Retrofitted natural ventilation systems for a lightweight office building

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Retrofitted natural ventilation systems for a lightweight office building

by

Narguess Khatami

A Doctoral Thesis to be
Submitted in partial fulfillment of the requirements for the award of
Doctor of philosophy of Loughborough University

(September 2014)

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Abstract

This study aimed to develop retrofitted natural ventilation options and control strategies for existing office buildings to improve thermal comfort, indoor air quality and energy consumption. For this purpose, a typical office building was selected in order to identify opportunities and constraints when implementing such strategies. Actual performance of the case study building was evaluated by conducting quantitative and qualitative field measurements including physical measurements and questionnaire surveys.

Based on the actual building performance, a combination of Dynamic Thermal Simulation (using IES) and Computational Fluid Dynamics (using PHOENICS) models were built to develop appropriate natural ventilation options and control strategies to find a balance between energy consumption, indoor air quality, and thermal comfort. Several retrofitted options and control strategies were proposed and the best retrofitted natural ventilation options and control strategies were installed in the case study building.

Post occupancy evaluation of the case study building after the interventions was also carried out by conducting physical measurements and questionnaire surveys.

Post refurbishment measurements revealed that energy consumption and risk of overheating in the refurbished building were reduced by 9% and 80% respectively. The risk of unacceptable indoor air quality was also reduced by 60% in densely occupied zones of the building. The results of questionnaire surveys also revealed that the percentage of dissatisfied occupants reduced by 80% after intervention.

Two new products including a “Motorized ceiling tile” and “NVlogIQ”, a natural ventilation wall controller, were also developed based on the results of this study.
Acknowledgements

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<td>( A )</td>
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<tr>
<td>( Q_{IAQ} )</td>
<td>Volumetric air flow rate to provide acceptable indoor air quality ((m^3/s))</td>
</tr>
<tr>
<td>( R )</td>
<td>Heat transfer by radiation ((W))</td>
</tr>
<tr>
<td>( RES )</td>
<td>Heat loss by respiration ((W))</td>
</tr>
<tr>
<td>( S )</td>
<td>Heat storage in the body ((W))</td>
</tr>
<tr>
<td>( Ta )</td>
<td>Internal air temperature ((^\circ C))</td>
</tr>
<tr>
<td>( Tc )</td>
<td>Operative temperature ((^\circ C))</td>
</tr>
<tr>
<td>( T_{comf} )</td>
<td>Comfort temperature ((^\circ C))</td>
</tr>
<tr>
<td>( T_{ed-1} )</td>
<td>Daily mean external temperature for the previous day ((^\circ C))</td>
</tr>
<tr>
<td>( Ti )</td>
<td>Inside air temperature ((^\circ C))</td>
</tr>
<tr>
<td>( To )</td>
<td>Outside air temperature ((^\circ C))</td>
</tr>
<tr>
<td>( T_{rm} )</td>
<td>Running mean temperature ((^\circ C))</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>Temperature difference ((^\circ C))</td>
</tr>
<tr>
<td>( u )</td>
<td>Velocity component in (x) ((m/s))</td>
</tr>
<tr>
<td>( U_m )</td>
<td>Wind speed measured in open country at a standard height of 10 m ((m/s))</td>
</tr>
<tr>
<td>( U_z )</td>
<td>Building height wind speed ((m/s))</td>
</tr>
<tr>
<td>( V )</td>
<td>Flow velocity ((m/s))</td>
</tr>
<tr>
<td>( v )</td>
<td>Velocity component in (y) ((m/s))</td>
</tr>
</tbody>
</table>
Nomenclature

\( W \)  Mechanical work done by the body (W)
\( w \)  Velocity component in \( z \) (m/s)
\( Z \)  Building height (m)
\( \rho \)  Density (kg/m\(^3\))
\( \rho_0 \)  Air density at 237°K (kg/m\(^3\))
\( \Phi \)  Total heat gain (W)
1 Introduction

1.1 Background

Much of the existing building stock typically found on business parks and industrial estates is poorly designed in terms of energy efficiency, occupants’ thermal comfort and indoor air quality (IAQ). According to Roaf et al. (2009) due to the poorly insulated modern lightweight structures and overglazing in office buildings, overheating occurs in summer and overcooling occurs in winter leading to increased energy consumption and thermal discomfort. Moreover, open plan modern offices face a higher risk of overheating due to extensive use of artificial lighting, false ceilings and high internal heat gains of office equipment (Gratia and De Herde, 2004). It is also expected that climate change will increase the demand for ventilation and cooling in the future. According to CIBSE KS 03 (2005) it is predicted that UK external air temperatures will increase by 4° to 6°C in the next 50 to 80 years resulting in increased cooling demand in buildings.

Due to the increasing cost of energy and environmental issues, interest in energy efficient buildings in general and natural ventilation in particular, as an alternative to mechanical ventilation and cooling, has increased in recent years (Sartori and Hestnes, 2007; Bangalee et al., 2012). According to Allocca et al. (2003) the energy costs of naturally ventilated buildings are 40% less than equivalent air conditioned buildings. Additionally, based on the results of several studies, occupants of naturally ventilated buildings feel comfortable in a wider range of temperatures (De Dear and Brager, 1998; Nicol and Humphreys, 2002; Wagner et al., 2007; Moujalled et al., 2008; de Dear, 2009) and have lower IAQ expectations compared to air conditioned buildings (Hummelgaard et al., 2007).

Naturally ventilated buildings aim to provide acceptable environmental conditions and thermal comfort and indoor air quality for occupants by optimum use of natural forces (IEMA, 2006). They take advantage of their forms, construction details and materials to minimise reliance on mechanical plant.
Natural ventilation is highly influenced by external climatic conditions such as temperature, wind velocity and wind direction (Liddament, 1996) as well as internal conditions such as layout, construction type, vent positions and occupancy patterns. Therefore it is necessary to introduce some form of control in order to protect occupants and buildings from undesired conditions and to maximise the efficiency of the natural ventilation systems by taking advantage of the existing opportunities such as the building’s layout or construction (BSRIA, 2000).

Although it is good practice to consider natural ventilation in the early stage of building design, there are some techniques such as retrofitted natural ventilation that can be applied to existing office buildings to reduce energy consumption and improve occupants’ thermal comfort and indoor air quality (Burton, 2000). It should be noted that improving the performance of natural ventilation in existing buildings can be challenging since design options are often limited. Therefore it is essential to predict and test the performance of different design options before carrying out any retrofit interventions.

Moreover, due to the complex nature of natural ventilation and the control of natural ventilation, applying different prediction methods to develop appropriate designs is essential (Santamouris, 2002a). Prediction methods vary from simple analytical methods to detailed dynamic thermal simulation (DTS) and computational fluid dynamics (CFD) (Ohaba and Lun, 2010). Analytical methods such as methods suggested by CIBSE AM10 (CIBSE AM10, 2005) are used to estimate required free areas. Analytical methods are also used as indicators since calculations in such methods are done based on broad assumptions (Chen et al., 2010). DTS models are often used to give an overview of the buildings’ performance throughout a typical year (Cook and Short, 2009). Results of DTS models may be used to demonstrate bulk air flow from and through the building as well as average temperature, CO₂, relative humidity and other performance indicators in each zone (Good et al., 2008). The accuracy of DTS models can be tested by comparing the simulation results with the actual building performance. CFD models can provide a snapshot with much more detail (Appleby, 2011). CFD models are used to
investigate the airflow pattern and temperature in the most critical zones of the buildings.

Due to increasing demand for ventilation and a higher risk of overheating in office buildings as a result of poor design and high internal heat gains, this study focused on the effect of retrofitting natural ventilation systems in existing office buildings.

1.2 Aims and objectives

The aim of this research was to use a combination of different prediction methods to explore natural ventilation options and control algorithms for existing office buildings. Suitable natural ventilation options and control strategies are proposed for existing office buildings to improve:

- Thermal comfort (Aim 1)
- IAQ (Aim 2)
- Energy consumption (Aim 3)

Various natural ventilation retrofit options were selected to investigate the relationships between energy consumption, indoor air quality, and thermal comfort. Since this study focused on the environmental impact of natural ventilation, the performance of the proposed options were investigated in terms of thermal comfort, IAQ and energy consumption rather than reporting ventilation flow rate. Increasing flow rate in naturally ventilated buildings helped to increase mixture of outdoor and indoor air. Since usually outside temperature and CO₂ level is lower than inside temperature and CO₂ level, mixing indoor outdoor air helped to reduce internal temperature and CO₂ level (Seppänen et al., 1999) while it could increase heating demand.

The following seven objectives were identified to achieve the above aims:

1. **Review literature**: This provided general knowledge on natural ventilation options and control strategies and helped to evaluate the current research in this area and identify a suitable foundation for this study. The literature review also covered the effect of natural ventilation
on occupants’ comfort in order to identify appropriate assessment tools for natural ventilation performance.

2. **Identify a case study building and appropriate research methods.** The case study building needed to be representative of typical office buildings in the UK and appropriate research methods to achieve the aims and objectives were identified.

3. **Monitor the performance of the case study building in terms of thermal comfort IAQ and energy consumption before intervention:** In order to propose energy efficient solutions it is necessary to understand the performance of the case study building before any intervention takes place. Understanding a building’s performance before intervention helps to identify potential opportunities that can be considered to improve the building’s energy performance and occupants’ comfort. Performance of the case study building before intervention was assessed by conducting qualitative and quantitative studies.

4. **Propose natural ventilation refurbishment options:** Based on the results of the current building performance using quantitative and qualitative studies (objective 3), various natural ventilation options were proposed. First analytical methods were used then based on results of analytical methods, DTS and CFD models of the building were developed and the effects of introducing different options on thermal comfort, IAQ and energy consumption could be tested.

5. **Develop control algorithms based on the computer simulation:** Since it is necessary to introduce some form of control to protect naturally ventilated buildings from undesired external conditions, this objective investigated the effect of introducing different control strategies. Two sets of control strategies were proposed to control temperature and CO₂ concentration. Effects of applying the control strategies on the best natural ventilation option (identified in objective 4) were tested by conducting DTS models and the best control strategies for the case study building were identified.
6. **Monitor the performance of the case study building after intervention**: Building performance after intervention was studied using qualitative and quantitative analysis and results were compared with the results of building performance before intervention (objective 3).

7. **Draw conclusions and recommendations**: Based on the results and findings of this study sets of conclusions and recommendations for introducing retrofitted natural ventilation options were proposed.

1.3 **Thesis structure**

This study contains four sections and nine chapters. As shown in Figure 1-1 following the first section (Chapter 1), the literature review (Chapter 2) and methodology (Chapter 3) form the second section of this study. The second section addresses objectives 1 and 2 and provides the foundation for this study.

Section 3 describes the results and discussions. It contains five chapters. Results of studies on pre-intervention building performance are discussed in Chapter 4 which addresses objective 3. Building performance in terms of thermal comfort, IAQ and energy consumption were evaluated by conducting quantitative and qualitative methods. Objective 4 is addressed in Chapter 5 by discussing results of applying different natural ventilation options. DTS and CFD models were applied to assess the performance of proposed natural ventilation options. Chapters 6 and 7 discuss results of applying different CO₂ and temperature based control strategies. These two chapters are designed to cover objective 5. DTS models were applied to evaluate the effectiveness of the proposed control strategies. Performance of the case study building following retrofit intervention is reported in Chapter 8 in order to address objective 6. Post occupancy evaluation of the case study building after intervention was carried out using quantitative and qualitative methods and results were compared with the results of building performance evaluation before intervention.
The final section of this study is formed by Chapter 9 which addresses objective 7.

Figure 1-1: Structure of this study
2 Literature review

2.1 Introduction

Current interest in natural ventilation and passive cooling strategies is growing as these methods can deliver thermal comfort (by increasing air movement) and acceptable IAQ (by providing fresh air) with lower energy consumption compared to mechanical ventilation (Breesch et al., 2005; Steemers, 2006). Results of studies by Allocca et al. (2003) showed that, typically, energy costs of naturally ventilated buildings are around 40% less than equivalent air conditioned buildings. Natural ventilation is a method of ventilating indoor environments by exploiting natural forces of wind and stack effect (Liddament, 1996). As natural ventilation is highly influenced by external climatic conditions such as temperature, wind velocity and wind direction, it is necessary to introduce some form of control to protect the building from undesired effects such as draughts, overcooling and overheating, and to minimise the heating and cooling energy demands.

Control of natural ventilation can be manual, automatic or a combination of both (BSRIA, 2000). Results of Heieslberg (2008) and Khatami et al. (2011) showed that usually occupants are very slow to control their thermal environment and react to thermal discomfort too late. Late reaction of occupants to their thermal environment leads to higher risk of overheating and an increase in cooling demand. At the same time results of studies by Griffiths and Eftekhar (2008) and Khatami et al. (2011) suggest that occupants are often unaware of IAQ and for this reason it is not recommended to rely on occupants’ manual control alone.

2.2 Principle of natural ventilation

Natural ventilation in a building can be delivered as a result of the pressure difference due to the wind effect, the stack effect or a combination of both.
Wind induced strategies:

Wind driven ventilation works as a result of a pressure difference between leeward and windward sides of the building’s envelope. Due to this pressure difference (shown in Figure 2-1) wind enters to the building from the high pressure zones and exits from low pressure zones (Liddament, 1996).

![Figure 2-1: Wind driven flow (Source: Liddament, 1996)](image)

Relative to static pressure, wind pressure at any point of a building’s envelope can be estimated (shown in Equation 2-1) as follows (Liddament, 1996):

\[
P_w = \frac{1}{2} \rho C_p V_z^2 \tag{2-1}
\]

Where:

- \(P_w\) = Wind pressure at specific point on the building envelope (Pa)
- \(\rho\) = Reference density (kg/m\(^3\))
- \(C_p\) = Pressure coefficient at a specific opening (usually generated by a wind tunnel test)
- \(V_z\) = Building height wind speed (m/s), estimated as shown by Equation 2-2:

\[
V_z = V_m \times k \times Z^a \tag{2-2}
\]

- \(V_m\) = Wind speed (m/s), measured in open country at a standard height of 10m
- \(Z\) = Building height (m)
and $k, a$ are constant values depend on the terrain surrounding the building.

**Stack induced strategies:**

Stack effect (buoyancy effect) takes place as a result of a temperature difference between the inside and outside or between different zones of a building. When the internal temperature is higher than the external temperature cool air enters the building via low level openings while lighter hotter air exits through high level openings (Figure 2-2) (Awbi, 2003 and Liddement, 1996).

![Figure 2-2: Stack induced flow, (Source: Liddement, 1996)](image)

Stack pressure can be estimated as follows (Liddement, 1996):

$$P_s = \rho_0 g 273(\Delta h)\left[\frac{1}{T_e} - \frac{1}{T_i}\right]$$  \hspace{1cm} (2-3)

Where:

- $P_s =$ stack pressure between the inside and outside of the building (pa)
- $\rho_0 =$ air density at 237°K ($kg/m^3$)
- $g =$ acceleration due to gravity ($m/s^2$)
- $T_e =$ external temperature (K)
- $T_i =$ internal temperature (K)
- $\Delta h =$ height difference between openings (m)

Pressure difference is the driving force of natural ventilation (shown in Equation 2-4). Natural ventilation is also affected by free opening areas (CIBSE AM10, 2005). In terms of natural ventilation control, the free areas are the
controllable parameters and the effective free areas (”Cd A” in equation 2-4) determine the flow rate through and out of the building’s envelope.

\[ Q = C_d A \sqrt{\frac{2|\Delta P|}{\rho}} \]  

(2-4)

Where:
- \( Q \) = volumetric flow rate through openings (m\(^3\)/s)
- \( C_d \) = discharge coefficient which depends on opening type
- \( A \) = free area of opening (m\(^2\))
- \( \Delta P \) = pressure difference due to wind and stack effect between openings (Pa)
- \( \rho \) = the air density (kg/m\(^3\))

As natural ventilation is highly affected by external environmental conditions which vary during the time, estimating air flow rate using analytical methods are very complex (Alfonso, 2013). For this reason experimental methods such as tracer gas or measurements of air velocity through the openings are applied to measure ventilation rate in a building (Kiwan et al, 2012). However, these methods could be expensive and accuracy of the results are highly affected by measurement techniques, specially in larger spaces (Chao et al., 2014). In this situation in naturally ventilated buildings environmental variables such as CO\(_2\) or air temperature which are affected by flow rate can be used to assess effectiveness of natural ventilation.

Increasing flow rate in naturally ventilated buildings helped to increase mixture of outdoor and indoor air. Since usually outside temperature and CO\(_2\) level is lower than inside temperature and CO\(_2\) level, mixing indoor outdoor air helped to reduce internal temperature and CO\(_2\) level. Therefore as suggested by Seppänen et al. (1999) these parameters can be used as indicators of air flow rate in naturally ventilated buildings.
2.3 **Advantages and disadvantages of each strategy**

Natural ventilation can be applied in a building in the form of single sided, cross or stack ventilation, or a combination of them. In any of these strategies wind and stack effects are the main driving forces.

According to Lomas (2007), providing stack ventilation is more reliable and predictable than wind induced ventilation. This is because there are almost always some temperature differences between the inside and outside of the building. Lomas *et al.* (2007) mentioned that this strategy can adapt itself to changes in internal heat gains as the increase or decrease of internal heat gains leads to higher or lower temperature differences and consequently higher or lower ventilation rates. According to Cook and Short (2009), in this method, hot lighter air exhausts through high level openings allowing for denser cooler air to enter from low level openings. For this reason stack induced ventilation usually contains low and high level openings. According to Kolokotroni *et al.* (2006), stack ventilation is the most suitable natural ventilation strategy in UK offices because it is largely independent of wind variations and can be used for day and night cooling. According to Nguyen and Reiter (2011) compared to wind induced ventilation, stack induced ventilation performed better in moderate and cold climatic conditions like in the UK where there are higher internal and external temperature differences.

The results of Hughes and Mak (2011) also reveals that wind induced ventilation, in terms of providing a higher flow rate, could be 76% more effective than buoyancy alone ventilation. According to Straw *et al.* (2000), wind induced ventilation has two major components: a “mean component” which takes place as a result of mean pressure differences between ventilation openings; and a “fluctuating component” which takes place as a result of fluctuating pressure and unsteady flows around the openings. Straw *et al.* (2000) recommended introducing vents in different areas around the buildings with different wind pressures to dominate the mean component over the fluctuation components as a result of higher mean pressure difference than fluctuating ones. Therefore, the locations of ventilation devices have a significant effect on the effectiveness of wind induced natural ventilation. Haw
et al. (2012) suggested introducing openings on leeward and windward walls to maximise pressure differences due to the wind. According to studies by Khan et al. (2008), even in wind induced ventilation strategies, if external wind velocity is low it is expected that stack effect will dominate.

Considering all of these issues, providing stack induced natural ventilation options, which can be enhanced by wind effect, is identified as a reliable and effective natural ventilation strategy for spaces with high internal heat gain such as office buildings.

2.4 Natural ventilation and occupants’ thermal comfort

Improving occupants’ comfort is one of the major incentives for refurbishment in buildings (Abu Aisheh, 2011). Occupants’ comfort in this context refers to air quality, thermal, acoustic, visual and functional comfort (Morris, 2013). Since both air quality and thermal comfort can be improvise through natural ventilation this study mainly concentrates on improving thermal comfort and providing acceptable indoor air quality in order to enhance occupants’ comfort.

The results of Seppanen et al. (2005a) reveal that there is a direct relationship between internal temperature, occupants’ thermal comfort and occupants’ productivity in office buildings. Based on the results of this study, occupants’ productivity reduces incrementally by 2% per °C increase in internal air temperature when the indoor temperature rises above 25°C. At the same time, the results of Roaf et al. (2009) found a relationship between the temperature in which occupants feel comfortable and the overall energy consumption in the occupied area. If occupants do not feel thermally comfortable, they will change their environment to make it comfortable by, for example, increasing the set-point of the heating system or opening the windows which could lead to higher energy consumption (Roaf et al., 2009). Results of several studies show that due to the extensive use of mechanical ventilation in recent years, occupants’ perception regarding thermal comfort has been changing resulting in higher temperature expectations (Singah et al., 2011; Brager and de Dear, 1998).
Thermal comfort is often assessed based on two approaches known as the “Heat balance approach” and the “Adaptive approach”. Identifying different thermal comfort models can help to find the appropriate assessment tool for the evaluation of natural ventilation options of occupants’ thermal comfort. (Djongyan et al., 2010).

2.4.1 Heat balance approach

In this method it is assumed that thermal comfort is achieved by finding a thermal balance between the amount of heat generated and lost by the human body. Heat loss from our bodies usually take place as a result of heat transfer by convention, conduction, radiation and evaporation. The four environmental parameters that affect human heat loss in buildings are as follows (Awbi, 2003; Roaf et al., 2009 CIBSE KS 06, 2006):

1. Air temperature (°C)
2. Air velocity (m/s)
3. Relative humidity (%)
4. Mean radiant temperature (°C)

The heat balance is also affected by the two personal parameters of metabolic rate (which itself is a function of activity level) and clothing type (CIBSE KS 06, 2006). Awbi (2003) suggested the following heat balance equation in order to evaluate comfort condition:

\[ S = M + W + R + C + K - E - RES \]  \hspace{1cm} (2-4)

Where:

- \( S \) = the heat storage in the body (W)
- \( M \) = the metabolic rate (W)
- \( W \) = the mechanical work done by the body (W)
- \( R \) = the heat transfer by radiation (W)
- \( C \) = the heat transfer by convection (W)
- \( K \) = the heat transfer by conduction (W)
- \( E \) = the evaporative heat loss (W)
- \( RES \) = the heat loss by respiration (W)
Occupants can be considered as comfortable if the value of heat storage in the body (S) in Equation 2-4 is equal to zero. However, it should be noted that a zero value of “S” in Equation 2-4 is insufficient, since it could be equal to zero due to one part of the body becoming cold while other parts are hot.

The most famous heat balance method was proposed by Fanger in 1970 (Nicol and Roaf, 2007). This method is also known as the ASHRAE 55 (2004) and BS EN ISO 7730 (2005) methods. Fanger introduced the PMV (Predicted Mean Vote) index. The PMV index is calculated based on the above mentioned four environmental parameters (air temperature, mean radiant temperature, relative humidity, and air speed) and two personal factors (level of activity and clothing type). According to BS EN ISO 7730 (2005):

“PMV is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale, based on the heat balance of human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment. In a moderate environment, the human thermoregulatory system will automatically attempt to modify skin temperature and sweat secretion to maintain heat balance.

The 7-point scale suggested by BS EN ISO 7730 (2005) is shown in (Table 2-1).

<table>
<thead>
<tr>
<th>PMV</th>
<th>Thermal Sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3</td>
<td>Hot</td>
</tr>
<tr>
<td>+2</td>
<td>Warm</td>
</tr>
<tr>
<td>+1</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cool</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
</tr>
<tr>
<td>-3</td>
<td>Cold</td>
</tr>
</tbody>
</table>

The PMV index is used to estimate the percentage of dissatisfied occupants using the PPD (Predicted Percentage of Dissatisfied) index. Figure 2-3 shows relation between PMV and PPD.
Chapter 2: Literature review

Figure 2-3: Relationship between PMV and PPD (Source: Djongyan et al., 2010)

The PMV method was developed based on the field study in a climate chamber where the environmental conditions were assumed to be steady state, while in real buildings environmental conditions are an unsteady state. Therefore, this could potentially be a source of error (Nicol and Roaf, 2007). Moreover, in the calculation of PMV, it is usually necessary to make some assumptions regarding occupants' clothing or activity levels which again can be sources of further errors (Orosa and Oliveria, 2011).

Humphreys (1978) found a relationship between climatic difference, occupants' habits and thermal comfort expectations which is ignored in the PMV method. Although the results of Van Der Linden et al. (2008) showed similar performance of PMV and other thermal comfort assessment methods (i.e. the adaptive thermal comfort method) for moderate temperature conditions, the results of PMV index for extreme environmental conditions could be misleading.

For these reasons, in recent years the ability of the PMV method to predict thermal sensations in naturally ventilated buildings has been questioned by many researchers. De Dear and Brager (2002) believe that the classic ASHRAE 55 and BS EN ISO 7730 methods give reasonable prediction of occupants' perceptions in mechanically ventilated buildings; however, since this method ignores external weather conditions and occupants' adaptive actions, it may overestimate the risk of overheating in naturally ventilated buildings (Mahdavi et al., 2013). This led to the introduction of another approach to assess thermal comfort in naturally ventilated buildings, the adaptive approach.
2.4.2 Adaptive approach

In naturally ventilated buildings internal temperature is affected by external temperature since windows open more frequently and natural ventilation works as a result of pressure differences caused by internal/external temperature differences and wind. Results of different studies by de Dear and Brager (1998), Nicol and Humphreys (2002), Wagner et al. (2007), Moujalled et al. (2008) and De Dear (2009) revealed that occupants in naturally ventilated buildings feel comfortable in a wider range of temperatures compared to air conditioned buildings. Thus it is proposed that occupants’ perception regarding thermal comfort is affected by their past thermal history (De Dear and Brager, 1998).

