - A Preliminary Study, *Elsevier – Building and Environment.*

2. Ncube, M. and Yuehong, Su, 2011, The Removal of Volatile Organic Compounds from Indoor Air using Desiccant Packed Columns, *Elsevier - Sustainable Cities & Societies.*

3. Ncube, M., Chilengwe, N., and Riffat, S. B., 2010, The Development of a Methodology for a Tool for Rapid Assessment of IEQ in Office Buildings in the UK, *Proceedings of 9th International Conference on Sustainable Energy Technologies*' , 24 to 27 August 2010, Shanghai, China, SE-056.