It is believed that this wider range of satisfaction is achieved as a result of different forms of adjustments being made by occupants in naturally ventilated buildings (De Dear and Brager 1998). Three categories of occupants’ adjustments to thermal discomfort are listed as follows:

- Behavioural adjustments: This group of actions, such as changing clothing or drinking cold or hot drinks, are taken by occupants to reach heat balance (De Dear and Brager 1998).

- Psychological adjustments: These adjustments take place through time and can lead to change in perception of occupants regarding thermal comfort. Psychological adjustments are affected by occupants’ experiences, habits and expectations (De Dear and Brager 1998 and Peeters et al. 2009).

- Physiological adjustments: This form of adjustment is slower than the first two groups especially in moderate internal temperature conditions. This group of adjustments has the least effect on the occupants’ perceptions regarding thermal comfort. Genetic adaptations and acclimatization during lifetime belongs to this category (De Dear and Bager 1998).

The adaptive approach is developed based on field studies over 21,000 office buildings in different regions (De Dear and Bager, 1998). In this
approach thermal comfort is affected by occupants’ behaviour and expectations in naturally ventilated buildings (Djongyan et al., 2010). In contrast to the heat balance approach, which provides an index to describe thermal comfort, in the adaptive approach comfort temperatures are estimated to make it simpler for designers to use and to make estimates (Van Der Linden et al., 2008).

Humphreys (1978) suggested an equation to estimate comfort temperature in naturally ventilated buildings. Based on the Humphrey’s equation, CEN standard EN15251 (BS EN 15251, 2007) suggests the following two equations to estimate comfort temperature in naturally ventilated buildings (Equations 2-6 and 2-7):

$$T_{comf} = 0.33 T_{rm} + 18.8 \quad \text{(where } T_{rm} > 10^\circ C) \quad (2-5)$$

$$T_{comf} = 0.09 T_{rm} + 22.6 \quad \text{(where } T_{rm} \leq 10^\circ C) \quad (2-6)$$

Where:

- $T_{comf}$ = the comfort temperature ($^\circ C$)
- $T_{rm}$ = the running mean temperature for today which is weighting with higher influence of recent days (Nicol and Humphreys, 2010) ($^\circ C$). It is determined according to Equation 2-8 below:

$$T_{rm} = (1-\alpha). \{T_{ed-1} + \alpha. T_{ed-2} + \alpha^2. T_{ed-3} + \ldots\} \quad (2-8)$$

Where:

- $T_{ed-1}$ = the daily mean external temperature for the previous day ($^\circ C$)
- $T_{ed-2}$ = the daily mean external temperature for the day before ($^\circ C$) and so on

$\alpha = \text{constant and Tuohy et al., 2009 suggest to use 0.8 for } \alpha.$

Instead of Equation 2-8, according to CEN standard BS EN 15251 (2007) to minimise the calculation complexity, an alternative equation can be used to estimate mean running temperatures. This is Equation 2-9 below.
Chapter 2: Literature review

\[ T_{rm} = (T_{ed-1} + 0.8 T_{ed-2} + 0.6 T_{ed-3} + 0.5 T_{ed-4} + 0.4 T_{ed-5} + 0.3 T_{ed-6} + 0.2 T_{ed-7})/3.8 \]  

(2-9)

Where:
- \( T_{rm} \) = the running mean temperature for today (°C)
- \( T_{ed-1} \) = the daily mean external temperature for the previous day (°C)
- \( T_{ed-2} \) = the daily mean external temperature for the day before (°C) and so on

The adaptive approach was initially developed based on data collected in office buildings. The capability of this approach in terms of predicting thermal comfort in different types of buildings and in buildings which are not located in moderate climatic conditions has been questioned (Schweiker et al., 2012). However, the results of various studies have shown that this approach can be applied in different types of naturally ventilated buildings in different climatic conditions with reasonable success (Kwak and Chun, 2003; Nguyen et al., 2012; Liang et al., 2012).

Since in this method the assessment of thermal comfort is simplified and defined only as the function of external temperature, there are some critics regarding the adaptive approach. For this reason, Halawa and Van Hoof (2012) suggested combining both adaptive and heating balance approaches.

2.5 Natural ventilation and indoor air quality (IAQ)

A low ventilation rate leads to poor indoor air quality (IAQ) and reduces occupants’ comfort and productivity. The results of studies by Bakó-Biró (2012) in school buildings and Seppanen et al. (2005b) in office buildings confirm the relationship between IAQ and occupants’ productivity. Risk of Sick Building Syndrome (SBS) is highly increased when acceptable IAQ and enough ventilation are not provided. Although well designed mechanically ventilated buildings can reduce the risk of SBS (Clausen, 2004), natural ventilation is a reliable lower cost alternative solution for SBS.

In crowded spaces a high ventilation rate is required to provide acceptable IAQ. High ventilation rates potentially increase energy loss and risk of draught and discomfort for occupants (Becker et al., 2007). Providing a
constant ventilation rate is much easier through mechanical ventilation but it reduces occupants’ control over the environment (Mumovic et al., 2009).

Lan et al. (2011) find a direct relationship between thermal comfort and acceptable IAQ. The results of this study show that occupants became more sensitive regarding IAQ when they are thermally dissatisfied.

Results of Hummelgaard et al. (2007) reveal that occupants of naturally ventilated buildings are not only more tolerant regarding temperature but also have lower IAQ expectations and can tolerate poorer IAQ. Moreover, according to the same study, occupants reported symptoms of SBS less frequently in naturally ventilated buildings. The results of Toftum (2010) reveal that providing control is more important than the ventilation mode (mechanical or natural) and it affects occupants’ perception and tolerance regarding IAQ. It also found that symptoms of SBS were less frequently reported when more control options are provided for occupants. According to Gratia et al. (2004) in naturally ventilated buildings occupants are less sensitive about draught.

The results of studies by Avgelis and Papadopoulos (2004) show that the building and the occupants are usually the main sources of pollution in a building. Since occupants are the main sources of the pollution in occupied spaces and they constantly generate CO₂, CO₂ concentration is the most common indicator of IAQ in buildings. Results of studies by Santamouris et al. (2008) show that there is a close link between ventilation rate and CO₂ concentration in a building. Hence, high CO₂ level in occupied zones can show IAQ is not acceptable and that there is not enough ventilation. Therefore, as suggested by BB101, (DFE, 2006) and BS EN 15251 (2007), CO₂ concentration can be used as an indicator of indoor air quality in occupied spaces.

Although there are different assessment criteria for the evaluation of thermal comfort in naturally and mechanically ventilated buildings, there is a single assessment criteria for IAQ in both naturally and mechanically ventilated buildings and usually it is assessed by measuring CO₂ concentration in occupied zones.
2.6 Control of natural ventilation

As mentioned in Sections 2.4 and 2.5 the results of several studies have shown that occupants of naturally ventilated buildings feel comfortable in a wider range of temperatures (De Dear and Brager, 1998; Nicol and Humphreys, 2002; Wagner et al., 2007; Moujalled et al., 2008; De Dear, 2009) and can tolerate poorer IAQ compared to air conditioned buildings (Hummelgaard et al., 2007) since in naturally ventilated buildings occupants feel they have more control over their environment.

As natural ventilation is highly influenced by external climatic conditions such as temperature, wind velocity, and wind direction, it is necessary to introduce some form of control in order to protect occupants and buildings from undesired conditions. Control of natural ventilation can be manual (opening and closing windows by occupants), automatic (opening and closing the windows with automated actuator) or a combination of both (BSRIA, 2000). Results of Heieslberg (2008) and Khatami et al. (2011) show that occupants are usually very slow to control their thermal environment and react to thermal discomfort too late. At the same time, the results of studies by Griffiths and Eftekhari (2008) and Khatami et al. (2011) suggested that occupants are often unaware of CO₂ levels as an indicator of IAQ and for this reason it is not recommended to rely on manual controls alone. Although providing automatic control in naturally ventilated buildings has been found to be essential especially in lightweight buildings (CIBSE AM13, 2000), results of studies by Ackerly et al. (2011) showed that, in mixed mode buildings, introducing automatic control may eliminate the above mentioned advantages of occupants’ control in naturally ventilated buildings such as wider acceptable temperature in such buildings. Moreover, according to Frontczak et al. (2012), occupants much prefer manual controls in naturally ventilated buildings. Results of Barlow and Fiala (2007) show that in office buildings the most preferred adaptive action, in terms of providing thermal comfort, is opening and closing windows.

Considering all of the above issues, proposed control strategies need to be designed with consideration for occupants’ manual control and also provide
the opportunity for occupants to manually override automatic control. Otherwise, controlled natural ventilation system may fail to meet occupants’ requirements and reduced their satisfaction since they feel the systems decide for them (Kolokotroni et al., 2001). Moreover, occupants need to be aware of the control strategies and be educated on how to use the system. Brager et al. (2007) suggest introducing informal control systems in which occupants become aware of the time when vents need to be opened by some indicators such as red and green lights.

2.6.1 Occupants’ manual control in naturally ventilated buildings

Manual controls and occupants’ adaptive actions, such as opening and closing windows, have a direct impact on the overall energy consumption of buildings (Roaf et al., 2009). Furthermore, a good control strategy should be designed in correlation with manual control. For this reason it is vital to understand and predict occupants’ behaviours especially when the adaptive thermal comfort approach is employed. Traditionally, in the field of building simulation, fixed schedules are defined for window opening and closing patterns often based on differences between internal and external temperature, to represent occupants’ behaviour in naturally ventilated buildings (Borgeson and Brager, 2008). In recent years, a number of factors have been identified as important issues for determining occupants’ manual control in naturally ventilated buildings. The following paragraphs discuss some of the identified influential factors on occupants’ behaviour (Roetzel et al., 2010; Borgeson and Brager, 2008).

**Temperature:** Temperature is the most important parameter of occupants’ behaviour. Results of studies by Rijal et al. (2008) and Haldi and Robinson (2008) revealed that occupants usually open windows or vents according to the internal temperature and the temperatures in which they feel thermally comfortable, and close the windows for low external temperature and/or high wind velocity.

**Draught:** Occupants usually close the windows as results of draught or wind velocity (Haldi and Robinson, 2008). Results of Dutton and Shao, 2010) studies showed that although occupants close the windows as a result of
internal high air speed (draught), external wind velocity or direction did not affect the occupants’ behaviour to close the windows.

**Season**: As expected, occupants open the windows or vents during the summer and keep them closed during winter. Highest opening and closing frequency is expected during spring and autumn (Rijal, *et al.*, 2008).

**Type of heating systems**: Fritsch *et al.* (1990) believed that the type of heating systems also affect the occupants’ choice of temperature control. For example in building in which heating is controlled by thermostatic radiator valves, occupants prefer to open the windows or vents as it is quicker compared to adjusting the heating system.

**Time of the day**: Results of studies by Yun and Steemers (2008) showed that there is a direct relationship between the times of the day, room occupancy pattern and windows or vents position. Highest frequency of opening and closing windows or vents were observed during the beginning and at the end of the working days. Results of Yun and Steemers (2008) and Borgeson and Brager (2008) also revealed that occupants were usually less sensitive towards the changes during the occupied period (e.g. changes in temperature).

**Opening types**: Occupants prefer to open smaller openings with smaller fraction more frequently, which can be associated with the lower risk of draught when windows are opened a fraction (Herkel *et al.*, 2008). This suggests that providing larger high level vents which do not directly affect the occupants may reduce the disruption effects of external climatic conditions on the occupants.

**Location of occupants**: Occupants who has access to the openable windows/ opening more likely to open the window and therefore feel more comfortable in wider range of temperature (Khatami *et al.*, 2014).

**Outside noise level and air quality**: These are two other parameters that may affect the manual controls by occupants. However, Borgeson and Brager (2008) suggest these two parameters are not as important as the previous ones mentioned above since usually they are not permanent.
2.6.2 Automatic control in naturally ventilated buildings

Providing automatic control in open plan office buildings is a challenging issue. The results of Aggerholm (2003), on different buildings with automatic natural and hybrid ventilation, showed that providing automatic control to provide comfortable conditions in cellular offices was easier compared to open plan offices or educational spaces. This was because in cellular office occupants could have more individual control over their environment. The results of this study suggested that draught is the main problem in automated naturally ventilated buildings.

Control systems consist of at least three basic elements; sensors, controllers and controlled devices (Figure 2-4). Sensors measure variable parameters and send them out to a controller. Based on a control strategy, a controller specifies on output signal and then the output signal determines the position of the controlled device (CIBSE KS 04, 2005; CIBSE Guide H, 2009).

Figure 2-4 shows the components of a typical closed-loop automatic control system. For example in a naturally ventilated building sensors measures a variable (e.g. temperature) and send the signal to the controller, the controller then sends the output signal to the controlled device (e.g. actuator) based on predefined control strategies (e.g. if the temperature is higher than the set-point then open the windows) and this loop repeats regularly.
2.6.2.1 Sensors

Many sensors are usually required for natural ventilation. It is very important to place the correct type of sensors in the right places which are representative of the overall conditions of the measured area (CIBSE KS 04, 2005).

2.6.2.2 Controller

Basically the function of the controller is to process received data from sensors and determine the required actions by controlled devices. (CIBSE KS 04, 2005). The controller is a component in which natural ventilation control strategies are defined and coded.

In naturally ventilated buildings, control strategies are applied to protect buildings from unfavourable external conditions as well as providing an acceptable indoor environment. Control strategies are applied as a function of the controller (Priolo, 2002). Sivakumar et al. (2010) suggest that since
occupants’ requirements and outdoor climatic conditions vary during the day, control strategies should be flexible and be able to adapt to these changes.

Control strategies in naturally ventilated buildings should control flow rates and minimise the risk of high or low flow rates. Providing too much fresh air increases the risk of draught and overcooling while, providing insufficient flow rate increases the risk of overheating and poor IAQ (Darum, 2004).

Although defining a general rule for all buildings is impossible, there are some common principles that can be applied in most cases. Usually control strategies for natural ventilation are used to control temperature and IAQ. In buildings where applying night cooling is also applicable, similar or different control strategies to the day time control strategies should be introduced in order to improve the performance of the natural ventilation system (BSRIA, 1995). Different natural ventilation control strategies including temperature based, CO₂ based, night time ventilation etc. have been identified in different studies and a collection of common control strategies, proposed by different guidelines, is provided in Appendix A.

It is common to find some overlaps between different types of controllers. The control mode in a controller can vary from simple ON/OFF to different forms of logic based and model based controllers (CIBSE Guide H, 2000). Common control modes that are applied in the field of natural ventilation are as follows:

**ON/OFF controller:** This mode provides a coarse form of control and is commonly used in spaces where comfort condition is not sensitive and some deviation from comfort condition is acceptable (e.g. an atrium) (Kolokosta, 2009).

In this mode, to avoid frequent changes and a hunting effect (rapid changes in position of controlled device), a “dead band” is usually introduced which may lead to higher energy consumption (Dounis and Craiscos, 2009). A dead band or neutral zone is a specified range of a variable (e.g. temperature) in which controlled device will not move (CIBSE Guide H, 2009).
PID (Proportional- Integral- Derivative) controller: This mode of controller is more advanced than the ON/OFF mode. In a PID controller, the output signal is specified according to current errors in relation to the set-point (e.g. error = set-point – measured variable), the integral of past errors over the time and the prediction of the future errors by examining the rate of changes in errors (Levermore, 2000; Johnson, 2006). According to Kolokotroni et al. (2001) PID controllers are more effective in systems with a single input/output. Poorer PID control performances are reported in systems with multiple inputs and outputs. The application of PID controllers in natural ventilation may lead to constant operation and hunting effects. This can happen as a result of highly variable external weather conditions (Priolo, 2002). To solve this problem, similar to the ON/OFF controller, a dead band is introduced.

Logic based controller: This form of controller affects the output signals based on a set of predefined rules (IF condition, THEN consequence) and Boolean operators (AND, OR, etc.). This form of controller provides more flexibility to the changes compared to ON/OFF and PID controllers (Michel and El Mankibi, 2000)

This mode of controllers have been widely used in practice (Oldewurtel et al., 2012; CIBSE Guide H, 2009). The limitations of these controllers are their dependence on predefined rules. Despite this limitation, these controllers are capable of controlling complex systems and they have been widely used in the natural ventilation control industry (Michel and Mankibi, 2000; Priolo, 2002). Logic based controllers may be combined with a fuzzy controller using approximate reasoning to provide further flexibility (Eftekhar and Marjanovic, 2003; Darum, 2004).

Model based controller: A physical or non-physical model of the building is built to allow the controller to predict and affect the output signals based on some calculation or simulations (Mahdavi and Pröglhöf, 2008). According to Kolokosta et al. (2009) neutral networks and self-learning algorithms (optimising the system progressively) are two common approaches which have been used as non-physical models (Smith, 2006). The dependency of neutral networks on reliable training data and the dependency
of self-learning algorithms to their experience are the main limitations of non-physical model based controllers. However, computational times of such controllers are fast. A physical approach uses simulation-assisted models. The main advantages of physical models are their capability to take into account the occupants’ reactions to the system while their disadvantages are the dependency of the output signals to the quality of the models as well as availability of input data (Kolokotroni et al., 2001; Kolokosta et al., 2009; Oldewurtel et al., 2012). The results of Michel and Mankibi (2000) and Spindler and Norford (2009) show that the application of model based controllers in an operating building is not common in practice.

2.6.2.3 Controlled device

Controlled devices act according to the output signals sent from the controllers. The most commonly used control device in natural ventilation is vent actuators. Actuators provide a link between controller and actual physical actions required in order to control indoor environment (CIBSE KS 04, 2005). There are different types of actuators such as linear and chain actuators which are installed on openings to open and close them automatic. Figure 2-5 shows an example of chain actuator. Actuators (controlled device) can control vents by ON/OFF, step control with fixed position or modulating control signals.

![Figure 2-5: Chain actuator (Source: SE Controls, 2014)](image)

Bordass et al. (2000) suggests using finer controlled devices with modulating or step control output signal for controlled devices near to occupants since they could provide finer control and allow occupants to adapt themselves to changes and, while coarser controlled devices are suitable for
opening which are located far from occupants (e.g. high level vents in an atrium).

2.7 Conventional automatic control in naturally ventilated buildings

In the natural ventilation control industry, CO₂ levels and/or temperatures in an occupied space are often detected by sensors and, if CO₂ levels and/or temperatures are greater than the set-point, vents open, allowing external air to enter the space until the CO₂ levels and/or temperatures fall back to the set-point value (CIBSE Guide H, 2009).

Natural ventilation could use conventional ON/OFF and PID controller or more advanced logic and model based ones. However, the results of Dounis et al. (1996a) and the follow up studies of Kolokosta (2003) show that due to the complexity of natural ventilation, classical ON/OFF and PID controllers are less suitable for the purpose of natural ventilation control because of multiple input/output in natural ventilation systems. Trobec Lah et al. (2006) recommend the use of more advanced controllers such as logic based controller. Kolokosta (2003) combined different PID, proportional (P), proportional integral (PI) and proportional derivative (PD) controllers with fuzzy controllers. The results showed that all of the combined fuzzy controllers performed better than classical PID controllers. Similar approaches were conducted by Calvino et al. (2004) and the effects of applying PID fuzzy controllers were tested. The results of this study also show stable and acceptable ranges of PMV in a room with a HVAC system.

Logic based control strategies are the standard approach to control natural ventilation (Gwerder et al., 2010). Logic based strategies can either control natural ventilation individually or can be combined with fuzzy approaches. Examples of generic logic based natural ventilation control strategies have been proposed by BSRIA (1998b), Priolo (2002), Heieslberg (2008) and CIBSE guide H (2009). These logic based control strategies specify the condition in which vents should be opened, closed or modulated to control temperature and IAQ.
Da Grace et al. (2004) propose rule based control strategies for some predicted scenarios. Da Grace (2004) tested effects of introducing control strategies into high level openings while low level openings were controlled manually. The results of applying the proposed strategies in EnergyPlus simulations showed that rule based control strategies provided acceptable environmental control. However, the performance of natural ventilation can be considerably affected by occupants’ manual control of low level openings and the risk of overheating was increased by 15% in cases where occupants had little or no intention to control temperature. This suggests that either introducing some form of automatic controls for low level openings, or educating occupants on how to use manual controls, would improve the performance of the system.

Van Moeseke et al. (2007) also proposed logic based control strategies for natural cooling. The results of this study showed that it is possible to reduce internal set-points and consequently lower heating energy demand if the target flow rate is reduced (i.e. using smaller free areas) based on external temperatures. Holmes and Hacker (2007) studied the effects of applying logic (rule based) control strategies in different case studies. Holmes and Hacker (2007) aimed to identify effects of the climate change on the occupants’ thermal comfort and energy consumption. The results showed that all the features of sustainable design (including control strategies and natural ventilation) should be considered together to achieve thermal comfort and low energy consumption targets. However, thermal mass was found to be more important compared to other low energy and sustainable design features. The results of Gwerder et al. (2010) showed the importance and effects of different rule based control strategies on the energy consumption.

Schulze and Eicker (2013) studied the effects of applying logic based temperature and CO₂ control strategies. To avoid unnecessary energy consumption and minimise the risk of draught and overcooling, the maximum provided free area (to control CO₂) was limited to 50% of the effective total free areas, and internal temperature set-points were increased during heating
seasons. The results revealed the capability of natural ventilation to minimise energy consumption compared to mechanical systems.

Dounis et al. (1996b), Kolokosta (2001), Marjanovic and Eftekhari (2004), Jaradat and Al-Nimr (2009) and Hellwig (2010) studied the effects of enhancing rule based control strategies combined with fuzzy logic using approximate reasoning. Fuzzy controllers are developed based on logic based controllers which contains logic based rules (if-then) and fuzzy reasoning input and output (Marjanovic and Eftekhari, 2004). Logic based rules in fuzzy controller are usually specified according to the knowledge of the expert which is called “fuzzy expert rules” (Eftekhari and Marjanovic, 2003). In all these studies, CO₂ concentration and temperature are considered as the input, and opening areas and/or fan rotation speed are defined as the output of the controller. Dounis et al. (1996b) conducted a set of simulations to demonstrate the capability of such systems to provide acceptable IAQ in naturally ventilated building. The findings of Kolokosta (2001) showed that fuzzy logic is capable of providing acceptable IAQ, thermal and visual comfort in the tested mechanically ventilated building. The results of Marjanovic and Eftekhari (2004) on rule based fuzzy logic control strategy showed better performance in terms of temperature control when greater resolutions (more membership functions and larger number of rules) are defined. Hellwing (2010) studied the effects of introducing CO₂ and temperature logic based fuzzy controller in an educational space ventilated by natural ventilation. The results of this study showed unacceptably low temperatures during winter suggesting that free areas were too large or radiators were not operating as expected.

May-Ostendrop et al. (2011), Mahdavi and Pröghöf (2008), Kololosta et al. (2009); Oldewurtel et al. (2010) developed model based controllers in which the performance of the building or the external climatic conditions were predicted based on data-driven or physical simulation models and specified the output signal based on predicted condition. The results of May-Ostendrop et al. (2011) and Mahdavi and Pröghöf (2008) show that strategies which were developed based on physical modelling performed better than data-driven ones.
The model based controller, proposed by Mahdavi and Pröghöf (2008) and Kololosta et al. (2009) contained several logic based (if-then) functions. The results of both studies showed capability of controller in terms of providing thermal comfort. Mahdavi and Pröghöf (2008) showed the potential of a model based controller to reduce heating and cooling demands. Although the results of Kololosta et al. (2009) show significant variation between actual and predicted CO₂ level in building with model based controllers, occupants were satisfied with indoor condition and more than 95% of them described their comfort condition as good or very good. It was not mentioned if this satisfaction was the direct effect of applying control strategies or it was as a result of providing natural ventilation in general.

According Kolokotroni et al., (2001) and Dounis and Caracos (2009), modelled based controller could control natural ventilation effectively. However, since this type of controller a model of the building is required, and controls may vary from building to building. The success of this type of controller highly affected by the accuracy of the model inputs, and each individual building required individual design.

Night cooling in naturally ventilated buildings is another issue which is often associated with the control of natural ventilation. Results of several studies (Da Grace et al., 2002; Artmann et al., 2007, Lissen et al., 2007) show the importance of night cooling in naturally ventilated buildings. Night cooling is usually applied in the building to pre-cool the building’s structure during unoccupied hours in order to provide a heat sink during the occupied hours, and prevent overheating and exhaust the absorbed heat during occupied periods (Le Dréau, 2013). Since occupants are not present in most non-domestic buildings during night time, to control ventilation during this period some form of automatic control is essential. Although providing automatic control during night time is very important according to the results of BSRIA (1995), the type of control strategies is less important, as similar results were achieved when different control strategies are applied.

The effect of applying model based control strategies in conjunction with night cooling is more favourable in buildings with high thermal mass
Kolokotroni et al. (2001). Kolokotroni at al. (2006) studies showed that introducing night cooling in a building with thermal mass could reduce energy demand by 71% and 84% in rural and big cities respectively. The results of Becker and Paciuk (2002) show that although providing night cooling in buildings with high internal heat load and high thermal mass can help to reduce cooling requirements, it can lead to higher energy consumption in building with low heat gains since night cooling reduce air temperature and increase heating demand during occupied hours.

The results of two studies showed the performance of standard rule based controller/strategies are improved when used in conjunction with fuzzy or model based controllers (El Mankibi and Michel 2005; Zhang and Ji, 2007). However, since logic based controllers can be used as a source of fuzzy and model based controller (Jou et.al, 2005) and they are the standard approaches to control natural ventilation, designed control strategies in this study was mainly concentrated on identifying suitable generic standard logic based control strategies that can be used in the case study building.

2.8 Summary

Due to the high risk of overheating in office buildings, introducing some form of ventilation system is essential. Since natural ventilation can reduce energy costs by up to 40%, natural ventilation is good alternative to air condition systems in temperate weather conditions.

Natural ventilation in buildings can be introduced as a function of stack effect, wind effect or a combination of both. Since the stack effect is more reliable and available in buildings with high internal heat gains such as offices, the performance of natural ventilation can be more predictable and guaranteed when stack effect is the main natural ventilation driving force. For this reason, the proposed natural ventilation options in this study (described in Chapter 5) are designed in a way to take advantage of the stack effect as the main running force and enhanced by the wind effect.
Thermal comfort and IAQ are the main parameters which could to be improved in naturally ventilated buildings. Natural ventilation can change the occupants' perception regarding comfort in general and thermal comfort and IAQ in particular. Due to higher level of controls, occupants of naturally ventilated buildings can tolerate a wider range of temperatures. Therefore, the adaptive approach is more suitable for the assessment of thermal comfort in naturally ventilated buildings. However, there is some debate within the community regarding applying the adaptive approach and its reliability to predict occupants’ comfort. For this reason both heat balance and adaptive approaches are applied in this study to assess the occupants’ thermal comfort.

CO₂ concentration can be used as an indicator of IAQ. Although, according to the results of the literature review, it was identified that, in naturally ventilated buildings, occupants are more flexible regarding IAQ, a single assessment criteria (measuring level of CO₂ concentration in occupied zones) is considered for both naturally and mechanically ventilated buildings.

Although introducing an automatic control was found to be essential in naturally ventilated buildings, it should not limit the occupants’ control over their environment. Limiting occupants’ control may result in reduction in the range of comfortable conditions which may lead to occupants’ dissatisfaction and higher energy consumption respectively.

The findings of the literature review showed that classical ON/OFF and PID controllers are less capable of providing controls in naturally ventilated buildings. Therefore, for the purpose of natural ventilation control, logic based or model based controllers are more appropriate. As the logic based strategies can also be used to provide and feed appropriate control strategies for fuzzy and model based controllers, this study focuses on standard logic based control strategies.
3 Methodology

3.1 Introduction

This chapter describes the research methods that were applied in this study. A typical office building was selected as the case study building. Quantitative and qualitative methods were used to assess the performance of the case study building. This was done by studying the actual building performance through conducting physical measurements as well as distributing questionnaires to evaluate the occupants’ comfort and satisfaction. Understanding building performance in terms of energy consumption, thermal comfort and IAQ before any retrofit interventions helped to identify potential retrofit opportunities that could be considered to improve the performance of the case study building. It also provided information to conduct and validate computer simulations.

Four natural ventilation options and four control strategies were proposed based on the results of both Dynamic Thermal Simulation (DTS) and Computational Fluid Dynamic (CFD) models. The best natural ventilation option and control strategies for the case study building were identified and implemented. The actual retrofit took place during two weekends to avoid any disruption. Since then, the natural ventilation system has been operating in the case study building. Post Occupancy Evaluation (POE) was conducted to study the actual effects that the intervention had on energy consumption, thermal comfort and IAQ. The results of the pre and post intervention investigations were then compared with each other and with the typical benchmarks and guidelines.

This chapter contains five sections; after the Introduction the case study building is described in Section 3.2. Section 3.3 outlines the methods used in this study and Section 3.4 briefly describes the methods which are used in Chapters 4 to 8. Finally, the findings of this chapter are summarised in Section 3.5.
3.2 Case study building

A large proportion of the UK’s office buildings were constructed between 1960 and 2000 (Jenkins et al., 2009). According to BSRIA (1999) office buildings built after the 1960s typically have a lightweight structure and poor insulation with low floor-ceiling height. Open plan is the common layout in such buildings, especially in those built after the 1970s (Barlow and Fiala, 2007). High internal heat gains due to extensive use of office equipment and artificial lighting are the other characteristics of UK office buildings (Gratia and De Herde, 2004). According to CIBSE Guide A (2006) the typical thermal heat gain in the UK offices is around 40 W/m².

The case study building (Lancaster House) is a lightweight two-storey commercial building located in Lichfield near Birmingham. It was originally built in 1992 and was formerly a warehouse with office spaces. It was internally refurbished to extend the size of the open plan office in 2005. The construction of the building envelope reflects this by comprising brick and block walls, false ceilings and metal cladding.

The case study building was chosen since it is representative of UK lightweight retrofitted open plan office buildings with low floor-ceiling height and high internal heat gain.

The case study building is located on a typical UK trading estate surrounded by similar two storey retrofitted lightweight buildings and open green fields. The building orientation is 22° clock-wise from north (Figure 3-1).
Chapter 3: Methodology

The total building floor area is 1,100m² and a densely occupied open plan office is located on the first floor. The training room which also is used as meeting room, kitchen, toilets and the warehouse are located on the ground floor (Figure 3-2). Heating is provided by a gas-fired central heating system controlled by thermostatic radiator valves. No mechanical cooling is installed; however, during hot seasons personal desktop fans are used to provide air movement for occupants in the open plan office. Ventilation in the open plan office is provided by cross and single sided ventilation through 14 top hung openable windows on the north, north-east and north-west facades, each measuring 1.14m by 1m while in the training room and kitchen there are four top hung openable windows (each 1m by 1.14m) with a sill height of 0.95m. Furthermore, a mechanical supply and extract system with 0.9 l/s/m² capacity helps to ventilate the open plan office on the first floor.

No external solar shading is present and solar control is provided by internal vertical fin translucent blinds on all windows. The blinds are used extensively during summer by the occupants who are located on north east elevation of the building. It should also be mentioned that since November 2012 there are not any occupants in the warehouse and it is used as a storage area only.

Figure 3-2: Plan of Case study building

(a): Ground floor

(b): First floor
3.3 Outline of the methods used in this study

3.3.1 Physical measurements

To assess actual building performance, physical measurements were taken and thermal comfort, IAQ and energy consumption were evaluated based on ASHRAE Standard 55 (2004), ISO 7730 (2005), BS EN 15251 (2007) and CIBSE Guide A (2006) methods. For this purpose air temperature, CO₂ sensor and relative humidity sensors were installed in three main zones of the building; the training room, the warehouse and the open plan office (Figure 3-2). As shown in Table 3-1, due to the size and number of occupants five temperature sensors were installed in the open plan office while one sensor was installed in each of the other zones.

CO₂ sensors were installed in the training room and open plan office as the main zones which had high numbers of occupants, while due to the large size of the warehouse and low occupancy level, the risk of high CO₂ levels was low and it was therefore not measured in the warehouse. An external sensor was also installed on the north elevation of the building. Specifications of sensors and data loggers are shown in Table 3-1. Energy consumption was recorded using monthly gas and electricity meter readings.
According to BSRIA (1998a) guidelines, all the internal sensors were installed at a height of 1.0 m above the floor level (to represent the height of a seated occupant) and away from direct solar radiation and heat sources to provide realistic accurate measurements. As shown in Figure 3-3 external sensors were placed in plastic boxes with several holes which allowed air to move around the sensors freely while protecting them from rain and direct sunlight. As recommended by BSRIA (2009) the plastic box was suspended from bushes on the north orientation. Although the location of external sensor was not ideal and vegetation could create a microclimate, considering the layout of the site it was the best available position for the external sensor.
Sensors were calibrated using the side by side comparison method suggested by Bauman et al. (1993). Sensors located next to each other for a period of 4 days with recording intervals of 30 seconds and reasonable agreements were found between sensors (±0.5 °C for internal air temperature, ±0.1 °C for the external temperature and ±10 ppm for CO2).

**Assessment of physical measurements**

To assess the risk of thermal discomfort in the case study building, both adaptive and heat balance approaches were used. In both methods the risk of thermal discomfort was evaluated by calculating the percentage of time when the operative temperature or PMV were not within the comfortable range and the frequency of discomfort was reported in each method.

As discussed in Section 2.4.1, according to the heat balance approach occupants’ thermal sensation is evaluated based on four environmental parameters (air temperature, mean radiant temperature, relative humidity, and air speed) and two personal factors (level of activity and clothing type (Awbi, 2003; Roaf et al., 2009). By considering all these parameters, occupants’ thermal sensation can be predicted by calculating the predicted mean vote (PMV). The indoor environment is considered to be comfortable if the PMV value is in the range of ±0.5.

Based on data collected by sensors and field observations, temperature, relative humidity, air speed, activity level and clothing code were known, but it
was necessary to estimate values of mean radiant temperature (MRT) to calculate PMV. MRT was estimated by using Equation 3-1 which is proposed by Han et al. (2007)

\[
MRT = 0.99 \times Ta – 0.01
\]  

(3-1)

Where:

\( Ta = \) internal air temperature (°C)

With regards to air speed, based on the field observations and Matthews et al. (1989) recommendations, the work spaces were divided into two areas as follows:

- Area 1: near to windows and external openings (accounts, main office and the training room in Figure 3-2) where air velocity is assumed to be 0.15 m/s
- Area 2: away from the windows and external openings (R&D and warehouse) where air velocity is assumed to be 0.05 m/s.

With regards to relative humidity, to minimise the complexity of the PMV calculations, mean monthly relative humidity was used.

Activity level and clothing code assumptions for each zone of the case study building is shown in Table 3-2. These were specified according to the field observation and CIBSE Guide A (2006) recommendations. Considering all the above assumptions and data collected by the sensors, PMV values were calculated using the Nilsson (2005) online tool. Based on the calculated PMVs the percentage of dissatisfied occupants were predicted using the PPD (Predicted Percentage of Dissatisfied) index. The relationship between PMV and PPD was discussed in Section 2.4.1.

<table>
<thead>
<tr>
<th>Room type</th>
<th>Activity (met)</th>
<th>Clothing (clo)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td>Open plan office</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Training room</td>
<td>1.4</td>
<td>1</td>
</tr>
<tr>
<td>Warehouse</td>
<td>1.8</td>
<td>1</td>
</tr>
</tbody>
</table>
As discussed in Section 2.4.2, the adaptive method assesses thermal comfort based on the mean running outside temperature (T<sub>rm</sub>) using Equations 2-6 and 2-7. Based on this method occupants feel comfortable if indoor operative temperature is between ±3 °C of calculated comfortable temperature (BS EN 15251, 2007). In addition, according to CIBSE Guide A (2006) in naturally ventilated buildings, occupants start to feel thermal discomfort if the operative temperature is higher than 25 °C. Therefore as shown in Table 3-3 thermal discomfort was assessed by reporting frequency of the time operative temperature was higher than an acceptable level. As suggested in CIBSE Guide A (2006), the operative temperature (T<sub>c</sub>) was calculated as the average of air temperature and mean radiant temperature.

### Table 3-3: Adopted assessment criteria to study results of physical measurements

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Method</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal comfort</td>
<td>Heat balance 1. % of occupied hours PMV in not in the range of ±0.5 2. Maximum PPD</td>
<td>BS EN ISO 7730, 2005</td>
</tr>
<tr>
<td></td>
<td>Adaptive 1. % of occupied hours T&lt;sub&gt;c&lt;/sub&gt; &gt; 25 °C</td>
<td>CIBSE Guide A, 2006</td>
</tr>
</tbody>
</table>
|                   | 2. Heating seasons = % of occupied hours T<sub>c</sub> is not in the range of 20 °C to 24 °C  
|                   | Cooling season = % of occupied hours T<sub>c</sub> is in in the range of calculated T<sub>comf</sub>±3 °C  
|                   | 3. Maximum P                                                           | Nicol et al., 2009          |
| IAQ               | % of occupied hours CO₂ >1000ppm<sup>1</sup> (as target value)         | BB101:2006                  |
|                   | % of occupied hours CO₂ >1200ppm<sup>2</sup> (as acceptable value in existing buildings) | BS EN 15251, 2007           |
|                   | % of occupied hours CO₂ >1500ppm<sup>3</sup>                           | Petty, 2013                 |
|                   | Maximum recorded level<sup>4</sup>                                    | BB101                       |
| Energy consumptions | Comparison with actual energy consumption and benchmarks (140 kWh/year/m²) | CIBSE Guide F, 2012         |

1. 1000 ppm is the target value  
2. 1200 ppm is acceptable value in existing buildings  
3. 1500 ppm is CO₂ level in which usually all the occupants reported some symptoms of Sick Building Syndrome (SBS)  
4. Maximum acceptable level is 5000ppm. However, since maximum CO₂ level existing sensors could record was 2000ppm results of this Section should be studied with more care

To calculate T<sub>rm</sub> (refer to Equation 2-9) external temperature data was required but the external temperature data logger was only installed in December 2010 therefore data for external temperature was not available prior to this date. For this reason the missing external mean running temperature (for the period of July 2009 to December 2010) was estimated based on
meteorological data. This is justified by comparing measured external temperature and recorded meteorological data (Figure 3-4). As shown in Figure 3-4 although results of local measurements recorded slightly higher temperature, in general good correlation was found between meteorological temperature data for “Birmingham” as the closest site to the case study building (Weather underground, 2013), and local temperature (data collected by external sensors). Slightly higher temperature recorded by external sensors could occur due to the location of the sensors which might be affected by solar radiation.

Figure 3-4: Meteorological and local mean running outside temperature (Trm) in 2012

The Proportion (P) of occupants who were not comfortable was also estimated as adaptive approach was considered. P values were estimated based on Equation 3-2 which was suggested by Nicol et al. (2009) and maximum calculated P values for each zone were reported to show peak conditions:

$$P = \frac{e^{(0.4734 \times \Delta T - 2.607)}}{1 + e^{(0.4734 \times \Delta T - 2.607)}}$$

(3-2)

Where:

- P = proportion of occupants who are not comfortable
- \(\Delta T\) = difference between operative temperature and comfort temperature.

To assess IAQ, as discussed in Section 2.5 CO\(_2\) concentrations during occupied hours were used as indicator of IAQ. Therefore as shown in Table 3-
3, IAQ was assessed based on the frequency of time when CO₂ concentration were higher than 1000ppm as the target value, 1200ppm as an acceptable level in existing building, and 1500ppm as the level in which usually all the occupants reported some symptoms of Sick Building Syndrome (SBS) (Petty, 2013). According to BB101, (DFE, 2006), the maximum CO₂ level in each zone should not exceed 5000 ppm and for this reason the maximum value is reported. However, since the maximum CO₂ level the existing sensors could record was 2000 ppm, the results of this Section should be investigated with more care and maximum CO₂ concentration was only used as an indicator of poor IAQ.

Monthly gas and electricity meter readings were available from June 2009 and were used to assess the energy consumption in the case study building. The results of the meter reading were compared with benchmarks proposed by CIBSE Guide F (2012). Based on the definition of building types in CIBSE Guide F, the case study building was categorised as Building Type 2 (naturally ventilated open plan office). Although the case study building was categorised as a naturally ventilated open plan office, there is a mechanically ventilated computer room (server room) in the case study building and for Building Type 2 no computer/server room is assumed. Therefore a value of 14 kWh/year/m² was added to the energy consumption of the benchmark.¹ Energy consumptions was also used as the base line to check the accuracy of DTS models. Table 3-3 shows a summary of the assessment criteria used to assess the results of the physical measurements in this study.

### 3.3.2 Questionnaire

Subjective responses to thermal comfort and IAQ were measured by a questionnaire (See Appendix B). The questionnaire was designed based on the Indoor Environmental Quality (IEQ) survey from the Centre of the Built Environment at the University of California, Berkeley (Huizenga, 2002), a questionnaire for studies of sick building syndrome designed by BRE (Raw, 1995 and Nasrollahi et al., 2006 and Building Use Studies (BUS) survey

¹ 14kWh/year/m² is add to the original value this was specified according to the electricity consumption benchmarks for Building Type 3 (air conditioned office building) (CIBSE Guide F, 2012)
(usablebuildings, 2012)). The questionnaire was divided into three sections as follows:

1. Section 1: personal workplace, used to classify the results.
2. Section 2: control, used to evaluate the control type that had been applied by each occupant and occupants’ perception regarding control.
3. Section 3: comfort, the main section of the questionnaire designed to evaluate occupants comfort in both winter and summer time.

In the comfort section, occupants were asked to assess and rate their overall comfort as well as individual parameters such as temperature, air movement, indoor air quality and humidity that have a direct or indirect effect on their comfort in both winter and summer (Heerwagen and Zagreus, 2005). Moreover, occupants were asked to rate the effects of temperature and indoor air quality on their productivity. ASHRAE’s seven point scale ranging from -3 to +3 was used to evaluate comfort in the case study building (Heerwagen and Zagreus, 2005).

It is good practice to identify any error and problems in questionnaires by conducting a pilot test (Anderson and Arsenault, 2002). For this reason four volunteers (almost 15% of total respondents) filled in the pilot questionnaires and final questionnaires were modified according to their comments. Samples of pre- and post-intervention questionnaires can be found in Appendix B.

3.3.3 Dynamic Thermal simulation (DTS)

DTS models are often used to give an overview of a building’s performance throughout a typical year (Cook and Short, 2009). Since this project aims to propose a retrofitted natural ventilation option and control algorithm for a typical lightweight office building and to find a balance between energy consumption, IAQ and thermal comfort, DTS models are suggested as an appropriate tool to predict thermal and energy performance of the building.

As the accuracy of simulation is highly affected by the inputs, it is important to set a computer model correctly to achieve reasonable results. A DTS model of the case study building was built to provide detailed information regarding building performance for a typical year. Among the different DTS
software packages, IES-VE was chosen since it models the thermal processes and their interactions with each other in the simulated building (Muhaisen and Gadi, 2006). It also provides detailed information about building performance such as operative temperature, CO₂ concentration and energy consumption. Detailed information generated by IES-VE (IES-VE, 2011) enables designers to optimise comfort and energy consumption (Crawley et al., 2008).

For air flow, IES-VE simulations are considered as a multi-zone network model (Moore and Ouzts, 2012) to simulate air flow. In multi-zone network models it is assumed that a building consists of several pressure nodes (rooms or simulated zones) connected to each other and to the external environment through flow paths (Chiaus and Allard, 2005). The pressure of external nodes is usually known or generated from weather data and since external pressure nodes are connected to the internal nodes, pressure values of internal nodes are estimated according to mass balance equation at each node (Santamouris, 2002a).

The following model inputs and assumptions were made in order to set the DTS model for this study.

**Physical geometry**

The physical geometry and orientation of the case study building were modelled according to the actual building information. Surrounding buildings were ignored in the simulation due to their distance from the case study building. The effects of short bushes and green hills, which create some shading for the ground floor windows located on north and north east sides of the building were modelled (see Figure 3-5).
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Figure 3-5: Model represent the case study building and its surroundings in IES-VE

Structural assumptions

Table 3-4 shows the construction types used in IES simulations. Types of structural elements were specified according to observation. However, since U-Values were not known, for unknown elements, to model the worst case scenarios, the maximum acceptable U-Values specified in the approved part L of building regulations published in 1992 (when the actual case study building was built) were used (0.45, 0.45, 0.6, 3.3 and 3.3 W/m²K for external walls, roof exposed walls and windows and roof lights in the buildings other than dwelling) (HMSO, 1992). Details of each construction type and U-Values are shown in Appendix C.

Table 3-4: Construction assumptions and approximations of the case study building

<table>
<thead>
<tr>
<th>Construction element</th>
<th>Construction Type</th>
<th>U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>Type 1: Breeze block wall: Break (0.1m), Insulation (0.06m), Concert (0.1m), Cavity (0.02m), Plaster (0.01m)</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Type 2: Aluminium (0.003m), Cavity (0.1m), Insulation (0.085m), Plaster (0.01m)</td>
<td>0.34</td>
</tr>
<tr>
<td>Roof</td>
<td>Aluminium roof : Aluminium (0.003m), Cavity (0.1m), Insulation (0.085m), Aluminium (0.003m)</td>
<td>0.38</td>
</tr>
<tr>
<td>Ground floor</td>
<td>Type 1 (warehouse): Soil (0.75m), Insulation (0.053m), Concrete (1m) Flooring screed (0.05m)</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Type 2: Soil (0.75m), Insulation (0.053m), Concrete (1m) Flooring screed (0.05m), Chipboard (0.025m),</td>
<td>0.41</td>
</tr>
<tr>
<td>Internal partition</td>
<td>Type 1: Plasterboard (0.013m), Insulation (0.004m) Plaster board (0.013m)</td>
<td>1.99</td>
</tr>
<tr>
<td></td>
<td>Type 2: Plasterboard (0.013m), Brick (0.105m), Plaster board (0.013m)</td>
<td>1.68</td>
</tr>
<tr>
<td>Internal Ceiling / floor</td>
<td>Type 1: Carpet (0.02m), Fibreboard (0.02m), Cavity (0.2m), concrete (0.15m) Cavity (0.2m), ceiling tile (0.015m)</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Type 2: Insulation (0.02m), Ceiling tile (0.02m)</td>
<td>0.94</td>
</tr>
<tr>
<td>Glazing</td>
<td>Glass (0.004m), Cavity (0.016m), Glass (0.004m)</td>
<td>3.20</td>
</tr>
<tr>
<td>Roof light</td>
<td>Polycarbonate (0.005m) , Cavity (0.2m), Polycarbonate (0.005m)</td>
<td>3.20</td>
</tr>
</tbody>
</table>
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Internal heat gain assumptions

There were three main sources of internal heat gains in each zone which were defined according to the actual conditions of the zones. Sources of heat gain in each zone are listed in Table 3-5. Heat gain assumptions were specified based on actual building heat gain profile and Table 6-2 in CIBSE Guide A (2006) heat gain assumption for general offices.

Table 3-5: Heat gain assumption in the case study building

<table>
<thead>
<tr>
<th>Room type</th>
<th>People (m²/person)</th>
<th>Lighting (W/m²)</th>
<th>Equipment (W/m²)</th>
<th>W</th>
<th>Total W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open plan office</td>
<td>10</td>
<td>18</td>
<td>14</td>
<td>12744</td>
<td>38.5</td>
</tr>
<tr>
<td>Training room</td>
<td>3</td>
<td>12</td>
<td>5</td>
<td>2242</td>
<td>47</td>
</tr>
<tr>
<td>Kitchen</td>
<td>9</td>
<td>15</td>
<td>16</td>
<td>1239</td>
<td>37.2</td>
</tr>
<tr>
<td>Toilet</td>
<td>9</td>
<td>15</td>
<td>5</td>
<td>1405</td>
<td>27.2</td>
</tr>
<tr>
<td>Meeting room</td>
<td>5</td>
<td>15</td>
<td>5</td>
<td>696</td>
<td>38</td>
</tr>
<tr>
<td>Warehouse</td>
<td>25</td>
<td>12</td>
<td>12</td>
<td>12269</td>
<td>26.6</td>
</tr>
<tr>
<td>Mezzanine</td>
<td>25</td>
<td>12</td>
<td>12</td>
<td>2316</td>
<td>25.5</td>
</tr>
<tr>
<td>Corridors and stair cases</td>
<td>-</td>
<td>12</td>
<td>0</td>
<td>546</td>
<td>12</td>
</tr>
<tr>
<td>server room</td>
<td>-</td>
<td>3.75</td>
<td>75</td>
<td>712</td>
<td>75.2</td>
</tr>
</tbody>
</table>

The case study building occupancy patterns in the simulations were assumed to be similar to the actual building as between 9:00 to 17:30 Monday to Friday in all zones except the training room. The occupancy profile in the training room was derived from the actual occupancy profile in the training room based on observations. For two days (Mondays and Wednesdays) the space is fully occupied from 9:00 to 15:30, for other days it is assumed that there are two training session or meetings of 60 minutes.

HVAC and natural ventilation assumptions

Similar to the actual building, heating was modelled using a gas-fired central heating system controlled by thermostatic radiator valves with a set-point of 20°C in cold seasons (October to May). Similar to the actual building no heating system was used in the server room (refer to Table 3-5), while unlike the other parts of the building the server room was equipped with a mechanical cooling system.

Natural ventilation was provided by top hung openable windows on the north, north-east and north-west facades, each measuring 1.14 m × 0.95 m.
Similar to the actual building, a mechanical supply and extract system with 0.9 l/s/m² capacity was also used to ventilate the open plan office and the meeting room. During the heating season, supply air is heated up to 20°C to prevent draught.

IES uses default pressure coefficient (Cp) (refer to Equation 2-2) to simulate the wind effect and pressure differences due to wind. Cp values are functions of wind directions which are defined by weather data and opening types, which are specified by users. Openings on exposed walls, exposed roofs (11° to 30° pitch) and exposed flat roofs in low rise buildings were used as the opening types in IES simulations based on the IES macroflow guidelines and Liddement (1996) recommendations. Table 3-6 shows default wind pressure coefficients that were used in these simulations.

<table>
<thead>
<tr>
<th>Angle of attack</th>
<th>0.0°</th>
<th>22.5°</th>
<th>45.0°</th>
<th>67.5°</th>
<th>90.0°</th>
<th>112.5°</th>
<th>135.0°</th>
<th>157.5°</th>
<th>180.0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed wall (windows)</td>
<td>0.700</td>
<td>0.606</td>
<td>0.350</td>
<td>-0.041</td>
<td>-0.500</td>
<td>-0.465</td>
<td>-0.400</td>
<td>-0.276</td>
<td>-0.200</td>
</tr>
<tr>
<td>Exposed roofs (11° to 30° pitch) (roof vents)</td>
<td>-0.400</td>
<td>-0.435</td>
<td>-0.500</td>
<td>-0.553</td>
<td>-0.600</td>
<td>-0.553</td>
<td>-0.500</td>
<td>-0.435</td>
<td>-0.400</td>
</tr>
</tbody>
</table>

Regarding infiltration rate, since the case study building was refurbished in 2004 it needed to follow approved document L (HMSO, 2004) requirements and for this reason, air infiltration rate of the case study building was estimated as 0.3 ach (average infiltration rate for two story office type 2 recommended by CIBSE Guide A (2006)). However, it should be noted that suggested values by CIBSE A (2006) is average values and since the case study building has a light weight contraction in terms of air permeability the building performance may be worse than this.

Thermal performance of a building is also highly affected by external weather conditions. Test Reference Year (TRY) weather data for Birmingham (Birmingham TRY-05) (CIBSE, 2008) was chosen as the closest weather conditions to Lichfield. TRY weather data is representative of typical site weather data and is generated based on 20 years of actual weather data (CIBSE Guide J, 2002). Due to the high importance of weather data on the results, heating and cooling degree days were calculated based on both actual
external temperature and TRY weather data by using CIBSE TM 41 (CIBSE TM 41, 2006) method and reference temperature of 15.5 °C. As shown Figure 3-6 overall through the year there is a reasonable agreement between results of weather data and actual recorded temperature.

![Figure 3-6: Heating and cooling degree day](image)

Occupants’ manual controls were specified according to the occupant’s thermal comfort and actual occupant’s behaviours based on field observations. According to Rijal et al. (2011) occupant start opening the windows when they thermally feel uncomfortable and close the windows if they feel it is cold.

The only zones of the building in which occupants have some sort of control over temperature are the open plan office, the training room and the kitchen (Figure 3-2). As the kitchen is usually used for short periods only, occupants’ behaviour in the kitchen does not have a significant effect on the building’s total heating energy consumption and thermal behaviour. For this reason occupant’s manual control in the kitchen were ignored and the effects of the vents opening and closing regime in the training room and open plan office were simulated. Based on observations in the open plan office, during summer time occupants usually start opening the windows when air temperature reached to 24 °C to 25 °C and all the vents were opened when it reached to 27 °C to 28 °C. During winter time usually the occupants open the vents at the same temperature as summer time but with smaller opening sizes. In Spring and Autumn, based on external temperature occupants open the vents similar to summer time during hotter days and similar to winter time during colder periods. Occupants have less tolerance to the higher temperature in the Training room and will open the vents earlier. This is due
to the room usually being used as a meeting room and therefore occupants’
having a more formal dress code. Table 3-7 shows opening and closing profile
applied in the DTS models.

Table 3-7: Opening profiles in model represents current building performance

<table>
<thead>
<tr>
<th>Training room</th>
<th>Open plan office</th>
</tr>
</thead>
</table>
| Windows linearly open when internal air temperature is in range of 23.5 °C to 27.5 °C | Winter (Jan to Feb & Nov to Dec): Windows linearly open when internal air temperature is in range of 24 °C to 28 °C  
Windows will close if To<10 °C or wind velocity is higher than 8 m/s  
Summer (May to September): Windows linearly open when internal air temperature is in range of 24 °C to 27 °C  
Spring Autumn: (March to April & October)  
If external temperature =>18 °C Windows linearly open when internal air temperature is in range of 24 °C to 27 °C  
If external temperature <18 °C Windows linearly open when internal air temperature in range of 24 °C to 28 °C |

Accuracy of DTS models

Based on the actual building information, a DTS model of the case study
building (before intervention) was developed. As suggested by Sargent (2007)
the accuracy of DTS models were checked by comparing the results of
simulation with the actual building performance. For this purpose, both
measured and simulated gas and electricity energy consumption were
compared over a period of one year. Additionally the percentage of occupied
hours when measured and simulated operative temperatures were higher than
25ºC were compared. 25ºC was chosen as the reference temperature, since
according to CIBSE Guide A (2006), 25ºC is the temperature in which
occupants start to feel uncomfortable. The frequency of the occupied hours
when CO₂ in the actual and DTS models was higher than 1000 ppm, 1200 ppm
and 1500 ppm was also compared.

3.3.4 Computational Fluid Dynamics (CFD)

In CFD the simulated domain is divided into several cells and governing
equations are solved for each cell. For the purpose of natural ventilation
simulations the governing equations are known as Navier -Stokes equations
which is the mass, the momentum and energy conservation equations,
Equations 3-3:3-7 summarise governing equations in CFD (Santamouris,
2002a).
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- Continuity equation:
  \[
  \frac{\partial \rho}{\partial t} = \nabla \cdot (\rho V) = 0
  \]  
  (3-3)

- Momentum equations:
  - **x component**
    \[
    \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u V) = -\frac{\partial p}{\partial x} + \rho f_x
    \]  
    (3-4)
  - **y component**
    \[
    \frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho v V) = -\frac{\partial p}{\partial y} + \rho f_y
    \]  
    (3-5)
  - **z component**
    \[
    \frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho w V) = -\frac{\partial p}{\partial z} + \rho f_z
    \]  
    (3-6)

- Energy equation:
  \[
  \frac{\partial}{\partial t} \left[ \rho \left( e + \frac{v^2}{2} \right) \right] + \nabla \cdot \left[ \rho \left( e + \frac{v^2}{2} \right) V \right] = \rho q - \frac{\partial (up)}{\partial x} - \frac{\partial (vp)}{\partial y} - \frac{\partial (wp)}{\partial z} + \rho f \cdot V
  \]  
  (3-7)

Where:
- \(V\) = flow velocity (m/s)
- \(u, v\) and \(w\) = the velocity component in \(x, y\) and \(z\) (m/s)
- \(\rho\) = density which is function of temperature and pressure \((\rho=f(p,T))\) (kg/m\(^3\))

Unknown variables for pressure, velocity and temperature are then referred to boundary and initial conditions. For this reason, the accuracy of CFD models are affected by mesh sizes which determine cell and grid arrangements, boundary and initial conditions which determine unknown parameters (Anderson, 1995; Santamouris, 2002a).

Based on the actual data and IES model the worst case scenario in terms of providing thermal comfort was identified and simulated in PHOENICS. These data were used to determine geometry of the domain, mesh sizes, boundary and initial conditions.

**Geometry and mesh sizes**

Geometry of the domain was defined based on the open plan office as the area with poorest thermal comfort performance and roof (loft) area which connects open plan office to the external environment.
Very fine mesh arrangement leads to longer simulation time and defining coarse meshes increases risk of inaccuracy (Tu et al., 2013). A common approach to deal with this problem is running several models with different mesh sizes and comparing the results to find the optimum mesh sizes and grid arrangements in which results become independent of mesh sizes (Awbi, 2003; Nijemeisland and Dixon, 2004). Figure 3-7 shows the CFD domain of the model which is representative of the open plan office. The CFD model was developed based on the actual building layout shown in Figure 3-2. Details of domain and mesh agreements are discussed in Section 4.4.2.

![Figure 3-7: Mesh distribution in the model with 111,000 cells](image)

**Boundary and initial condition**

According to Chiaus and Allard (2005) “boundary condition is the physical condition which constrains the flow at its boundary and state of flow at an initial time”. Boundary and initial conditions for this study were specified according to the measured and IES results. People objects in PHOENICS were applied to simulate internal heat gain. People objects are the fixed heat flux which are used to represent the large heat loads. It allows air to move freely through the objects which creates similar effects as actual heat gain in office (air freely move around occupants and their work stations (CHAM, 2012). Total heat gain were specified according to the results of DTS model and divided into 7 objects according to the actual layout of the open plan office (red boxes in Figure 3-7).

Other objects except openings were defined as adiabatic (no heat source (CHAM, 2014)). Physical sizes of the openings were specified according to the effective free area of the windows. Openings in PHOENICS were fixed pressure boundary conditions which connect the ambient and local
environment together. Results of Cook et al. (2003) studies which compare analytical, experimental and CFD models showed that imposing constant pressure boundary conditions on openings can generate robust results. According to PHOENICS (2010) in openings a difference between ambient pressure and local pressure is calculated as follow:

\[ \Delta P = \frac{1}{2} f \rho U_n^2 \]  

(3-9)

Where:

- \( f \) is the loss coefficient = \( \frac{1}{C_d^2} \) and according to AM 10 the discharge coefficient (\( C_d \)) was assumed to be 0.62 (CIBSE AM10, 2005).
- \( \rho \) is the density (kg/m³)
- \( U_n \) is the time-mean velocity normal to the opening (m/s)

Velocities were specified as deduced, which means flow value will be calculated at run time based on mass flow rate (CHAM, 2012).

A CFD model was created based on 2009 peak temperature condition (11/08/09 at 17:30). According to collected data peak external temperature was recorded as 24 °C and wind velocity was recorded as 4.1 m/s from a North Westerly direction.

Recorded temperature was used as the ambient temperature and ambient pressure due to wind on each opening was calculated based on Equation 2-1. As discussed in Section 2.2 the wind pressure is the function of wind velocity which can be obtained from local weather stations or weather data and pressure coefficient (\( C_p \)) (Lidemment, 1996). Results of Good et al. (2008) showed that for cubic shape buildings pressure coefficient (\( C_p \)) values from the air flow network model (IES in this case) can provide reasonable results; and as the building has a cubic shape and there were no obstructions near the case study building, value of \( C_p \) for each opening was specified according to Lidemmant (1996) (refer to Table 3-6).

**Turbulence model**

For turbulent flows in addition to the governing equations mentioned in Section 3.3.4 (Equations 3.4 to 3.7) a turbulence model also needs to be
specified. Based on the recommendations of Jiru and Bitsumalak (2010) and Norton et al. (2007) the RNG k-ε turbulence model was applied. Since the density difference between inside and outside was low in this simulation, according to Yang et al. (2006) buoyancy can be modelled using the Boussinesq approximation.

**Accuracy of CFD models**

CFD equations are solved successively until the time convergence is achieved. For this reason, the number of iterations has a significant effect on the accuracy of results and the required time to run the simulations. For this study, the maximum number of iterations in which solutions were converged was 12,000.

As recommended by CHAM (2012) the convergence of solutions were assessed by checking all the following three parameters in each model:

1. **Source balance:** residual for mass and energy were checked in the CFD models. CFD solutions were considered as to achieve source balance when the difference between positive and negative sums was less than 0.1% and 1% for mass and energy respectively (Srebric, 2011).

2. **Residual or iteration error:** residual error should be reduced in each iteration. Iteration error is acceptable when residual errors continuously decrease for all variables (at least over the last 100 iterations) (Foster, 2007, Tu et al., 2013).

3. **Spot value:** over each iteration, PHOENICS reports calculated values (e.g. pressure, velocity, temperature, etc.) for a specified cell (spot value) in addition to residual errors. The results are acceptable when the spot value remained constant.

After achieving convergence in solutions, the actual measured temperatures in different areas of the open plan office were compared to the results of simulation in order to validate the CFD models.
3.4 **Methods used to meet research aims and objectives**

This section provides an overview of the methods that have been implemented in each chapter of this study. The reasons for applying each method and the full description of tested options are discussed in details in each chapter.

3.4.1 **Methods used in Chapter 4 (building performance before intervention)**

Performance of the case study building before intervention are investigated in Chapter 4 in order to identify opportunities for improving its environmental performance and energy efficiency. As shown in Table 3-8, a combination of physical measurements, questionnaire surveys and both DTS and CFD models were considered to evaluate the performance of the case study building. Physical measurements were conducted over a period of one year (June 2009 to July 2010) and questionnaire surveys were conducted in May 2010. Results of both physical measurements and questionnaire surveys were compared to see the correlations between subjective (questionnaires) and objective (physical measurements) results. Awareness of occupants regarding thermal comfort and IAQ and to understand effects of these parameters on their perceived productivity was also studied.

Results of physical measurements were also used to test accuracy and reliability of the computer models. For this purpose as shown in Table 3-8, the results of physical measurements over a period of one year (July 2009-July 2010) were compared with results of DTS model over a period of one typical year using Birmingham TRY 05 weather data for Birmingham. For this purpose frequency of the time when the operative temperature was higher than 25°C was reported. This assessment method was chosen since in contrast to PMV or comfortable temperature based on $T_m$, in this assessment method, thermal comfort was not relative to external temperature or occupant’s activity level and room type. IAQ was assessed by reporting frequency of the time when CO$_2$ concentration was higher than 1000 ppm and 1200 ppm. DTS results then were compared in actual building and DTS models. Monthly and annual gas
and electricity consumption was also compared to study accuracy of DTS models in terms of modelling energy consumption. Further details of this are discussed in Section 4.4.3. A CFD model was also used to provide detailed information for the most critical condition when there is a high risk of overheating in the open plan office. For this purpose the CFD model was set based on the hottest day during 2009-2010 in the open plan office and then measured temperatures in different areas of the open plan office were compared with the CFD results. Validated CFD and DTS models in this chapter are used as the based models for further investigations in Chapters 5, 6 and 7.

Table 3-8: Methods used in Chapter 4

<table>
<thead>
<tr>
<th>Method</th>
<th>Purpose of using this method</th>
<th>Data used</th>
<th>Assessment criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical measurements (See Section 4.2)</td>
<td>To identify opportunities to improve building performance</td>
<td>Physical data collection including temperature CO$_2$ level, relative humidity and energy consumption between July 2009 to July 2010</td>
<td>Frequency of the time operative temperature and PMV values are not in comfortable range (BS EN ISO 7730, 2005; CIBSE Guide A, 2006) Maximum PPD and P (BS EN ISO 7730, 2005; Nicol et al., 2009) Frequency of the time CO$_2$ level is higher than acceptable range (BS EN ISO 7730, 2005; BB101, 2006) Percentage of dissatisfied occupants (PPD and P) in each zone (Heerwagen and Zagreus, 2005)</td>
</tr>
<tr>
<td>Questionnaires (See Section 4.3)</td>
<td>To understand occupants' subjective responses to thermal comfort and IAQ</td>
<td>Questionnaire surveys were conducted during May 2010</td>
<td>Mean vote values in each zone of the case study building Percentage of dissatisfied occupants (PPD and P) in each zone (Heerwagen and Zagreus, 2005)</td>
</tr>
<tr>
<td>DTS (See Section 4.4.1)</td>
<td>To set up accurate DTS models that can be used in the next stages of this study by comparing DTS and physical measurement results</td>
<td>Data from physical measurements which were conducted between June 2009 and June 2010 Data from DTS model using Birmingham TRY 05 weather data (CIBSE, 2008)</td>
<td>Frequency of the time operative temperature and were higher than 25 °C (CIBSE Guide A, 2006) Frequency of the time CO$_2$ concentration and was higher than 1000 ppm, 1200 ppm &amp; 1500 ppm (BS EN ISO 7730, 2005)</td>
</tr>
<tr>
<td>CFD (See Section 4.4.2)</td>
<td>To set up accurate CFD model that can be used in the next stages of this study by comparing CFD and physical measurement results</td>
<td>Data recoded for the hottest day of year 2009-2010 and data form CFD model</td>
<td>Comparison of temperature in different zones of the open plan office</td>
</tr>
</tbody>
</table>
3.4.2 Methods used in Chapter 5 (Proposed retrofit options)

Chapter 5 addressed objective 4 of this study mentioned in Chapter 1. As shown in Table 3-9 the effects of reducing ventilation demand are tested first in Section 5.2 using three approaches:

- Reducing internal heat gain (Case A)
- Introducing automatic control (Case B)
- Combining reduced internal heat gain and automatic control (Case C)

These were tested using the DTS model. In Section 5.3 effects of introducing four different natural ventilation options (Windcatcher, Two ducts, Stack Ducts and Roofvents) are tested. For each natural ventilation option, three free area scenarios are simulated as follows:

- As built,
- AM10 method
- Combination of as built and AM10 method

The DTS models were used in order to study building performance over a period of one typical year using Birmingham TRY 05 weather data (CIBSE, 2008). The DTS models in this section were developed based on Case C DTS model above since Case C provided the best performance. Based on the results of the DTS models worst case scenarios in terms of controlling over heating were identified and simulated using CFD models in Section 5.4. CFD simulations were conducted for Stack duct and Two ducts options. Boundary conditions for CFD models were set based on the base case CFD model which represented building performance before intervention (Section 4.4.2) and initial conditions were modified based on the results of DTS model for the hottest occupied hour in the open plan office (results of Section 5.3). Two sets of CFD models were conducted. In the first set of CFD simulations wind effects have ignored and it was assumed that ventilation was provided only through stack effect. When the only running force assumed to be stack effect atmospheric pressure set as $1.013\times10^5$ Pa and ambient pressures were set as 0. In the second set of simulations wind effect was also included. Results of this chapter
helped to identify the most appropriate natural ventilation option for the case study building.

### Table 3-9: Methods used in Chapter 5

<table>
<thead>
<tr>
<th>Method</th>
<th>Purpose of using this method</th>
<th>Data used</th>
<th>Assessment criteria</th>
</tr>
</thead>
</table>
| DTS        | To study the effects of reducing internal heat gain and ventilation demand by testing three cases as follows:  
- Case A: lower internal heat gain  
- Case B: automated openings  
- Case C: combination of Cases A and B | Validated DTS model developed in chapter 4 were used as base case and effects of applying each case were tested over a period of one year using CIBSE Birmingham TRY 05 weather data (CIBSE, 2008) | Frequency of the time operative temperature is higher than 22°C, 25°C and 28°C  
Maximum operative temperature (CIBSE Guide A, 2006)  
Frequency of the time CO₂ level is higher than 1000ppm, 1200ppm and 1500 ppm (BS EN ISO 7730, 2005)  
Maximum CO₂ concentration  
Monthly and annual gas and electricity consumption (CIBSE Guide F, 2012) |
| (See Section 5.2) |                                                                                               |                                                                                                      |                                                                                                                                                                                                                      |
| DTS        | To study effects of introducing different natural ventilation options by testing four design options and three free area scenarios as follows:  
- Windcatcher FA²: As built  
- FA : AM10 method  
- FA : combination of As built and AM10 method  
- Two ducts FA : As built  
- FA : AM10 method  
- FA : combination of As built and AM10 method  
- Stack ducts FA : As built  
- FA : AM10 method  
- FA : combination of As built and AM10 method  
- Roofvent FA: As built  
- FA : AM10 method  
- FA : combination of As built and AM10 method | DTS models in this part of study were developed based on Case C DTS model described in above row. DTS models studied building performance over a period of one typical year using CIBSE Birmingham TRY 05 weather data (CIBSE, 2008). | Same as above                                                                                                                                                                                                  |
| (See Section 5.3) |                                                                                               |                                                                                                      |                                                                                                                                                                                                                      |
| CFD        | To study building performance over critical conditions  
CFD simulations were conducted for two options as follows  
- Two ducts/ FA: combination of As built and AM10 method  
- Stack ducts/ FA: combination of As built and AM10 method | Boundary condition was set based on the validated CFD model developed in chapter 4 and initial conditions were modified based on the results of DTS model for the hottest occupied hour in open plan office as the worst case scenario. | Comparing average temperature and velocity at different heights of the open plan office  
Tracking velocity pattern  
For each option two sets of simulations were conducted as follows:  
1. Stack effect was assumed as the only driving force.  
2. Both wind and stack effects was assumed as the natural ventilation driving forces. |
| (See Section 5.4) |                                                                                               |                                                                                                      |                                                                                                                                                                                                                      |

² FA = Free area
3.4.3 Methods used in Chapter 6 (CO$_2$ based control strategies)

In Chapter 6 effects of introducing CO$_2$ based control strategies were tested in order to address objective 5. As shown in Table 3-10, to find the appropriate control strategies the DTS was conducted to test the effects of introducing different control strategies on IAQ and energy consumption over a period of one typical year using Birmingham TRY 05 weather data (CIBSE, 2008). For this purpose, effects of adopting three series of typical control strategies and 18 models were tested first in Section 6.3. Then based on the results of typical control strategies further refinements were conducted in order to improve performance of the typical control strategies by testing two series of control strategies which included 44 different models (Sections 6.4 and 6.5). DTS models in Chapter 6 were developed based on Case C, since the results of Case C in Section 5.2 show the requirements of introducing more advanced CO$_2$ based control strategies than typical control strategies.

To study the effectiveness of CO$_2$ based control strategies the average CO$_2$ concentrations during the occupied period as well as the maximum CO$_2$ level was reported. In addition annual heating energy consumption were reported and compared with good practice energy bench marks. Reasons for applying this method of assessment are discussed in Chapter 6.

<table>
<thead>
<tr>
<th>Method</th>
<th>Purpose of using this method</th>
<th>Data used</th>
<th>Assessment criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTS (See Sections 6.3-6.5)</td>
<td>To test effects of applying three typical and two refined CO$_2$ based control strategies on IAQ and energy consumption</td>
<td>Case C DTS model described in Section 3.4 was used as based case. DTS models then used to study building performance over a period of one typical year using CIBSE Birmingham TRY 05 weather data (CIBSE, 2008).</td>
<td>Average CO$_2$ concentration during occupied hours. Peak CO$_2$ concentration. Annual gas consumption. (BB101, 2006). Annual gas consumption (CIBSE Guide F, 2012).</td>
</tr>
</tbody>
</table>

3.4.4 Methods used in Chapter 7 (temperature based control strategies)

Chapter 7 addressed objective 5 of this study mentioned in Chapter 1. Temperature based control strategies were developed in this chapter. As shown in Table 3-11 similar to the Chapter 6 effects of introducing two series of typical control strategies and 12 models were studied first (Section 7.3). Based on the results of typical control strategies two groups of control
strategies were developed to improve performance of the typical control by testing 30 models (Sections 7.4). DTS models in Chapter 7 were developed based on the Roof vent option since results of chapter 5 show this option to be the most appropriate natural ventilation option for the case study building.

To study effectiveness of temperature based control strategies both frequency and severity of thermal discomfort were studied. Moreover to study effects of control strategies on energy consumption annual heating energy consumption was studied. Details of adopted methods to study effectiveness of each strategy are discussed in Section 7.2.

<table>
<thead>
<tr>
<th>Method</th>
<th>Purpose of using this method</th>
<th>Data used</th>
<th>Assessment criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTS</td>
<td>To test effects of applying two typical and two refined temperature based control strategies on occupants’ thermal comfort and energy consumption</td>
<td>DTS model for roof vent option FA (combination of as built and AM10 method) described in Section 3.4.2 was used as based case. DTS models then used to study building performance over a period of one typical year using CIBSE Birmingham TRY 05 weather data (CIBSE, 2008).</td>
<td>Frequency of the time operative temperature is higher than, 25°C and 28°C (CIBSE Guide A, 2006) Maximum operative temperature (CIBSE Guide A, 2006) Frequency of the time operative temperature is in comfortable range (BS EN ISO 7730, 2005) Degree hours of cold and warm period (BS EN ISO 7730, 2005) Annual gas consumption (CIBSE Guide F, 2012)</td>
</tr>
</tbody>
</table>

### 3.4.5 Methods used in Chapter 8 (building performance after intervention)

The most appropriate natural ventilation options and control strategies were identified based on the results of Chapters 5 to 7. A new design based on results of the Roof vent option (proposed and tested in Chapter 5) was developed and installed on 2nd of July 2011, details of actions were done in order to implement retrofitted options described in Section 8.2. Two control strategy types were tested in the actual building as follows:

- Manual control in which occupants were responsible to control natural ventilation in the case study building (July 2011 to December 2011).
- Automatic control in which control strategies developed in chapters 6 and 7 were implemented (January 2012 onward).
The effects of natural ventilation option (Roofvent) and manual control on thermal comfort, IAQ and energy consumption were studied for a period of six months (July 2011 to January 2012). During this period as shown in Table 3-12 physical measurements were conducted. Adopted methods to investigate physical performance of the case study building after intervention were identical to methods that were adapted to study building performance before intervention and same assessment methods were used to study performance of the case study building (See Section 8.3).

As shown in Table 3-12 the performance of the case study building with natural ventilation system and automatic control is studied. Physical measurements were conducted for one year.

In addition to the physical measurements, questionnaire surveys were used to assess the performance of the automated natural ventilation (Table 3-12 and Section 8.4.2)

Distributed questionnaires before and after intervention were almost identical (See Appendix B). However, since after intervention more control options were provided, three additional questions were added to the control section of the original questionnaire (pre-intervention) to test if occupants took any advantage of the controls. Results of Rijal et al. (2007) showed that occupants’ characteristics have a significant effect on their behaviour to adapt themselves to the environmental conditions and according to the same study occupants can be classified as passive or active occupants. Moreover, although several control options were provided after intervention, it was important to understand the occupants’ perception regarding provided controls (Hummelgaard et al., 2007). Occupants feel more comfortable if they feel they have more control over their environment. Results of Deuble and de Dear (2012) show that, in addition to occupants’ characteristics (passive/active) and their perception regarding control, occupants feel more comfortable if they understand how the building is operating. For this reason occupants were asked to answer the following questions which were developed based on the tested questionnaires by Rijal et al. (2007) and Toftum (2010):
Chapter 3: Methodology

1. “To which degree do you feel you control the thermal conditions of your workspace?”
2. “How often do you actually make adjustments to control your thermal conditions (e.g. opening the windows)?”
3. “Could you please specify adjustment actions you usually do to feel more comfortable?”

First question was asked to check whether occupants were happy with the provided control or not, and second question was asked to evaluate if the occupant were active or passive. First two questions have multiple chose answers, while in the third question occupants should write their own answers to check whether occupants understood the proposed natural ventilation options or not.

<table>
<thead>
<tr>
<th>Method</th>
<th>Purpose of using this method</th>
<th>Data used</th>
<th>Assessment criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical measurements (See Section 8.4.1)</td>
<td>To study actual effects of introducing advanced natural ventilation system and automatic control</td>
<td>Physical data collection including temperature CO₂ level, relative humidity and energy consumption between Jan 2012 to Dec 2012.</td>
<td>As above</td>
</tr>
<tr>
<td>Questionnaire (See Section 8.4.2)</td>
<td>To understand occupants’ Subjective responses to thermal comfort and IAQ when the natural ventilation system and automatic control was introduced into the case study building</td>
<td>Questionnaire surveys were conducted during May 2013</td>
<td>Mean vote values in each zone of the case study building Percentage of dissatisfied occupants (PPD and P) in each zone (Heerwagen and Zagreus, 2005)</td>
</tr>
</tbody>
</table>

3.5 Summary

In order to achieve the objectives of this study it was necessary to identify a typical office building in the UK and understand the performance of the
building before intervention. The case study building was identified as a typical office building in the UK and the performance of the building was assessed by conducting quantitative and qualitative studies through physical measurements and questionnaires.

Due to the complex nature of natural ventilation, two simulation methods of DTS and CFD were used. DTS and CFD models were set based on the actual building performance. Simulation results were then compared with the measured data in terms of thermal comfort, IAQ and energy consumption to evaluate the accuracy and reliability of simulated models.

Computer simulations including CFD and DTS were then applied in order to test different scenarios and options. DTS models were used to investigate the effects of introducing retrofitted natural ventilation options and control strategies over a period of one typical year, while CFD models were used to investigate the performance of retrofitted natural ventilation options in the most critical conditions.

After implementation of the natural ventilation option and control strategies in the actual building, qualitative and quantitative studies were conducted and results of physical measurement and questionnaire were compared with the results of building performance before intervention in order to evaluate effectiveness of the proposed options in the real building.

Next chapter discusses results of building performance before intervention.
4 Building performance before intervention

4.1 Introduction

This chapter investigates the case study building performance in terms of thermal comfort, IAQ and energy consumption as the three main areas which were targeted for improvement (refer to the aim of this study discussed in Section 1.2). The aim of this chapter is to provide more detailed information regarding building performance to firstly identify problems and opportunities of the existing building and secondly to provide information to develop realistic and reliable computer models. In this chapter the results of physical measurements are compared with the results of qualitative studies and results of computer simulations.

This chapter contains five sections; after the Introduction the results of physical measurements are reported in Section 4.2. In this section the thermal comfort of the building occupants is investigated by applying heat balance and adaptive assessment methods. IAQ is studied by measuring CO₂ concentration and finally energy consumption is reported by measuring annual gas and electricity consumption (details of the assessment methods used can be found in Section 3.3.1 and Table 3-3).

Section 4.3 describes the results of qualitative studies through a questionnaire survey. The aim of the questionnaire was to assess the overall comfort and parameters such as temperature and IAQ which influence occupants’ comfort to prioritise the proposed natural ventilation and control options based on occupants’ requirements. The results of the questionnaire were also compared with results of physical measurements. This was done to study the awareness of occupants regarding their thermal comfort and IAQ and to understand effects of each parameter on their perceived productivity. The results of this section are then used to evaluate the occupants’ perception as to which physical assessment method (heat balance and adaptive method) is more reliable in this case study building.
Section 4.4 presents the results of DTS and CFD simulations. DTS models are developed based on the assumptions mentioned in Section 3.3.3 and the results are compared with the results of the physical measurements from Section 4.2. This includes the comparison of measured and simulated annual gas and electricity consumption, the frequency of overheating (percentage of time $T_c > 25^\circ$C) and poor IAQ (percentages of the time $CO_2$ concentration $> 1000$ppm, $1200$ppm and $1500$ppm). The DTS models also made it possible to study the performance of building in more detail and provided information regarding the unoccupied areas (e.g. the loft) where physical measurements were not conducted. The CFD model was set based on the hottest day during 2009 to 2010 in the open plan office (11/08/09 at 17:30) as the worst case scenario. Here the measured temperatures are compared with the CFD results.

Section 4.5 forms the summary of this chapter. In this section the main findings of each section are listed and described.

### 4.2 Physical measurements

#### 4.2.1 Thermal comfort

Both adaptive and heat balance approaches were used to study the risk of thermal discomfort in the case study building. In both methods risk of thermal discomfort was evaluated by calculating the percentage of time when the operative temperature (adaptive approach) or PMV (heat balance approach) were not within the comfortable ranges, and the frequency of discomfort was reported in each method for the period of one year (July 2009 to July 2010). Details of calculation methods were discussed in Section 3.3.1.

The results showed that overall the heat balance approach predicted considerably higher risk of thermal discomfort in all zones except in the warehouse and the training room (Table 4-1).
Table 4-1: Results of thermal comfort assessment in the case study building

<table>
<thead>
<tr>
<th>Method</th>
<th>Criteria</th>
<th>Zones(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Open Plan Office</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Main office</td>
</tr>
<tr>
<td>Heat balance (PMV)</td>
<td>1. % of occupied hours PMV in not in the range of ±0.5</td>
<td>37.2%</td>
</tr>
<tr>
<td></td>
<td>2. Maximum PPD (Predicted Percentage Dissatisfied)</td>
<td>72.0%</td>
</tr>
<tr>
<td>Adaptive</td>
<td>1. % of occupied hours Tc&gt;25ºC</td>
<td>26.6%</td>
</tr>
<tr>
<td></td>
<td>2. % of occupied hours Tc is not in the range of calculated T(_{\text{comf}}) ±3 ºC</td>
<td>6.2%</td>
</tr>
<tr>
<td></td>
<td>3. Maximum P (proportion of occupants who are not comfortable)</td>
<td>22.0%</td>
</tr>
</tbody>
</table>

1. Zones in the case study building were described in Section 3.2 and Figure 3-2

The thermal discomfort shown in Table 4-1 is the combination of overheating and overcooling\(^3\). Figure 4-1 shows the results of the thermal comfort calculations for the five occupied zones of the case study building by reporting frequency of overheating and overcooling. In this figure for each zones, the left hand column represents results of thermal discomfort predictions using heat balance approach and right hand columns represents results thermal discomfort predictions using adaptive approach. Besides, in this figure frequency of the time when operative temperature and PMV were higher than comfortable ranges shown as overheating periods and frequency of the time PMV and operative temperature were lower than comfortable ranges shown as overcooling period.

As shown in Figure 4-1 further investigations into the thermal conditions of the warehouse and training room showed considerably higher risk of overcooling when the adaptive approach was applied (e.g adaptive approach predicted 28.8% risk of overcooling in warehouse and 17.5% in training room while heat balance approach predicted less than 2% risk of overcooling in these zones). One explanation for this is the fact that adaptive approach was developed, based on the field observations in office buildings (De Dear and Brager, 1998), where occupants’ activity levels are lower than areas like warehouses or training rooms. For this reason, the adaptive approach may

---

\(^3\) Although overcooling is usually used for air conditioned buildings since there is not an expression to describe the period in which occupants of naturally ventilated building feel uncomfortable due to low temperature, in this study overcooling was used.
potentially overestimate the risk of overcooling in areas where occupants do heavier activities than in offices.

![Figure 4-1: Frequency of thermal discomfort](image)

To study the risk of thermal discomfort, in addition to reporting the frequency of thermal discomfort, the percentage of occupants who felt thermally uncomfortable was also predicted by calculating PPD and P values (see Equation 3-2 and Section 2.4.1) and maximum values were reported to show the worst conditions (predicted annual PPD and P can be found in appendix D). As shown in Table 4-1, although the frequency of thermal discomfort (combination of both overheating and overcooling) calculated by heat balance and adaptive approaches were similar in the warehouse and training room, recorded maximum PPD and P in the warehouse and training room showed considerably lower values when adaptive approach was used (compare maximum PPD and P in each zone in Table 4-1). This suggests better thermal conditions in the warehouse and training room.

As shown in Figure 4-2 and Table 4-1 maximum and overall air temperature in the warehouse and training room were lower than the open plan office and the percentages of the time operative temperatures were higher than 25°C in these zones were considerably lower than the open plan office. This could occur due to the lower internal heat gains in the warehouse (see Table 3-5) and lower occupied periods in the training room (see Section 3.3.3). For example, the recorded maximum temperature in the R&D area reached
32°C while the maximum recorded temperature for the training room and the warehouse were 26.5°C and 30°C respectively.

As shown in Figure 4-1 and Figure 4-2, compare to the other zones overheating is the main problem in the open plan office. In the open plan office itself when both assessment approaches were applied the occupants of R&D suffered the most overheating as there were no openings in this area (see Figure 3-2). In contrast a lower risk of thermal discomfort was recorded for the Main office and Accounts area, where unlike the R&D area, occupants had access to openable windows and natural ventilation (Table 4-1, Figure 4-1).

![Figure 4-2: Annual internal and external air temperature in different building zones](image)

Figure 4-3 shows temperature data for typical summer and winter weeks. In this Figure the CO₂ levels are also plotted to show the occupied periods. Temperature data in all zones of the case study building indicated that during summer (Figure 4-3) the air temperature rose rapidly when occupants entered the office, and since most of the employees remained in the building, internal
heat load remained high for most of the working hours. Air temperature then started decreasing when occupants left the building at 17:30. Since there is no form of night cooling during summer days, air temperature is relatively high at the start of the next working day (refer to high air temperature of 24°C during early working hours of 12/08/09 in Figure 4-3-a). High air temperature in the mornings and unoccupied periods suggested providing some form of ventilation during unoccupied periods can prevent overheating during working hours.

The effect of the lightweight structure of the case study building can be seen during the weekends (e.g. beginning of days on 15/8/09 and 16/8/09 in Figure 4-3) when there were no internal heat gains. Under these circumstances, indoor air temperature closely tracked the outdoor temperature. Internal temperatures also were affected by solar heat gain in the open plan office and training room where, unlike the warehouse, there are some glazed windows.

![Graphs showing temperature and CO2 measurements for typical summer and winter weeks](image)

**Figure 4-3: Temperature and CO2 measurements for typical summer and winter weeks**

Measured temperature data showed considerable temperature differences between the mornings and afternoons. This could be explained by the inflexible heating set points (same set-point for all zones of the building).
and high internal heat gains which led to overheating during winter afternoons. Moreover, sudden increases and decreases in temperature between occupied and unoccupied periods could be due to the lightweight structure, high infiltration rate and poor insulation, especially in the warehouse (Figure 4-3-c and d) which resulted in unnecessary heat loss.

### 4.2.2 CO₂ concentration and IAQ

CO₂ concentration, as an indicator of indoor air quality, was also measured in the training room and the open plan office as the main zones had high numbers of occupants. It should be mentioned that, due to the large size of the warehouse and low occupancy level, the risk of high CO₂ levels was low and it was therefore not measured in the warehouse. IAQ was assessed based on the percentage of the time when CO₂ concentration was higher than 1000 ppm as the target value, 1200 ppm as an acceptable level in existing buildings, and 1500 ppm as the level at which usually all the occupants reported some symptoms of Sick Building Syndrome (SBS)) (Petty, 2013). Table 4-2 summarises the results of this section.

In the open plan office, since the space was quite large and the mechanical supply and extract system was operating during the occupied period, CO₂ levels were within recommended ranges. The CO₂ concentration in the open plan office exceeded 1200 ppm for five weeks and exceeded 1500 ppm for two weeks only in winter (Figure 4-4). In the training room, since the occupant density was much higher than in the open plan office and there was no supply and extract system, higher CO₂ levels were recorded and CO₂ concentrations exceeded 1500 ppm several times.

<table>
<thead>
<tr>
<th>Table 4-2: IAQ in case study building</th>
<th>Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria</td>
<td>Open plan office</td>
</tr>
<tr>
<td>% of occupied hours CO₂&gt; 1000ppm (as target value)</td>
<td>3.8%</td>
</tr>
<tr>
<td>% of occupied hours CO₂&gt; 1200ppm (as acceptable value in existing buildings)</td>
<td>2.8%</td>
</tr>
<tr>
<td>% of occupied hours CO₂&gt; 1500ppm (as value in which usually 100% of occupants reported some symptoms of SBS)</td>
<td>0.5%</td>
</tr>
<tr>
<td>Maximum recorded CO₂ concentration (ppm)</td>
<td>1690</td>
</tr>
</tbody>
</table>
Studying CO$_2$ concentrations in the open plan office over a year showed that, as expected, CO$_2$ concentration in summer time was lower than winter time due to the more frequent use of windows with larger opening sizes. The CO$_2$ profile in the open plan office followed a similar pattern throughout the year. There was a sharp rise in CO$_2$ level as soon as occupants entered the office, CO$_2$ levels usually dropped slightly during lunch times and sharply dropped at the end of working days (Figure 4-3 and Figure 4-4). This showed a strong correlation between CO$_2$ concentration and the occupancy patterns. This also implied high infiltration rates of the case study building, because all external doors and windows were closed after working hours suggesting that the drop in CO$_2$ concentration was mainly as a result of high building air infiltration.

According to the results of this section, in the training room although CO$_2$ concentration was slightly lower in summer time, it was still higher than acceptable limits. The results of this section revealed that similar to the results of Griffiths and Eftekhari (2008) occupants usually open the windows based on thermal comfort and were less likely to open the windows based on the IAQ (CO$_2$ level). This can be seen by comparing CO$_2$ concentration and air temperature during the period of 10/08/09 and 11/08/09 in Figure 4-3-b. On 11/08/09 although internal temperature was higher than the temperature on 10/08/09, CO$_2$ concentration was considerably lower which was as a result of opening the windows during the hotter day (11/08/09). Lower CO$_2$ concentrations during hotter periods (June and July 2010 in Figure 4-4) implies
that if windows were opened at the right time (earlier with larger free area), they would be capable of providing acceptable IAQ. The results of this section show the importance of educating occupants about IAQ in their working environments and the importance of introducing informal controls such as a traffic light control in which occupants become aware of IAQ and indoor CO₂ concentration by red, amber and green lights (Brager et al., 2007). Providing informal controls may improve occupants’ awareness and encourage them to control IAQ.

4.2.3 Energy consumption in the case study building

Current energy consumption in the case study building was evaluated based on meter readings and it was compared with good practice and typical energy consumption benchmarks. Total energy consumption was 171 kWh/m²/year which was almost 14% higher than good practice benchmarks and 29% less than typical energy consumption for this building type (Figure 4-5).

![Figure 4-5: Comparison of actual energy consumption and typical and good practice energy consumption benchmarks.](image)

As a result of installing a new boiler in 2004, gas consumption was only 13% higher than gas consumption in a good practice benchmark (CIBSE Guide F, 2012). Moreover, due to high internal heat gain and high internal temperature in the case study building there was a lower demand for a heating system. Electricity consumption in the case study building was 22% higher
than good practice electricity consumption. This could be as a result of old lighting systems and the supply and extract system operating in the open plan office.

The main energy consumers in the building were gas heating systems, electrical lighting and electrical equipment. The electricity consumption remained almost constant throughout the year while Gas consumption increased significantly in winter when heating systems were operating (Figure 4-6).

![Figure 4-6: Energy consumption in the case study building](image)

### 4.3 Questionnaire

The questionnaire was completed by 32 people which represented 91% of regular occupants in the open plan office and warehouse. More than 80% of the participants spend more than 30 hours/week in the case study building. Since the training room was used for staff training and meetings, the training room was not considered to have permanent occupants and therefore excluded from the questionnaire.

In the main part of the questionnaire, occupants were asked to assess and rate their overall comfort as well as individual parameters such as temperature and indoor air quality. The results of the questionnaire are discussed below.
4.3.1 Temperature

Occupants were asked to evaluate and describe their workplace in terms of temperature in both summer and winter. Figure 4-7 shows occupants’ mean votes based on the ASHRAE 7-point thermal sensation scale in winter and summer in different areas of the case study building. Generally, occupants felt that temperature was more neutral in winter while they described their workplace as hot in the summer.

Table 4-3 provides more details of the occupants’ temperature perception and compares it with the results of physical measurements. In this table a similar approach as Nasrollahi et al., 2007 is adopted and, “-3” and “-2” are considered to be overcooled occupants and “+2” and “+3” were regarded as overheated ones. Moreover, April to September was assumed as summer while October to March was considered as winter time.

Comparisons between subjective and objective responses indicate that there is a good agreement between data obtained from sensors and questionnaires. Based on the results of this section there is a link between the frequency of time when measured temperature was not in a comfortable range and the percentages of occupants who were thermally uncomfortable (Table 4-3). In general, results of both measurements and questionnaire follow the same pattern. According to the results of both quantitative and qualitative studies, the R&D area was the warmest area of the case study building in both seasons.

The results of this section confirmed that there is a direct relationship between occupants' thermal sensation and provided control. In the Accounts
area there are four windows for five occupants while there are six windows for eighteen occupants in the Main office area and therefore, it seems that occupants in Accounts have more control options. The results showed that, although temperature in the Accounts area was slightly higher than the Main office, occupants felt more comfortable in the Accounts area, this could be explained by the availability of more control options in this area. Moreover, occupants of the Accounts area may feel more comfortable in higher temperatures. For the Accounts area, results of the subjective investigation were more comparable with the results of investigations based on the adaptive approach (Table 4-3). From the results of this section it can be concluded that, the investigation method should be chosen based on availability of control and occupants preferences rather than availability of natural ventilation in general.

The results of comparison between subjective and objective responses (Table 4-3) also showed that heat balance approach provides better prediction of occupant thermal sensation in the warehouse. It is while several control options were provided for occupants of the warehouse. The results suggest that since, in the adaptive approach, activity level is ignored, the heat balance approach provides better thermal comfort prediction for the occupants with higher activity levels such as occupants of the warehouse.

Table 4-3: Comparison of subjective and objective responses regarding temperature

<table>
<thead>
<tr>
<th></th>
<th>OVERHEATING</th>
<th>OVERCOOLING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Objective</td>
<td>Subjective</td>
</tr>
<tr>
<td>Summer</td>
<td>48.3%</td>
<td>9.0%</td>
</tr>
<tr>
<td>Winter</td>
<td>22.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Summer</td>
<td>50.0%</td>
<td>12.2%</td>
</tr>
<tr>
<td>Winter</td>
<td>25.9%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Summer</td>
<td>71.8%</td>
<td>24.3%</td>
</tr>
<tr>
<td>Winter</td>
<td>44.4%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Summer</td>
<td>38.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Winter</td>
<td>25.1%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>
According to the results of the questionnaire, more than 74% of participants believed that their productivity decreased due to uncomfortable air temperature in summer and less than 10% of the occupants reported that their productivity was enhanced in winter due to air temperature (Figure 4-8).

![Figure 4-8: Perceived effects of air temperature on participants’ productivity](image)

Occupants of the case study building were also asked to rate temperature stability in both winter and summer. The results of the questionnaire showed similar results in both seasons showing that more than 55% of occupants felt temperature is not stable during the working days. It is while, actual measurements (Figure 4-3) showed higher temperature variations during winter. This could be explained by overall more uncomfortable thermal conditions in summer which made occupants dissatisfied with all parameters.

### 4.3.2 Air movement

Figure 4-9 shows the mean values of air movement rated by the occupants in different areas of the building. Although in summer, windows were opened most of the time, even those occupants who were near the windows (such as the Accounts area) felt air movement in summer was too low and was less than in the winter. This may occur as the temperature of the incoming air is above comfort conditions and the air movement was not perceived as comfortable. This also shows that windows and the existing supply extract system did not operate well and could not provide enough air movement in summer.
4.3.3 Air quality

Participants were also asked to assess IAQ in terms of humidity and freshness. There was generally good agreement between data obtained from RH sensors and the results of the questionnaires. Occupants felt their working environment was drier in winter in comparison to summer which was confirmed by RH measurements (Figure 4-10 and Appendix D).

In terms of air freshness, occupants felt conditions were worse in summer (Figure 4-11), despite the fact that windows were open and CO$_2$ concentration was considerably lower during this season (refer to Figure 4-4). The results suggest that occupants were unaware of the effects of CO$_2$ concentrations (which were usually below 1200 ppm) on their health and wellbeing and CO$_2$ level is only an indicator of IAQ in occupied zones.
4.3.4 Noise level

According to the results of the questionnaire most of the occupants described the noise level of their workplace as neither noisy nor quiet (Figure 4-12). It shows that, although during summer, vents were opened, noise level was not disruptive.

4.3.5 Overall Comfort

Occupants were also asked to describe their comfort in terms of temperature, IAQ and overall comfort both in winter and summer (Figure 4-13). The results of this section suggest that occupants’ comfort was closely determined by the temperature rather than the air quality. Overall comfort of occupants follows a similar pattern to their thermal comfort, specially during summer. This has apparently been due to the extremely uncomfortable thermal conditions in the building which has led to occupants neglecting other parameters.
The results of this section and those shown in Figure 4-8 suggest that providing better overheating controls can help to increase occupants’ productivity and overall comfort.

Figure 4-13: Occupants comfort perception in winter and summer

Comparison of the results of this section with maximum PPD and P values in Table 4-4 shows that in zones in which natural ventilation was not effective and occupants did not have enough control over their environment, the heat balance approach (PPD) predicted more realistic results. On the other hand in zones in which occupants had control options (Accounts) the adaptive approach (P) was more reliable. Moreover, since in the study occupants were asked to assess their thermal conditions over a year and thermal conditions in the building were extremely uncomfortable (refer to Table 4-3), occupants rank their thermal conditions based on their worst experiences. Therefore, the maximum PPD and P were considered as reliable indicators to predict the percentage of uncomfortable occupants.

<table>
<thead>
<tr>
<th>Table 4-4: Subjective and objective prediction of comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>% of Uncomfortable occupants</strong></td>
</tr>
<tr>
<td><strong>OBJECTIVE</strong></td>
</tr>
<tr>
<td>Heat balance (PPD)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td><strong>Main office</strong></td>
</tr>
<tr>
<td>Summer</td>
</tr>
<tr>
<td>Winter</td>
</tr>
<tr>
<td><strong>Accounts</strong></td>
</tr>
<tr>
<td>Summer</td>
</tr>
<tr>
<td>Winter</td>
</tr>
<tr>
<td><strong>R&amp;D</strong></td>
</tr>
<tr>
<td>Summer</td>
</tr>
<tr>
<td>Winter</td>
</tr>
<tr>
<td><strong>Warehouse</strong></td>
</tr>
<tr>
<td>Summer</td>
</tr>
<tr>
<td>Winter</td>
</tr>
</tbody>
</table>
4.4 Computer Simulations

The accuracy of simulation depends on the inputs, and it is therefore important to set a model correctly to achieve reliable results. For this reason, based on the results of physical measurements and observations such as measured temperature, CO₂ concentration, energy consumption and occupancy pattern a DTS model of the case study building was defined to provide detailed information regarding building performances for one typical year. A CFD model was also used to provide detailed information for the most critical condition in the open plan office during the hottest day of year. The results of both models were compared with the results of the actual measurements to test the accuracy of the computer models. Set up of computer models were described in Sections 3.2.2, 3.3.3 and Appendix E.

4.4.1 DTS model results

Figure 4-14 shows the frequency of time when the operative temperature was higher than 25ºC in different zones of the case study building. Comparing the results of this section with physical measurements shows relatively good agreement between measured and simulation results. It should be mentioned that since IES provides a single temperature for a zone, measured temperatures for the open plan office shown in Figure 4-14 were the average temperature in the open plan office and calculated based on the average temperature of the Main Office, Accounts and R&D Zones.

![Figure 4-14: Overheating frequency in actual building and DTS model](image-url)
Results of both actual measurements and computer predictions showed that overheating was the main problem in the open plan office. One major contributor to overheating was high internal heat gain. Internal heat gain (including people, equipment and lighting systems) in the open plan office generates almost five times more heat than heating system during a year (Figure 4-15). Therefore, reducing internal heat gain in the open plan office may help to reduce the risk of overheating and energy consumption. Among all heat sources in the open plan office, lighting systems were assumed to consume the highest amount of electricity and generate the highest amount of heat (Table 3.5). Therefore, improving the lighting systems could help to reduce both internal heat gain and electricity consumption.

![Figure 4-15: Heat balance in the open plan office](image)

Comparison of the temperature in the open plan office and roof space (as an unoccupied zone connected to the open plan office) demonstrates the potential of taking advantage of cold and unpolluted air of the roof space to increase the air movement in the office during hot and moderate conditions by introducing some new opening at ceiling level (Figure 4-16). Opening the low level windows in the open plan office during cold and moderate external conditions, may lead to overcooling and consequently thermal discomfort and could increase the risk of draught and higher heating energy demand.

During hotter periods, since there were no vents on the roof, generated heat from the building as well as the roof space structural heat gain trapped in the roof space. Therefore, introducing some vents to the roof space may help to enhance air movement and reduce temperatures during hot periods in the open plan office.
Chapter 4: Building performance before intervention

Figure 4-16: CO₂ concentration and temperature in the open plan office and roof space (DTS results)

The percentages of the occupied hours during which CO₂ concentrations were higher than 1000, 1200 and 1500 ppm are shown in Figure 4-17. Although for the training room there is a significant difference between measured and simulation predictions (Figure 4-17-a) the pattern of CO₂ distribution is similar (Figure 4-17-c and Figure 4-4). CO₂ levels in both the computer model and actual measurements fell during hotter periods (as a result of switching on natural ventilation) and increased during colder periods.

As shown in Figure 4-3, CO₂ levels in the case study building were highly influenced by occupancy patterns as well as the vent's position (open/closed). In the training room, which was also used as a meeting room, due to the irregular occupancy patterns in the actual building, defining an accurate computer simulation was not possible which explains the differences between the measured and simulated results.
Comparison between simulated energy consumption and good practice and typical energy consumption benchmarks showed that similar to the actual measurements, simulated energy consumption was between typical and good practice benchmarks (Figure 4-18).

There is a good agreement between measured data and computer predictions (Figure 4-19). Simulated electricity consumption was slightly lower
than the actual electricity consumption (1%) which may be due to several reasons including the operation of machinery and equipment which should not have been operating during the unoccupied periods (e.g. occupants forgot to turn off their computer, etc.). The results also showed a good agreement between the measured and simulated gas consumptions. However, results of simulations were 0.6% lower than the actual gas consumption. This is probably due to higher external temperatures in the Birmingham TRY 05 during winter compared to when the measurements were carried out (Figure 4-19).

4.4.2 CFD model results

The CFD model was built based on the assumptions mentioned in Section 3.3.4. The accuracy of the CFD model was then compared with the measured temperatures. The model was built based on the worst case scenario identified in Sections 4.2.1, 4.3.1 and 4.4.1. Overheating in the open plan office and poor IAQ in the training room were identified as the main problems of the case study building. Lower CO₂ concentration during the summer time, when natural ventilation was applied more frequently (Figure 4-4), showed that existing windows were able to provide acceptable IAQ if an appropriate control strategy was introduced. Therefore, CFD models were only used to study building performance in the open plan office. Moreover, the results of Section 4.2.1 showed that external temperature is one of the major contributors to overheating (Figure 4-2). For this reason, performance of the open plan office for the recorded peak temperature was investigated.
Several models with different mesh sizes were simulated to find optimum mesh sizes where CFD results become independent of the mesh size used. Figure 4-20 shows predicted pressure in the centre of the domain along the x axis (refer to Figure 3.6). As can be seen, there are no significant changes in the results of above 111K cells. Therefore, 111 K was used as the optimum size for the simulations.

![Figure 4-20: Effects of applying different mesh sizes on pressure in the middle of the office (x-coordination)](image)

Initial conditions for the CFD model were developed based on the actual external weather conditions for the hottest day of the year in 2009 (11/08/09 at 17:30) when the building was occupied. On that particular day, external temperature, wind speed and direction were recorded as 24° C, 4.1m/s and 340° from north respectively.

The predicted temperature distribution (Figure 4-21) agrees well with the measured values (Figure 4-22). Temperatures in the Main office 01, Main office 03, and Accounts were found to be similar, while temperatures in the Main office 02 were slightly higher and a significant temperature difference was observed between the R&D and other areas. Although temperature distributions in the CFD model were similar to the actual open plan office, the results of CFD showed slightly lower temperatures in different zones (Figure 4-22).
4.5 Summary

In this chapter a combination of physical measurements, questionnaire surveys and both DTS and CFD models were used to evaluate the performance of the case study building. Physical measurements and questionnaire surveys were conducted to study actual building performance in terms of thermal comfort, IAQ and energy consumption. Results of physical measurements were then used to test the accuracy and reliability of the computer models. Table 4-5 reviews the results of this chapter.
Table 4-5: Building performance before intervention

<table>
<thead>
<tr>
<th></th>
<th>Computer model</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open plan office</td>
<td>28.8% of annual occupied hours Tc&gt; 25 °C</td>
<td>30.8% of annual occupied hours Tc&gt; 25 °C</td>
</tr>
<tr>
<td></td>
<td>Max= 32°C</td>
<td>Max= 31.24°C</td>
</tr>
<tr>
<td><strong>CO₂ level:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Training room</td>
<td>68% of annual occupied hours CO₂&gt; 1000ppm</td>
<td>32% of annual occupied hours CO₂&gt; 1000ppm</td>
</tr>
<tr>
<td></td>
<td>Max= 3071 (ppm)</td>
<td>Max= 2000ppm</td>
</tr>
<tr>
<td><strong>Energy consumption:</strong></td>
<td>Whole building</td>
<td>169.25 (kWh/year/m²)</td>
</tr>
</tbody>
</table>

The main findings of this chapter can be summarised as follows:

- The open plan office was identified as the most critical zone in the case study building in terms of thermal comfort while the training room had the worst performance in terms of providing acceptable IAQ.

- Due to high internal heat gains, the lightweight structure and limited ventilation devices, ventilation was ineffective in the case study building and it is necessary to improve this condition especially during summer time when almost 80% of occupants described their thermal condition as uncomfortable.

- Although occupants felt uncomfortable due to the high air temperatures in the case study building, they reacted slowly to these conditions. This suggested that introducing more vents into the space may firstly enhance natural ventilation performance and, secondly, provide valuable user controls. Providing more control options may help to change occupants’ behaviour making them more active in controlling their working environment. Additionally, to control overheating during unoccupied or low occupancy period it was necessary to provide some sort of automatic controls.

- The results suggest that it might be useful to provide some form of automatic controls which control overheating during unoccupied, low

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4 These values are generated based on average temperature in the open plan office
occupancy periods. This may help to prevent overheating during hot and moderate summer days.

- The results of this study indicate that since the training room was densely occupied and occupants were unaware of high CO\textsubscript{2} levels, IAQ was relatively poor in the training room and more than 23% of occupied hours showed CO\textsubscript{2} levels greater than 1000 ppm.

- The results revealed that since in the adaptive approach activity level is ignored, the heat balance approach provides better predictions for the areas with higher activity levels such as the warehouse.

- Comparisons between computer prediction and physical measurements indicate that there is a good agreement between measured data and computer predictions in terms of thermal comfort and energy consumption, and although the trend of CO\textsubscript{2} distribution is similar in both sets of data, there is a significant difference between measured and simulation predictions. This could be explained by the high dependency of CO\textsubscript{2} levels on occupancy patterns. However, due to the irregular occupancy patterns in the actual building, defining an accurate computer simulation was not possible.

According to the results of this chapter it was identified that improving occupants’ thermal comfort and introducing natural ventilation in the open plan office and introducing some form of control in training room to minimize risk of poor IAQ is essential. The next chapter describes the effects of introducing different strategies in order to improve ventilation and occupants’ comfort.
5 Proposed options to improve thermal comfort, IAQ and energy consumption

5.1 Introduction

This chapter reports on the results of testing proposed retrofitted natural ventilation options and comparing their performance with each other. The overall objective of this chapter is to investigate natural ventilation options that can be retrofitted in existing office buildings. The intention is to propose options with minimum disruption effects on the occupants whilst improving the performance of the case study building in terms of thermal comfort, IAQ and energy consumption. The results in chapter 4 revealed that overheating was the main problem in the case study building, especially in the open plan office. For this reason, this chapter aims to test the impact of introducing different options to minimise the risk of overheating in the open plan office. To test the proposed options, both DTS and CFD models are used.

This chapter contains five sections. In Section 5.2, the effects of reducing ventilation demand are reported. The results of Chapter 4 showed that high internal heat gains and slow reaction of occupants to the overheating were the two main contributors to overheating and for that reason, in this section, the effects of introducing automatic controls and reducing internal heat gains are tested using DTS models. DTS models were used to assess thermal comfort, IAQ and energy consumption as the three main areas which were targeted for improvement. Details of the assessment methods used can be found in Table 3-9.

In Section 5.3 a wide range of retrofitted natural ventilation options are tested which include different natural ventilation components with variable free areas. All natural ventilation options tested are stack based strategies which were developed based on the Advanced Naturally Ventilated (ANV) building forms (Lomas, 2007). To evaluate the performance of the proposed options, DTS models are used to predict thermal comfort, IAQ and energy consumption and the results are compared with the base case building performance.
In Section 5.4 the worst case scenarios (in terms of providing thermal comfort) as identified by DTS models, are simulated using CFD. This is done to provide detailed information about the air flow pattern, temperature and fresh air distributions. Two sets of CFD models were tested for each option. In the first sets, wind effects are ignored and stack effect is considered as the sole driving force for ventilation. In the second sets, the effects of wind are included. Section 5.5 summarises the results of this chapter.

5.2 Reduced internal heat gain to minimise risk of overheating (DTS results):

5.2.1 Description of cases with lower ventilation demand

This section reports on the results of three cases with lower ventilation demands and risk of overheating. The aim of the simulation reported here was to improve IAQ, thermal comfort and energy consumption by introducing minor changes to the case study building. According to the results of Chapter 4, high internal heat gain and slow reaction of occupants to thermal discomfort were the two main contributors to overheating and poor IAQ. Therefore, improving these areas helps to reduce ventilation demand and risk of overheating. Better IAQ and thermal comfort will be achieved by automating existing windows, coupled with control strategies to maximise the effectiveness of the existing openings and minimise energy consumption and internal heat gain by using low cost alternatives to improve the energy efficiency of existing equipment.

Three cases were tested: Case A, which adopted lower internal heat gain; Case B, in which effects of applying typical control strategies were tested; and Case C, in which cases A and B were combined (automatic control with lower internal heat gain).

Case A: Results of Section 4.4.1 and Figure 4-15 showed that there is high internal heat gain in the open plan office (including people, equipment and lighting system)\(^1\). These generated almost five times more heat than the heating system during a year. According to the results of Sections 4.2.3 and

\(^1\) Details of internal heat gain can be found in Table 3-5
input data shown in Table 3-5, lighting systems consumed the highest amount of electricity and generated the highest amount of heat.

The current power density of the lighting system installed in the open plan office is 18W/m² which is 33% higher than good practice benchmarks (CIBSE Guide H, 2012). In Case A, the effect of replacing existing light bulbs with PL-L Polar 36 W/830/4P were tested. This reduced the lighting installed power density from 18 W/m² to 13 W/m². It should be noted that as shown in Section 3.3.3 and 4.2.1 due to the irregular internal heat gain (occupancy pattern) risk of overheating was not high in the training room. Therefore, in Case A, the internal heat gain assumptions for the training room was the same as the original model internal heat gain assumptions shown in Table 3-5.

Case B: According to the results of Sections 4.2.1 and 4.3.1, although occupants were aware of their thermal conditions, they reacted slowly to overheating. The results of Figure 4-3 showed that occupants opened the vents when internal temperatures were high and this resulted in high internal temperatures. Moreover, poor IAQ and high CO₂ concentration in the training room as well as lack of awareness about CO₂ concentration demonstrated the need for introducing CO₂ control systems (Sections 4.2.2 and 4.3.3). Therefore, effects of introducing automatic temperature and CO₂ controls were tested in Case B. The control strategies tested in this section were developed based on the typical control strategies tested by Firth and Cook (2010) and Khatami et al. (2013). Details of the control strategies tested are shown in Table 5-1.

Case C: Here the effects of introducing automatic control and reducing internal heat gain were tested (combination of Cases A and B).

Table 5-1 shows all the cases tested in this section. All cases were compared with the original DTS models which were developed in the previous chapter (Section 4.4.). Effectiveness of each case was assessed using the criteria given in Table 3-9.
Chapter 5: Proposed options to improve thermal comfort, IAQ and energy consumption

Table 5-1: Description of test cases with lower internal heat gain and automated windows

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case A:</strong> Model with lower internal heat gains: reduce the lighting installed power density from 18 W/m² to 13 W/m² in the open plan office</td>
</tr>
<tr>
<td><strong>Case B:</strong> Model with automatic window control: adopted control strategies is as follows: If 22°C &lt; Internal temperature &lt; 26°C, then linearly open the vents until fully open or if Co2 &gt; 1000 ppm then open 30% of total free area</td>
</tr>
<tr>
<td><strong>Case C:</strong> Model with lower internal heat gains and automatic window control: combination of Cases A and B</td>
</tr>
</tbody>
</table>

5.2.2 Reduced ventilation demand – Thermal comfort

The risk of overheating was assessed by reporting the frequency of thermal discomfort and maximum temperature. The results of adopting any of the above cases revealed a reduced occurrence of thermal discomfort (Table 5-2). Although these minimal changes helped to reduce the occurrence of overheating by a maximum of 65%, none of them met thermal comfort requirements of CIBSE Guide A (2006). It was found that combining automatic control with lower internal heat gain in Case C provided the best performance in terms of improving thermal comfort (Table 5-2). Due to applying manual controls during very hot conditions and lower internal heat gains in Case A, in comparison to Case B, Case A was more effective in controlling peak temperatures (% of occupied hours Tc>28°C). However, it is still higher than acceptable conditions suggested by CIBSE Guide A (2006). The results show that although reducing the internal heat gain and providing automatic control helped to reduce ventilation demand, since any of the options tested could not provide thermal comfort, existing opening sizes were unable to control overheating and ventilate the existing heat gain.

Table 5-2: Thermal comfort performance in models with lower ventilation demand¹

<table>
<thead>
<tr>
<th>Description</th>
<th>Open Plan Office</th>
<th>Training room</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>original</td>
<td>Case A</td>
</tr>
<tr>
<td>1. % of occupied hours Tc&gt;22°C</td>
<td>82.8%</td>
<td>74.6%</td>
</tr>
<tr>
<td>2. % of occupied hours Tc&gt;25°C</td>
<td>28.8%</td>
<td>24.7%</td>
</tr>
<tr>
<td>3. % of occupied hours Tc&gt;28°C</td>
<td>2.6%</td>
<td>1.9%</td>
</tr>
<tr>
<td>4. Max Tc (°C)</td>
<td>32.9</td>
<td>32.2</td>
</tr>
</tbody>
</table>

¹ Green represents pass and Red represents fail
Chapter 5: Proposed options to improve thermal comfort, IAQ and energy consumption

For the training room, Cases B and C achieved all three thermal comfort requirements of CIBSE Guide A (2006). Results of applying automatic control in the training room (Cases B and C) showed that existing windows were able to provide thermal comfort if appropriate control strategies were introduced and there was no need for larger opening sizes.

5.2.3 Reduced ventilation demand – IAQ

Results of the coupled DTS and airflow models showed that introducing automatic control (Cases B and C) in the training room was effective in controlling CO₂ concentration while reducing internal heat gain in Case A slightly deteriorated IAQ as windows were opened less frequently (Table 5-3). Results of section 4.3.2 showed that occupants usually apply natural ventilation and open windows based on thermal discomfort rather than poor IAQ. For this reason, in buildings with lower temperature and without automatic control (Case A), natural ventilation is less likely to be adopted by the occupants. This explains the reason for slightly higher CO₂ concentrations in Case A compared with the original model.

Due to lower CO₂ concentrations in the open plan office and operating a supply and extract system in that area, adopting any of the above cases did not have any significant effects on the IAQ.

<table>
<thead>
<tr>
<th>Open Plan Office</th>
<th>Training room</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of occupied hours CO₂&gt;1000ppm</td>
<td>% of occupied hours CO₂&gt;1200ppm</td>
</tr>
<tr>
<td>original</td>
<td>Case A</td>
</tr>
<tr>
<td>0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

5.2.4 Reduced ventilation demand – Energy consumption

Energy consumption figures showed that, compared to the original model, Case A performed the best and reduced energy consumption by 2.2% (Figure 5-1) while Case B performed the worst and increased energy consumption by 1.4%. In all cases energy consumption is higher than good...
practice benchmarks and lower than typical ones (CIBSE Guide F, 2010). Gas consumption increased in all cases while electricity consumption reduced in Cases A and C and remained the same in Case B (See Figure 5-1). The results of the DTS models showed that in Case A, as a result of installing low energy consumption lighting systems, electricity consumption reduced by 5% while gas consumption increased slightly by 1.5% due to the lower internal heat gain. Therefore, although reducing internal heat gain helped to reduce overheating and electricity consumption, it increased heating demand.

In comparison to the original model, windows in Case B were opened more frequently during heating seasons to improve IAQ. Consequently, gas consumption increased by 3% while electricity consumption remained the same. It should be noted that, for the purpose of providing IAQ in the case study building, windows were usually only opened in the training room because CO₂ concentrations in the other zones were usually low. As the training room made up only 4.5% of the total floor area of the case study building, it could be expected that, for buildings with a higher number of occupants, where the risk of high CO₂ concentration is greater, typical CO₂ based control strategies can considerably increase energy consumption relative to the manually controlled buildings.

![Figure 5-1: Gas and electricity consumptions in models with lower ventilation demand](image-url)
5.3 Natural ventilation options to increase ventilation rate (DTS Results)

5.3.1 Description of natural ventilation options

According to the results of section 5.2.1, although reducing internal heat gain and introducing automatic control helped to reduce the risk of overheating, the open plan office still faced a high risk of overheating. To overcome this issue it is possible to either reduce ventilation demand by further reducing internal heat gain or increasing ventilation rate by introducing more openings. Results of Chapter 4 suggested that since ventilation devices and control options were limited, introducing more vents into the open plan office may enhance natural ventilation performance and provide more user controls. As discussed in section 4.3.1, occupants feel more comfortable if more control options are provided. For this reason the effects of introducing different natural ventilation options with more control openings were tested. All the models tested in this section were developed based on Case C in Section 5.2 (Table 5-1)

The opportunities to maximise the effects of natural ventilation in the case study building were limited due to the location and sizes of the existing openings (windows). Windows are located on only one side of the building. Therefore, the open plan office was ventilated by single sided ventilation which was inadequate.

Since stack effect is almost always present (Lomas, 2007), all the proposed options took advantage of stack induced ventilation as the main driving force. Several natural ventilation options were tested, all of which included introducing a new series of openings installed on or above the case study building’s roof level. As shown in Figure 5-2 the new series of openings were designed to act as high level openings (outlet) and existing windows acted as low level openings (inlet) to maximise stack effect. A new series of openings were also introduced at the ceiling level by replacing some of the suspended ceiling tiles with automated controllable vents. These ceiling vents
were designed to connect the open plan office to the unheated, unoccupied roof space (loft) providing an exhaust route for hot polluted office air.

Although all options tested were designed to take advantage of stack effect, wind effect could not be ignored. Therefore wind effect was also studied to determine how it could enhance or deteriorate the stack effect in the case study building. As shown in Table 5-4 two groups were tested. The first group studied the effects of introducing high level openings on opposite facades of stack shafts where, according to Hughes et al. (2012) the maximum pressure differences occur (surfaces A and B) as shown in Figure 5-3). In the second group the effects of introducing high level vents on the top surfaces of ventilation devices were studied. In this group, there is almost always a negative pressure field around the high level vents regardless of wind direction (surface C in Figure 5-3).

Figure 5-2: Natural ventilation principle in the case study building

Figure 5-3: Location of openings in groups 1 and 2 (Hughes et al. (2012))
Three free area scenarios were also tested as follows:

**Scenario 1 – AM10 method:** both high level and low level free areas were specified based on the AM10 method. The aim of this scenario was to find the minimum required free areas to minimise cost and structural load on the roof.

In this method sizes of openings were specified according to the peak heat gain in the open plan office and proposed method in AM10 (CIBSE AM10, 2005). Total heat gain for the hottest time of the year was calculated as 13.9 kW (DTS results of building performance in Section 5.2 confirmed this). Required flow rate to provide overheating control was estimated from Equation 5-1 which is proposed by CIBSE Guide B and Lomas, 2007:

\[
Q_{TC} = \frac{\Phi}{C_c \Delta T} = 2.3
\]

(5-1)

Where,
- \(Q_{TC}\) = volumetric flow rate to provide thermal comfort (m\(^3\)/s)
- \(\Phi\) = total heat gain (W)
- \(C_c\) = volumetric heat capacity of air =1200 (J/m\(^3\)K)
- \(\Delta T\) = temperature difference of room and supply air which in naturally ventilated building is maximum allowable temperature rise. According to CIBSE guide A (2006) for peak summer days 3K inside/outside temperature is allowable and based on Lomas (2007) usually in normal height room temperature at ceiling level is about 2-3K higher than mid-height room temperature. Therefore, 5K temperature deference were used.

Air infiltration rate of the case study building was estimated as 0.3 ach (infiltration rate for two story office type 2 recommended by CIBSE Guide A (2006)). Therefore, a ventilation rate of 10.2 ach (=2.25 m\(^3\)/s) is required to provide thermal comfort in the open plan office. Free areas were then calculated using the following equation (AM10 (2005)) for stack induced strategies:
Chapter 5: Proposed options to improve thermal comfort, IAQ and energy consumption

\[ C_dA = Q_{TC} \sqrt{\frac{\rho_0}{2\Delta P}} \]  

(5-2)

Where:

- \( C_d \): Aerodynamic free area (m²)
- \( A_i \): Aerodynamic free area
- \( Q_{TC} \): Flow rate (m³/s)
- \( T_i \): Internal air temperature = (Te+5)=33.8 (°C)
- \( T_e \): External air temperature = 28.8 (°C)
- \( \Delta T \): Difference between internal and external air temperature (K)
- \( g \): Gravitational force per unit mass (m/s²)
- \( Z \): Opening height (specified based on windows height on first floor)=3.4 (m)
- \( Z_n \): Neutral height (specified based on windows height and top level opening refer to Table 5-4) (m)
- \( \Delta \rho_0 \): Density difference = \( \frac{\Delta \rho_0}{\rho_0} = \frac{T_i - T_e}{T_e + 273} \) (kg/ m³)
- \( \rho_0 \): Reference density = (1.2) (kg/ m³)
- \( \Delta \rho_g \) and \( \Delta \rho_{gZ} \):

**Scenario 2 – As built:** both high level and low level free areas were specified based on the existing window sizes which is larger than calculated free areas by AM10 method. The aim was to take maximum advantage of the exiting low level free areas. However, due to the larger opening sizes in this scenario there were higher structural load and cost.

**Scenario 3 – Combination of Scenarios 1 and 2:** Low level free areas were specified based on the existing window sizes and high level free areas were specified based on the AM10 method (Equation 5-2). This was done to minimise cost and structural load on the roof while proposed options took advantage of the exiting low level free areas.

The same control strategies were used in all natural ventilation options and they were similar to the control strategies tested in section 5-2, Control
strategies tested in this section were developed based on typical control strategies tested by Firth and Cook, 2010 and Khatami et al., 2013. The control strategies tested, opened the openings in the following order: ceiling tiles, roof vents, and finally windows. This was done based on the results of Section 4.4.1 shown in Figure 4-16. The aim was to take advantage of lower/milder temperature and CO₂ concentration levels of the unoccupied roof space which acted as a buffer to reduce energy consumption. Details of the control strategies tested can be listed as follows:

- High level vents (e.g. roof vents): open continuously
- Low level openings (Ceiling tiles): If 20 °C < Internal temperature < 24°C, then linearly fully open the vents or If CO₂ > 800ppm then open 30%
- Low level openings (windows): If 22°C < Internal temperature < 26°C, then linearly fully open the vents or If CO₂ > 1000ppm then open 30%

A description of the natural ventilation options and free area scenarios that were tested in this chapter can be found in Table 5-4.
Table 5-4: Natural ventilation options tested in this chapter

<table>
<thead>
<tr>
<th>Ventilation options</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low level</td>
<td>High level</td>
<td>Low level</td>
<td>High level</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windcatcher</td>
<td>Calculated based on AM10 (Zn=6.3)</td>
<td>Calculated based on AM10 (Zn=6.3)</td>
<td>As built</td>
<td>Same size as low level</td>
</tr>
<tr>
<td>Wind direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group I</td>
<td></td>
<td></td>
<td></td>
<td>A duct with openings on four sides was assumed to be installed on the roof. Tower of Windcatcher was divided into several sub towers by internal partitions. Those internal partitions allow the windcatcher to act as inlet and outlet at the same time. (Roaf, 1988 and Soflaee, 2005)</td>
</tr>
<tr>
<td>2 ducts</td>
<td>Calculated based on AM10 (Zn=6.1)</td>
<td>Calculated based on AM10 (Zn=6.1)</td>
<td>As built</td>
<td>Same size as low level</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>In two ducts option, two ducts with openings on opposite facades were installed above roof level</td>
</tr>
<tr>
<td>Stack ducts</td>
<td>Calculated based on AM10 (Zn=6.5)</td>
<td>Calculated based on AM10 (Zn=6.5)</td>
<td>As built</td>
<td>Same size as low level</td>
</tr>
<tr>
<td>Group II</td>
<td></td>
<td></td>
<td></td>
<td>This option had two individual ducts with openings on top</td>
</tr>
<tr>
<td>Roofvent</td>
<td>Calculated based on AM10 (Zn=5.7)</td>
<td>Calculated based on AM10 (Zn=5.7)</td>
<td>As built</td>
<td>As Built</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Two vents on the pitched roof where due to the angle of the pitched roof which is less than 30° wind always creates negative pressure field around roof (Liddement, 1996)</td>
</tr>
</tbody>
</table>
5.3.2 Natural ventilation options – Thermal comfort predictions

Results of applying different natural ventilation options with different free areas showed that introducing any of the proposed NV strategies effectively controlled overheating in the open plan office. As shown in Figure 5-4, it is predicted that the options tested reduced the risk of overheating (percentage of occupied hours $T_c>25^\circ C$) by a minimum of 74% (Windcatcher in Scenario 1) and a maximum of 88.5% (stack ducts in Scenario 2).

![Figure 5-4: Effects of applying different natural ventilation options on temperature control](image)

As expected, providing larger opening sizes enhanced building performance in terms of overheating control, Scenario 2, with the largest free areas gave the best performance and Scenario 1 (AM 10 method) with the smallest free areas showed the poorest performance. Performance of different natural ventilation options in Scenario 3 showed that the risk of overheating was slightly higher than Scenario 2 whereas both were able to meet all the criteria of CIBSE Guide A (2006).

The peak temperature in all models occurred on the 5th of July at 17:30 when, according to the weather data, external dry bulb temperature was 28.8°C and in all models (except the Windcatcher in Scenario 1), the difference between the internal and external temperature deference was less than 3°C (Figure 5-4).
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Stack ducts and Roofvent options provided better performance in controlling overheating whereas they performed worse in controlling lower temperatures and the operative temperature rise above 22°C more frequently.

Poorer performance of the Windcatcher and Two ducts options in controlling overheating could be due to high internal heat gain in the open plan office. Since internal heat gain in the open plan office was high, there was always an upward flow due to the stack effect. It seems that in the Stack ducts and Roofvent options, the wind effect reinforced the stack effect and increased the upward air movement. In the Windcatcher and Two ducts options, it appears that when the wind speed was not high enough or internal temperature was high (and stack effect was the dominant force), the wind effect created an obstruction against upward air movement due to the stack effect reducing the ventilation rate. This confirms the results of Cook and Short (2009) in which they suggest introducing control strategies to control wind effect for high level openings in stack induced ventilation strategies. It should be noted that, introducing control to prevent this problem meant reducing the size of high level openings when wind and stack effects had different directions and reducing free areas which led to lower ventilation rates and a higher risk of overheating.

Poorer performance of the Stack ducts and Roofvent options in controlling lower temperatures (percentage of the time Tc is above 22°C) occurred under the two following conditions:

- During colder periods when low level openings were most likely to be closed (as shown in section 5.3.1, based on the control strategies tested to prevent draught opening set-points of low level openings were higher than opening set-points of high level openings). Under this circumstances natural ventilation mainly relied on high level openings. In this condition, due to the location of openings in the Two ducts or Windcatcher options, the positive wind pressure field was formed around one opening and negative pressure field was formed around the opening located on the opposite side. Therefore, fresh air entered from one opening and exited
from the other opening located on the opposite side. It is while in Roofvent and Stack duct options, due to the location of openings (top surface of ventilation device), there were always similar pressure field around both high level openings. Therefore, there was lower pressure difference and fresh air was less likely to enter the building.

- During the time when the internal and external temperature differences were small and wind effect was the main driving force. Therefore, Two ducts and Windcatcher performed better under these conditions since in these options, due to the wind there was higher pressure difference between high level inlets and outlets.

Comparison of the results of the Windcatcher and Two ducts options showed that the Windcatcher performed slightly better in controlling lower temperatures and poorer in controlling higher temperatures. This is due to the location of the high level vents in the Windcatcher which were located on 4 sides of the vertical shaft while in the Two ducts, high level openings were located only on 2 sides, meaning that the Windcatcher was affected more frequently by wind effects.

5.3.3 Natural ventilation options – IAQ prediction

The effect of different natural ventilation options on IAQ was tested by measuring the percentage of occupied hours during which CO$_2$ concentration was higher than 800 ppm and 1000 ppm. According to the IES results, CO$_2$ concentration never exceeded 1000 ppm and, for this reason, the effects of the natural ventilation options on IAQ percentages of the times when CO$_2$ concentration was higher than 800 ppm were also reported here.

As shown in Figure 5-5, since the supply and extract system was disabled in the options tested, compared to the original model, IAQ deteriorated in the proposed options. However, all of the proposed natural ventilation options achieved the assessment criteria (mentioned in Table 3-9) in terms of controlling CO$_2$ concentration.
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As can be seen in Figure 5-4 and Figure 5-5, the percentage of time when CO₂ is higher than 800ppm follows the same pattern as the percentage of time when the operative temperature (Tc) is higher than 22°C. Further investigations on IAQ showed that CO₂ concentration increased during colder periods when low level openings were less likely to be opened and natural ventilation was mainly provided by the high level openings. For this reason, natural ventilation options in Group 1 (Two ducts and Windcatcher options), which had openings on two opposite walls, were more likely to provide better IAQ control. This can be seen in Figure 5-6 which shows the total inflow rate through a ceiling tile as well as CO₂ concentration in the open plan office for a typical winter day. During this day, windows were not opened and ventilation was provided through the high level openings and ceiling tiles. As it is shown for the Roofvent and Stack ducts options (Group 2), the CO₂ concentration was higher and flow rate was lower in both options while Group 1 provided higher flow rate.
5.3.4 Natural ventilation options – Energy consumption predictions

The effects of applying different natural ventilation options on energy consumption was also studied. Since in all the proposed options there was no mechanical cooling or ventilation and as the control strategies in all options were similar, energy consumption was also similar. However, options with the smallest free areas (Scenario 1) had the lowest consumption while options with the largest free areas (Scenario 2) had the highest energy consumption (Figure 5-7). Comparison of the energy consumption in the original and proposed options showed minimum and maximum reduction of 2% and 5% respectively.
Although gas consumption in different scenarios was similar, in each scenario, gas consumption in Group 1 (Two ducts and Windcatcher options) was slightly higher which is likely to be due to the reliance of natural ventilation on high level openings. As explained in Sections 5.3.1 and 5.3.2, the Two ducts and Windcatcher options provided higher ventilation rates during colder periods which in turn increased the demand for heating (Figure 5-8).

From the results of this section it can be concluded that natural ventilation options in Group 1 require much more advanced control strategies in order to prevent unnecessarily high heating energy demand.

Electricity consumption in all options was the same and lower than the original model. The lower electricity consumption in the proposed strategies compared to the original model is due to relying on natural ventilation rather than mechanical supply and extract system (Figure 5-7).

**Figure 5-8: Inflow rate and heating energy consumptions for a typical winter day (scenario 3)**

### 5.4 Natural ventilation options (CFD results)

CFD models in this section were developed based on the CFD models described in Section 4.4.2. Since overheating was identified as the main problem of the open plan office, CFD models were applied to investigate the performance of the natural ventilation options for the hottest day of the year. CFD models were used to visualise temperature and velocity distribution and
to evaluate how internal heat gains could be removed from the open plan by
air movement in the open plan office. Since the natural ventilation options in
each group ([Windcatcher and Two ducts options] and [Roofvent and Stack
ducts options]) showed similar performance (Figures 5-4, 5-5 and 5-7), CFD
models were developed for the Two ducts and Stack ducts options only.

Results of Section 5.3.2 suggested that the wind effect limited
performance of the Two ducts option and enhanced the performance of Stack
ducts option. For this reason, two groups of CFD models were simulated. In
the first group wind effect was ignored and stack effect was assumed as the
only driving force. In the second group wind effect was also simulated.

5.4.1 CFD results: Stack Effect Alone

The effects of applying different natural ventilation options on the average
temperature and velocity distributions showed the same performance in both
options. As shown in Figure 5-9 and Figure 5-10 temperature differences
between the ankle and head levels in both models were measured as 1.7°C
which is within the allowed temperature difference of 2 K/m recommended by

![Figure 5-9: Effect of both options on average temperature and velocity (buoyancy alone) - CFD prediction](image)
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The direction and distribution of air within the space is shown in Figure 5-11 by using temperature streamline vectors. The results show that for each window, the entire window opening behaved as an inlet and cooler air entered from low level openings when the only driving force was buoyancy effect. Hot air then exited from the open plan office to the roof space through the ceiling tiles and then to the external environment through the roof mounted units (Figure 5-11 and Figure 5-12).
5.4.2 CFD results: Stack and wind effects

The results of this section showed good agreement with the results of the DTS models and similar to DTS results Stack duct option performed better in controlling overheating (Figure 5-13).

The results of the simulations for the Two ducts option showed significant temperature differences between the open plan office and the roof space (Figure 5-14-a) which suggests that there is insufficient mixing between the open plan office and the roof space air to reduce the temperature in the open plan office. As can be seen in Figure 5-14-b, in the Stack ducts case, there has been an upward flow from the open plan office to the roof space while in the Two ducts option there was downward flow due to the wind effect. In the Two
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ducts option, wind created an obstruction against the upward flow due to buoyancy effect. Therefore, natural ventilation became less effective in this model.

![Figure 5-14-a: Models with both buoyancy and stack effect](image)

**Figure 5-14: Models with both buoyancy and stack effect**
Figure 5-14-c shows direction and distribution of air entering and leaving the external openings by velocity streamline vectors. In the Two ducts option, due to the opposing forces of wind and stack effect, hot air does not exit through the ceiling tiles. The opposing forces of wind and stack effect also prevent fresh air entering the open plan office. Hence, a considerable amount of air entered the roof space from one duct and exhausted from the opposite duct before entering the open plan office. Therefore, a new design in which ducts were directly connected to the open plan office (Design B in Figure 5-15) was tested.

![Diagram](image)

*Figure 5-15: (a) Roof length Ducts/old design (Design A) – (b) Full length Ducts/new design (Design B)*

As shown in Figure 5-16-a, since external cooler air was ducted directly into the open plan office, ducts in design B performed better in terms of controlling the temperature in the open plan office; however, it led to considerably higher internal air velocity which increased the risk of draught. This can be seen in Figure 5-16-b in which air velocity of 1.5 m/s was predicted at the height of a seated person.

Figure 5-16-c shows the pattern and distribution of air entering from the inlet (Duct 1) and exiting from the outlet (Duct 2) by streamline vectors. It shows the effectiveness of Design B in terms of providing a larger flow rate of fresh air into the open plan office. According to the results, for Design A, almost all the fresh air entered from one duct (Duct 1) and left via the other duct (Duct 2) while in Design B air entered the open plan office through Duct 1 and exhausted through Duct 2.
Figure 5-16: Effect of applying two types of external duct when both wind and stack effect were introduced to the model
Comparing the average temperature and velocity at different heights of the open plan office also showed that, in terms of temperature control, Design B was more effective (Figure 5-17). However, compared to the Stack ducts option, the average temperature in the model with Design B was higher (c.f. Figure 5-13 and Figure 5-17). A possible explanation for this is that problems caused by the opposite flow direction in design B, were not completely resolved. Moreover, when Design B was applied, sizes of openable ceiling tiles were limited to the cross section area of the ducts, which was smaller than the size of openable ceiling tiles in the Stack ducts option.

Figure 5-17: Comparison of temperature and velocity distributions in different natural ventilation options - CFD predictions

### 5.5 Summary

The effects of introducing different natural ventilation strategies into the case study building have been tested and their performance investigated in terms of thermal comfort, IAQ and energy consumption using DTS and CFD models. Findings are as follows:

- Introducing automated windows (rather than relying on the occupants to control the openings), and reducing internal heat gain, reduced the risk of overheating in the open plan office by 64% and improved IAQ in the training room by 91%.
• Although electricity consumption was reduced by 5% as results of modifying the lighting systems and applying automatic controls, gas consumption increased by 3% as a result of windows being opened more frequently in the training room to control CO$_2$ concentration. As the training room was only 4.5% of the total floor area of the case study building, it could be argued that, in denser buildings, where the risk of CO$_2$ concentration is higher, typical CO$_2$ control strategies can considerably increase energy consumption. Therefore introducing more advanced CO$_2$ control strategies is essential to minimise energy consumption.

• All proposed natural ventilation options with additional openings reduced the risk of overheating (% of occupied time $T_c > 25$ °C) in the open plan office. The risk of overheating was reduced by a minimum of 74% (Windcatcher option in Scenario 1) and by a maximum of 88.5% (Stack ducts option in Scenario 2).

• Due to the high heat gain in the case study building, there was always an upward flow from the open plan office to the roof area, as a result of the stack effect. For this reason, Roofvent and Stack ducts options, in which wind and stack effects had the same direction, performed better in controlling higher temperatures.

• Comparison of the total energy consumption in the original and proposed options showed minimum and maximum reductions of 2% and 5% respectively. It should be noted that, although energy consumption was not reduced considerably, proposed options removed the need for using mechanical ventilation to provide acceptable IAQ and thermal comfort. Moreover, since the same control strategies were applied in all options, introducing more advanced control strategies can help to achieve further energy savings.

• The results of CFD simulations showed the similar performance for the options tested when the only driving force was stack (buoyancy) effect.
In these models, windows behaved as inlets, high level openings become outlets and there was always an up flow through the ceiling tiles.

- The results of CFD models for the Two ducts option showed that when ducts were not directly connected to the open plan office, hot air could not exhaust from the ceiling tiles and therefore, fresh air could not enter the open plan office due to the opposing forces of wind and stack effect. For this reason almost all the fresh air entered from one duct and left from the other one before entering the open plan office.

- In terms of temperature control, it is possible to improve thermal comfort in the Two ducts option by connecting the ducts directly to the open plan office in order to allow fresh air to be delivered directly into the open plan office. However, this would increase the risk of draught, costs and structural load on the roof.

According to the results of this chapter it can be concluded that the Roofvent and Stack ducts options have the similar performance and in terms of providing thermal comfort and IAQ, they are the most effective options for the case study building. However, as the Stack ducts option would need to be installed externally, planning permission, structural load and cost could be prohibitive. For this reason, and according to the building’s owner preferences as well as ease of implementation and installation procedures, the Roofvent option in Scenario 3 was chosen as the most suitable natural ventilation option which could deliver thermal comfort and IAQ. Table 5-5 compares the performance of the Roofvent option and the building before intervention in the most critical zones of the building in terms of thermal comfort, IAQ and energy consumption.
Table 5-5: Building performance before intervention and optimum natural ventilation option

<table>
<thead>
<tr>
<th></th>
<th>Building performance before intervention (Computer model)</th>
<th>Roofvent (scenario 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open plan office</td>
<td>28.8% of annual occupied hours Tc&gt; 25 °C Max = 32.0 °C</td>
<td>4.3% of annual occupied hours Tc&gt; 25 °C Max = 30.7°C</td>
</tr>
<tr>
<td>Training room</td>
<td>68% of annual occupied hours Co2&gt; 1000ppm Max = 3071 (ppm)</td>
<td>0% of annual occupied hours Co2&gt; 1000ppm Max = 840 ppm</td>
</tr>
<tr>
<td><strong>CO₂ level:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole building</td>
<td>169.25 (kWh/year/m²)</td>
<td>161.64 (kWh/year/m²)</td>
</tr>
<tr>
<td><strong>Energy consumption:</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6 CO₂ based control strategies

6.1 Introduction

This chapter describes natural ventilation control strategies to control CO₂ concentration in the case study building. According to the results described in Section 5.2.3, providing more advanced control strategies in the densely occupied zones such as the training room is essential. Moreover, the findings of Section 2-10 in the literature review suggested introducing the rule-based control strategies for naturally ventilated buildings. Therefore, the aim of this phase of the work is to investigate the performance of various rule-based CO₂ control strategies that maintain acceptable IAQ whilst minimising heating energy consumption in the naturally ventilated buildings.

Results of Section 4.2.2 showed how CO₂ levels in occupied zones were highly influenced by occupancy pattern as well as the position of vents (open/closed vents). Therefore, defining an accurate occupancy pattern has an important impact on the overall results. Findings of Section 4.4.1 revealed that due to the irregular occupancy patterns in the training room, defining actual occupancy patterns in the computer model was impossible. For this reason, in this chapter, the occupancy pattern of the training room is given in terms of two typical learning spaces referred to Seminar room and Classroom. The characteristics of the learning spaces were defined based on specified information in CIBSE Guide A (2006) and BB101 (DFE, 2006) for typical educational spaces.

The performance of each model in terms of providing acceptable IAQ was assessed against BB101 (DFE, 2006) criteria for indoor air quality in learning spaces by using DTS tools. Gas consumption is also assessed according to typical energy consumption suggested by CIBSE guide F (2010). A further issue that needs to be considered in terms of providing acceptable CO₂ control is the ability of the control strategies to avoid hunting (rapid changes in opening area) (Dounis et al. (1996b)). As the CO₂ concentration is very responsive to the flow rate, providing very low or high flow rates can lead
to rapid fluctuations of CO₂ levels and consequently a higher risk of hunting. Therefore the effects of CO₂ concentration on hunting are also assessed by investigating movement of vents during a typical day.

This chapter is structured into seven sections. The second section after the Introduction describes the options tested. Simulation results using the typical control strategies are discussed in the third section in which free areas of ventilation openings are determined according to the recommended free areas in BB101 (Department for Education, 2006), CIBSE Application Manual AM10 (2005) and CIBSE Guide B (2005), and typical set-points were used. Results of simulations which used minimum acceptable free areas and maximum acceptable set-points, are presented in the fourth section. The Section 6.5 shows the results of using the refined control strategies. All refined control strategies are intended to provide acceptable IAQ while reducing energy consumption. Finally, the findings of this chapter are summarised in Section 6.6.

6.2 Description of options tested

In this chapter, the effects of adopting typical control strategies are first tested, and based on these results, further refinements are conducted in order to improve the performance of the typical control strategies. To minimise the complexity of control strategies and study the direct effect of inputs (set-points) and outputs (free areas) on IAQ and energy consumption, the effect of applying control strategies with fixed CO₂ set-points and free areas were studied in each series. The variable parameter was either the set-point or the free area.
Chapter 6: CO₂ based control strategies

Table 6-1: Tested Control strategies in this chapter

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Opening sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group A</td>
<td>Constant opening area during occupied period when CO₂ exceeds 1000ppm or 1200ppm.</td>
<td>Maximum opening area is 5% of the floor area (BB101)</td>
</tr>
<tr>
<td>Group B</td>
<td>Constant opening area during occupied period when CO₂ exceeds 1000ppm or 1200ppm.</td>
<td>Maximum opening area is 1.5% of the floor area (30% of BB101)</td>
</tr>
<tr>
<td>Group C</td>
<td>Constant opening area during occupied period when CO₂ exceeds 1000ppm or 1200ppm.</td>
<td>Maximum opening area is 4.4% (seminar room) and 8.8% (classroom) of the floor area (AM10)</td>
</tr>
<tr>
<td>Refined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 1S</td>
<td>Opening area during occupied periods is determined by the CO₂ set-points from groups A, B and C which gave the best results for IAQ and energy. 1S indicates one-step control.</td>
<td>Opening area is 1.9% to 5% of the floor area</td>
</tr>
<tr>
<td>Group 2S</td>
<td>Opening area during occupied periods is determined by the CO₂ set-points from groups A, B, C and 1S which gave the best results for IAQ and energy. 2S indicates two-step control.</td>
<td>Opening area is 0.2% to 5.5% of the floor area</td>
</tr>
</tbody>
</table>

Three typical control strategies referred to as Group A, Group B and Group C (Table 6-1) were investigated to represent commonly used strategies in buildings of this type. For each group, a range of parameter variations were tested. Based on these results, two groups of refined control strategies were tested (Group 1S and 2S in Table 6-1). As discussed in Section 6.1 two heat gain scenarios were considered as “Seminar room” and “Classroom” (teaching space) configurations. All other physical, geometrical and structural properties of the two scenarios are the same as Case C described in Section 5.2). The details of the heat gain assumption was shown in Table 6-2. The occupancy profile was derived from information provided in BB101 (DFE, 2006) which states that spaces should be modelled as fully occupied from 9:00 to 15:30 Monday to Friday.

Table 6-2: Heat gain assumptions for training room

<table>
<thead>
<tr>
<th>Room configuration</th>
<th>People (m²/person)</th>
<th>Lighting (W/m²)</th>
<th>Equipment (W/m²)</th>
<th>Total (W/m²)</th>
<th>Total (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar room</td>
<td>3 = (16 occupants)</td>
<td>12</td>
<td>5</td>
<td>47</td>
<td>2242</td>
</tr>
<tr>
<td>Classroom</td>
<td>1.5 = (32 occupants)</td>
<td>12</td>
<td>10</td>
<td>77</td>
<td>3674</td>
</tr>
</tbody>
</table>

The typical control strategies used two set-points (1000ppm and 1200ppm). The value of 1000ppm was based on BB101 criteria (DFE, 2006) and the results of a study by Santamouris et al. (2008). The value of 1200ppm was based on ASHRAE Standard 62.1 (2010) in which 1200ppm is considered as the high end of the CO₂ level. This was to study the effects of the higher set-point on IAQ and energy consumption. The effects of applying two step
control strategies (where both 1000 and 1200ppm set-points were combined) were also evaluated for all typical control strategies (A-3, B-3, C-3 in Figure 6-1).

Since the training room was categorised as an educational space, the BB101 criteria were used in this study as the assessment method for IAQ. Moreover, since unlike measured CO₂ data, IES can simulate CO₂ concentration without any upper limit, the average and maximum values were reported. According to BB101, the following criteria regarding CO₂ concentration in teaching areas should be met:

1. during the continuous period between the start and finish of teaching on any day, the average concentration of carbon dioxide should not exceed 1500 parts per million (ppm);
2. the maximum concentration of carbon dioxide should not exceed 5000 ppm during the teaching day;
3. At any occupied time, including teaching, the occupants should be able to lower the concentration of carbon dioxide to 1000 ppm.
Energy consumption is evaluated against typical energy consumption for buildings of this type given in CIBSE Guide F (2012). Typical heating consumption for the lecture room is specified as 100 kWh/m\(^2\) and since there is no mechanical cooling system the effect of electricity consumption was not reported.

**Group A:** In Group A, a maximum free opening area is specified based on the rules of thumb given in BB 101 (DFE, 2006) which states that the minimum areas for worst-case scenario summer time ventilation for both temperature and CO\(_2\) control, is approximately 5\% and 2\% of the floor area in single sided and cross ventilated rooms respectively. In the test room windows under investigation are located on one side only; maximum free areas were therefore set to 5\% of the floor area.

**Group B:** Group B represents another common practice approach for CO\(_2\) based control. A single set-point is defined similarly to Group A. When CO\(_2\) reaches this set-point vents will open to 30\% of the maximum free area defined in Group A until CO\(_2\) levels fall below this set-point.

The aim of the Group B strategy was to minimise heating energy consumption by reducing the size of the ventilation opening and thus reducing the heating load during winter (Khatami et al., 2013). The main reason for this simulation study is to assess whether, in densely occupied spaces such as teaching spaces (the classroom configuration in this work), such a small free area can meet BB 101 requirements for acceptable IAQ.

**Group C:** In Group C, free areas were specified based on stack effect only using sizing methods given in CIBSE AM10 (CIBSE, 2005). The following assumptions were made:

- 16 occupants (seminar room configuration)
- 32 occupants (classroom configuration)
- required fresh air = 10 l/s per person (CIBSE Guide A (2006))
- internal temperature (T\(_i\)) = 20 °C
- difference between the internal and external temperature (\(\Delta T\))= 3K;
- effective opening height (h) = 0.15 m and
discharge coefficient \((C_d) = 0.62\).

Based on these assumptions, the required free area for the seminar room configuration was calculated as follows:

\[
Q_{\text{Seminar room}} = \frac{16 \times 10 \frac{l}{s/\text{person}}}{1000} = 0.16
\]

\[
C_dA_{\text{Seminar room}} = Q \sqrt{\frac{T_i + 273}{\Delta T gh}} = 1.3
\]

\[
A_{\text{Seminar room}} = 2.1 \ (m^2) = 4.4\% \text{ of floor area}
\]

Where,

\(Q = \text{volumetric flow rate (m}^3/s\text{) and } A = \text{opening free area (m}^2\text{)}\)

Similarly, the required free area in the classroom configuration was calculated as 4.2m\(^2\) (8.8% of floor area). It should be mentioned that as suggested by B101 (DFE, 2006) free areas in series A and B were specified based on percentage of floor area, to minimise variation for all tested options free areas were reported in terms of percentage of floor area.

**Group 1S:** Based on the results from groups A, B and C, a fourth group of simulations was conducted (Group 1S) to determine the optimum balance between the minimum opening free area and the maximum CO\(_2\) set-point. This was done by taking the best control strategies in terms of minimum heating energy consumption identified in groups A, B and C and reducing the maximum free areas and increasing the maximum set-point. In an attempt to reduce the energy consumption further, the maximum free opening area was gradually reduced. At the same time, the effects of increasing the set-points on both IAQ and energy consumption were tested. The simultaneous opening size reduction and set-point increases were continued until the CO\(_2\) concentration met the BB101 (DFE, 2006) requirements in terms of acceptable IAQ.

**Group 2S:** Group 2S contained the refined strategies based on the findings from groups A, B, C and 1S. Given that the results of Marjanovic and Eftekhari (2004) showed that when greater resolution was introduced into the
controller, improved results (in terms of thermal comfort) were obtained. Group 2S was created by extending this concept to the typical control strategies of groups A, B, C and 1S. In group 2S, more increments were added and the effects of two set-points and two free areas were studied. In this series the aim was to compare the effects of providing larger free areas and higher set-points with the effect of providing lower set-points and smaller free areas.

6.3 Results for typical control strategies (groups A, B and C)

6.3.1 Seminar room configuration

Table 6-3 summarises the effect of applying typical control strategies in the seminar room configuration and Figure 6-1 illustrates the typical control strategies for the space.

The results of the seminar room simulation showed that acceptable IAQ was achieved in all Group A simulations. CO₂ levels rapidly increase as occupants enter the room and rapidly fall when vents open, since opening areas are large. Therefore, these scenarios led to a consequential increase in heating energy consumption and hunting effect. This can be seen in Figure 6-2 which shows the effects of the A-1 control strategy on the CO₂ level, hunting effect and heating energy consumption during a typical winter day.

![Figure 6-2: effect of applying A1 control strategy on IAQ, hunting effect and energy consumption](image)
Group B simulations did not deliver acceptable IAQ with the maximum daily average CO\textsubscript{2} concentration during the occupied period higher than 1500 ppm (albeit for one day only). However, in all cases within Group B, heating energy consumption was reduced by almost 50% compared with Group A as the maximum free opening areas in Group B were smaller than Group A. Group C also achieved acceptable IAQ with almost 15% lower heating energy consumption compared with Group A. However, heating energy consumption in case C-3 was exactly the same as the heating energy consumption benchmark of 100 kWh/m\textsuperscript{2}/year for a good practice lecture room (CIBSE Guide F, 2012) and energy consumption in other cases in C series were higher than benchmarks.

Table 6-3: Results of typical control strategies in seminar room configurations

<table>
<thead>
<tr>
<th>ref</th>
<th>Set-point (ppm)</th>
<th>FA= % of floor area</th>
<th>Heating energy consumption (kWh/year/m\textsuperscript{2})</th>
<th>Average CO\textsubscript{2} level (ppm)</th>
<th>Maximum daily average CO\textsubscript{2} level (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB101 method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-1</td>
<td>1200</td>
<td>5</td>
<td>139</td>
<td>863</td>
<td>1284</td>
</tr>
<tr>
<td>A-2</td>
<td>1000</td>
<td>5</td>
<td>163</td>
<td>769</td>
<td>1139</td>
</tr>
<tr>
<td>A-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>5</td>
<td>122</td>
<td>817</td>
<td>1128</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common practice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-1</td>
<td>1200</td>
<td>1.5</td>
<td>66</td>
<td>957</td>
<td>1604</td>
</tr>
<tr>
<td>B-2</td>
<td>1000</td>
<td>1.5</td>
<td>75</td>
<td>891</td>
<td>1567</td>
</tr>
<tr>
<td>B-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>1.5</td>
<td>64</td>
<td>914</td>
<td>1581</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM 10 method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-1</td>
<td>1200</td>
<td>4.4</td>
<td>116</td>
<td>883</td>
<td>1309</td>
</tr>
<tr>
<td>C-2</td>
<td>1000</td>
<td>4.4</td>
<td>140</td>
<td>813</td>
<td>1132</td>
</tr>
<tr>
<td>C-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>4.4</td>
<td>100</td>
<td>838</td>
<td>1143</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Green = pass BB101 Criteria for IAQ, Red = fail BB101 Criteria for IAQ

6.3.2 Classroom configuration

Simulation results for Group A control strategies for the classroom configuration were similar to the seminar room results. When higher set-points were used (e.g. 1200ppm in case A-1), the control strategies could not provide acceptable IAQ (Table 6-4). When lower set-points (e.g. 1000ppm) were used, acceptable IAQ is achieved; however, heating energy consumption in all cases in group A is high in comparison to the good practice heating energy
consumption proposed in CIBSE Guide F (2012). One explanation for this is the relatively large size of the opening to floor area ratio (5% of floor area) and, as the classroom was more densely occupied than the seminar room, vents needed to open more frequently and for longer to provide acceptable IAQ (leading to higher heat losses from the space). For example, comparison of the A-2 cases showed a 20% increase in heating energy consumption in the classroom relative to the seminar room (c.f. Table 6-3 and Table 6-4).

Group B control strategies in the classroom do not achieve acceptable IAQ due to the small opening sizes. Group C strategies deliver acceptable IAQ in all cases; however, as free opening areas were the largest compared to group A and B strategies, energy consumption was considerably higher for Group C. As an example the heating energy consumption in case C-2 was around 35% and 67% greater than the heating energy consumption in cases A-2 and B-2 respectively.

### Table 6-4: Typical control strategies in classroom configurations

<table>
<thead>
<tr>
<th>ref</th>
<th>Set-point (ppm)</th>
<th>FA= % of floor area</th>
<th>Heating energy consumption (kWh/year/m²)</th>
<th>Average CO₂ level (ppm)</th>
<th>Maximum daily average CO₂ level (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB101 method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-1</td>
<td>1200</td>
<td>5</td>
<td>172</td>
<td>1068</td>
<td>1548</td>
</tr>
<tr>
<td>A-2</td>
<td>1000</td>
<td>5</td>
<td>184</td>
<td>1023</td>
<td>1372</td>
</tr>
<tr>
<td>A-3</td>
<td>1200</td>
<td>5</td>
<td>169</td>
<td>1015</td>
<td>1363</td>
</tr>
<tr>
<td>1000</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common practice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-1</td>
<td>1200</td>
<td>1.5</td>
<td>88</td>
<td>1212</td>
<td>2618</td>
</tr>
<tr>
<td>B-2</td>
<td>1000</td>
<td>1.5</td>
<td>93</td>
<td>1155</td>
<td>2619</td>
</tr>
<tr>
<td>B-3</td>
<td>1200</td>
<td>1.5</td>
<td>87</td>
<td>1157</td>
<td>2619</td>
</tr>
<tr>
<td>1000</td>
<td>0.75</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM 10 method</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-1</td>
<td>1200</td>
<td>8.8</td>
<td>246</td>
<td>810</td>
<td>1147</td>
</tr>
<tr>
<td>C-2</td>
<td>1000</td>
<td>8.8</td>
<td>281</td>
<td>752</td>
<td>1021</td>
</tr>
<tr>
<td>C-3</td>
<td>1200</td>
<td>8.8</td>
<td>230</td>
<td>766</td>
<td>1045</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 6.4 Results for one-step control strategy (Group 1S)

High heating energy consumption in both the seminar room and the classroom configuration suggested that the maximum free areas used in groups A and C were too large for the purpose of CO₂ level control, while failure of group B to provide acceptable IAQ showed that free areas were too small
in these cases. For this reason, further simulations were conducted to test the effect of different free areas and set-points on IAQ and heating energy consumption.

6.4.1 Seminar room configuration

Model C-1 with a total free area equivalent to 4.4% of floor area and set-point of 1200 ppm was chosen as the base case, since this strategy had provided acceptable IAQ with lowest heating energy consumption compare to the other one step typical control strategies (Table 6-5).

In the first series, to evaluate the effects of free areas on CO$_2$ concentration, the set-points were kept constant at 1200 ppm and free areas were reduced. The results of this series revealed that, for the seminar room scenario, the smallest free opening area that provided acceptable IAQ was equal to 2% of the floor area with a single set-point of 1200 ppm (1S.SR.FA2%). Applying the 1S.SR.FA2% option reduced energy consumption by 57%, 10% and 50% in comparison to the equivalent cases (set-points) in groups A, B and C respectively (Table 6-3 and Table 6-5).

Comparison of cases B-1 and 1S.SR.FA2% showed that, although set-points were the same in both models and the free area in 1S.SR.FA2 was larger than B-1, the energy consumption in 1S.SR.FA2 was 10% lower and IAQ was improved. A possible reason for this is that, as ventilation is more effective, vents open less frequently in the 1S.SR.FA2% case.

The results of models with variable set-points suggested that the size of the openings appears to be more important than the set-points in providing acceptable IAQ. Although, reducing the set-points from 1200 ppm to 800 ppm and opening the vents earlier with smaller opening sizes can provide acceptable IAQ, heating energy consumption increased by 30% (refer to 1S.SR.SP800 and 1S.SR.FA-2% in Table 6-5).

This illustrates that although the appropriate free opening area is essential for providing acceptable IAQ, set-points have a considerable influence on overall heating energy consumption in naturally ventilated buildings.
Table 6-5: Effects of one step control strategy in seminar room configurations

<table>
<thead>
<tr>
<th>Ref</th>
<th>Set-point (ppm)</th>
<th>FA= % of floor area</th>
<th>Heating energy consumption (kWh/year/m²)</th>
<th>Average CO₂ level (ppm)</th>
<th>Maximum daily average CO₂ level (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of FA(1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1S.SR.BC(^2) (C-1)</td>
<td>1200</td>
<td>4.4</td>
<td>116</td>
<td>884</td>
<td>1309</td>
</tr>
<tr>
<td>1S.SR.FA - 3%</td>
<td>1200</td>
<td>3.3</td>
<td>79</td>
<td>931</td>
<td>1335</td>
</tr>
<tr>
<td>1S.SR.FA - 2%</td>
<td>1200</td>
<td>2.2</td>
<td>59</td>
<td>999</td>
<td>1458</td>
</tr>
<tr>
<td>1S.SR.FA - 1.9%</td>
<td>1200</td>
<td>1.9</td>
<td>57</td>
<td>1005</td>
<td>1515</td>
</tr>
<tr>
<td>Effect of SP(4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1S.SR.SP- 1100ppm</td>
<td>1100</td>
<td>1.9</td>
<td>63</td>
<td>966</td>
<td>1505</td>
</tr>
<tr>
<td>1S.SR.SP-1000ppm</td>
<td>1000</td>
<td>1.9</td>
<td>70</td>
<td>928</td>
<td>1500</td>
</tr>
<tr>
<td>1S.SR.SP- 900ppm</td>
<td>900</td>
<td>1.9</td>
<td>77</td>
<td>895</td>
<td>1499</td>
</tr>
<tr>
<td>1S.SR.SP- 800ppm</td>
<td>800</td>
<td>1.9</td>
<td>85</td>
<td>856</td>
<td>1491</td>
</tr>
<tr>
<td>1S.SR.FA - 2%(^5)</td>
<td>1200</td>
<td>2.0</td>
<td>59</td>
<td>999</td>
<td>1458</td>
</tr>
<tr>
<td>1S.SR.SP6-1300ppm</td>
<td>1300</td>
<td>2.0</td>
<td>54</td>
<td>1037</td>
<td>1540</td>
</tr>
</tbody>
</table>

1. FA= Free Area  
2. 1S.SR.BC= one Step control. Seminar Room. Base Case  
3. Underline indicates changes in each model relative to the previous model.  
4. SP= Set-point  
5. Set-point of this option with free area =2% of floor area increased to find maximum set-point which could deliver acceptable IAQ.

6.4.2 Classroom configuration

Similar to the seminar room scenarios, a base case model was identified for the classroom configuration. According to the results of typical control strategies in groups A, B and C, model A-2 predicted acceptable IAQ with minimum heating energy consumption; therefore model A-2 with a set-point of 1000ppm and free area equivalent to 5% of floor area was chosen as the based case model.

As shown in Table 6-6, in the classroom, the best free area was found to be 4.5% of the floor area (1S.CR.FA4.5%) and the maximum acceptable set-point was found to be 1100ppm (1S.CR.SP1100ppm). By applying model 1S.CR.SP1100, heating energy consumption reduced by 15% and 45% compared to the equivalent control strategies in Group A and Group C respectively (c.f.Table 6-4 and Table 6-6). Compared to Group B, energy consumption increased by 40%. Lower energy consumption in Group B is due to the smaller free opening areas, however, it did not deliver acceptable IAQ.
The effects of providing smaller free areas with lower set-points were also tested for the classroom configuration. The results revealed that, similar to the seminar room, reducing the set point from 1100ppm to 700ppm increased heating energy consumption by 7%; however, unlike the seminar room, earlier opening of the vents with smaller free areas was ineffective in controlling CO$_2$ concentration as minimum required free area was not delivered (1S.CR.SP3-700ppm). From the results of this section it can be concluded that providing minimum free area is more important than providing the lower set-point in a single step control strategy, specially in the densely occupied areas such as classrooms.

### Table 6-6: Effects of one step control strategy in classroom configuration

<table>
<thead>
<tr>
<th>Ref</th>
<th>Set-point (ppm)</th>
<th>FA= % of floor area</th>
<th>Heating energy consumption (kWh/year/m$^2$)</th>
<th>Average CO$_2$ level (ppm)</th>
<th>Maximum daily average CO$_2$ level (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of FA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1S.CR.BC1 (A-2)</td>
<td>1000</td>
<td>5</td>
<td>184</td>
<td>1022</td>
<td>1372</td>
</tr>
<tr>
<td>1S.CR.FA-4.7%</td>
<td>1000</td>
<td>4.7</td>
<td>168</td>
<td>1034</td>
<td>1373</td>
</tr>
<tr>
<td>1S.CR.FA-4.5%</td>
<td>1000</td>
<td>4.5</td>
<td>159</td>
<td>1059</td>
<td>1413</td>
</tr>
<tr>
<td>1S.CR.FA-4.3%</td>
<td>1000</td>
<td>4.3</td>
<td>143</td>
<td>1059</td>
<td>1519</td>
</tr>
<tr>
<td>Effect of SP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1S.CR.SP1-900ppm</td>
<td>900</td>
<td>4.3</td>
<td>148</td>
<td>1022</td>
<td>1519</td>
</tr>
<tr>
<td>1S.CR.SP2-800ppm</td>
<td>800</td>
<td>4.3</td>
<td>155</td>
<td>919</td>
<td>1519</td>
</tr>
<tr>
<td>1S.CR.SP3-700ppm</td>
<td>700</td>
<td>4.3</td>
<td>167</td>
<td>845</td>
<td>1519</td>
</tr>
<tr>
<td>1S.CR.FA2-4.5%</td>
<td>1000</td>
<td>4.5</td>
<td>159</td>
<td>1041</td>
<td>1413</td>
</tr>
<tr>
<td>1S.CR.SP1100ppm</td>
<td>1100</td>
<td>4.5</td>
<td>156</td>
<td>1065</td>
<td>1492</td>
</tr>
<tr>
<td>1S.CR.SP-1200ppm</td>
<td>1200</td>
<td>4.5</td>
<td>149</td>
<td>1089</td>
<td>1538</td>
</tr>
</tbody>
</table>

### 6.5 Results for two-step control strategy (Group 2S)

The results of this section were developed based on the best control strategies identified in series 1S. Minimum free areas and set-points which can provide acceptable IAQ were 2% of the floor area and 1200 ppm in the seminar room configuration and 4.5% of the floor area and 1100ppm in the classroom configuration (1S.SR.FA2% and 1S.CR.SP1100). However, as IAQ in both rooms was assessed by using the same method (BB101) and one of the objectives of this section was to compare the strategies in both room configurations, the same set-points were used for the maximum set-point (1200ppm).
The set-point for the first increment was set to 1000 ppm according to BB101 (DFE, 2006) in both rooms. The size of the first free areas in the base cases was set to half of the maximum free area similar to the typical control strategies discussed in Section 6-3 (A-3,B-3,C-3).

The results of applying different control strategies in Group 1S showed that increasing the set-point helped to reduce heating energy consumption. Hence several simulations were carried out to evaluate the feasibility of increasing the upper set-points identified in Group 1S to reduce heating energy consumption. The results showed that, introducing new increments into the traditional controls enabled an increase in the set-points from 1200ppm (in the seminar room configuration) and 1100ppm (in the classroom configuration) to 1400ppm in both rooms. This reduced the heating energy consumption by almost 16% in both rooms while IAQ was improved through a reduced average CO₂ concentration (Table 6-5 and Table 6-6 and Table 6-7).

Increasing either the first or second set-point deteriorated IAQ. However, increasing the second set-point always led to lower energy consumption, which was not the case for the first set-point (refer to rows which show effects of first and second set-points in Table 6-7). The results of this section have shown that for control strategies with more increments by opening the vents earlier (lower first set-point) heating energy consumption is reduced. In these cases, if the vents open too late, the first increment becomes ineffective, resulting in more frequent use of the second increment with larger free area and leading to higher energy consumption. This is clearly evident in the classroom configurations with more occupants. Reducing the first set-point from 1300ppm to 800ppm reduced the heating energy consumption by 7% while IAQ was improved (Figure 6-3).
The results also revealed that it is possible to provide acceptable IAQ either by increasing the first or the second free areas. Increasing the sizes of the first free area increased heating energy consumption by 15% and 6% in seminar room and classroom configurations respectively (e.g. 2S.CR.SSP-1500ppm and 2S.CR.FFA-2. in Table 6-7). It shows that since most of the time control strategies operated based on the first increments, providing larger free areas in the first step, increased overall energy consumption.

Similar performance of (2S. SR. BC1), (2S. SR. FSP800), (2S. SR. FFA1.4%) and (2S. SR. SFA2.4%) models in the seminar room and (2S. CR. FSP800), (2S. CR. FFA2.75%) and (2S. CR. SFA5.5%) in the classroom configuration, in terms of providing acceptable IAQ (see Table 6-7), showed that it is possible to achieve similar IAQ when CO₂ levels are controlled either by introducing lower set-points and thus earlier opening of the vents (2S. SR. BC1), (2S. SR. FSP800), or by providing larger free areas and delaying the opening of the vents ((2S. SR. FFA1.4%4 and (2S. SR. SFA2.4%)). Introducing larger opening areas resulted in a rapid increase in the flow rate and consequently a sudden drop in CO₂ concentration which led to a higher risk of draught and hunting effect (compare the effect of free area on CO₂ concentration in models (2S.CR.BC1), (2S.CRFSP800), (2S.CR. FFA2.75%) and (2S. CR. SFA5.5%) shown in Figure 6-4). Similar behaviour was observed for the classroom configuration.
Chapter 6: CO$_2$ based control strategies

![Figure 6-4: Effect of control strategies with similar performance on CO$_2$ Concentration and free area](image)

Opening the vents earlier (e.g. when CO$_2$ concentration in the room reaches 800ppm rather than 1000ppm) made the control strategy more flexible by enabling a reduction in the size of the first free opening area. This not only improved the IAQ but also lowered the heating energy consumption (refer to models 2S.SR.FFA-0.8% and 2S.CR.FFA-2%). By using model 2S.SR.FFA-0.8%, the energy consumption reduced by 63%, 21% and 55% compared to cases A-1, B-1 and C-1 in the seminar room, and by applying 2S.CR.FFA-2%; in the classroom configuration energy consumption reduced by 35% and 51% compared with A-2 and C-2. However, energy consumption increased by 23% compared to case B-1. It should be mentioned that, although energy consumption in B-1 was lower, it could not provide acceptable IAQ. In addition, comparison of the best refined options (2S.SR.FFA-0.8% and 2S.CR.FFA-2%) with the optimum typical control strategy (C-1 in seminar room configuration and A-2 in classroom configuration) showed better control of the hunting effect for the refined options (Figure 6-5).
Chapter 6: CO₂ based control strategies

Figure 6-5: Hunting effect in the best refined and typical control strategy
### Table 6-7: Two-step control strategies in classroom and seminar room

<table>
<thead>
<tr>
<th>Seminar room configuration</th>
<th>Classroom configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ref</strong></td>
<td>Set-point (ppm)</td>
</tr>
<tr>
<td>2S. SR. BC1**</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1200</td>
</tr>
<tr>
<td>2S. SR. SSP1300</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1300</td>
</tr>
<tr>
<td>2S. SR. SSP1400</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. SR. SSP1500*</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>2S. SR. FSP1300</td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. SR. FSP1200</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. SR. FSP1100</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. SR. SSP1400</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. SR. SSP900</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. CR. SSP800**</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. SR. FFA-0.6%</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. CR. FFA-0.8%*</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>2S. SR. SSP1500</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>2S. CR. SSP1500</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>2S. CR. FFA-1.2%</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>2S. CR. FFA-1.4%*</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>2S. SR. FPA-1.6%</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>2S. SR. SSP1500</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>2S. CR. FPA-2.2%</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>2S. CR. FPA-2.4%*</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
</tbody>
</table>

1 Models with the same shaded colour showed changes in each model were conducted based on the previous same colour row
2 * = models with the similar performance
3 2S.SSP= Two Step. Seminar Room. Second Set-Point
4 2S.CR.SSP= Two Step. Classroom. Second Set-Point
5 Effects of reducing the first set-point to models 2S.SR. SSP1500 and 2S.CR.SSP1500 were also tested but since the second set-point was set to a high value (1500ppm) all the strategies failed to provide acceptable IAQ and they are not reported here.
6 Model with the best performance
6.6 **Summary**

$\text{CO}_2$ levels, as an indicator of IAQ in naturally ventilated spaces, depend closely on the $\text{CO}_2$ control strategies employed. The simulations in this chapter investigated the effects of a fixed set-point and fixed free areas on IAQ and energy consumption. In the proposed control strategies, vents were opened earlier than typical control strategies but with smaller free areas.

Dynamic thermal simulations were carried out for two typical occupancy (heat gain) scenarios in educational spaces (seminar room and classroom configurations). The main findings are summarised below:

- Both BB101 and AM10 methods of sizing ventilation openings led to acceptable IAQ. However, in both methods, heating energy consumption was higher than benchmarks published in CIBSE Guide F (2010).

- Specifying a lower set-point in single-step control strategies leads to higher energy consumption. For example in the classroom configuration, although the test set-point was reduced from 1000ppm to 700ppm, not only was acceptable IAQ not achieved, but the strategy also led to 15% higher energy consumption because the openings are required to be open (almost) continuously in an attempt to maintain acceptable IAQ, which leads to increased heating energy consumption.

- Spaces with lower occupant densities which delay the opening of vents with larger opening areas or trigger earlier opening of the vents with smaller areas, have a similar effect on heating energy consumption and IAQ. However, the use of vents with larger areas, even if they are not opened as soon as vents with smaller areas, increases the risk of hunting effect and draught.

- In more densely occupied spaces, earlier opening of the vents (lower set-point) with smaller free areas, helps to provide better IAQ and reduced energy consumption. It also helped to control the hunting effect more
effectively because when smaller free areas were used, CO$_2$ concentration was less likely to drop or increase rapidly.
Chapter 7: Temperature based control strategies

7 Temperature based controls

7.1 Introduction

This chapter describes temperature based natural ventilation control strategies to mitigate the risk of overheating in the case study building. According to the results of Section 4.2.1, high risk of overheating during a year (even during heating seasons) suggests that providing temperature based controls in the open plan office is essential. The results of Section 5.3.2 suggested that, since a single temperature control strategy was operating throughout a year and high level openings were assumed to be open constantly, providing more advanced control strategies which control openings throughout the year would also be essential. Furthermore, according to the results of Section 4.2.1, due to the regular occupancy pattern and the dependency of indoor temperature to internal heat gain in the open plan office, indoor air temperature was usually a function of time and it increased throughout a working day. Therefore providing temperature based control strategies which prevent overheating during the hot days, and which take advantage of internal heat gains during the cold days to minimise reliance on the heating system, can help to minimise the risk of overheating as well as unnecessary energy consumption. For this reason, the aim of the work in this chapter is to propose different logic-based temperature control strategies which self-adjust based on external weather conditions throughout the year to minimise risk of thermal discomfort and high heating demand. For this purpose, DTS models are applied and assessment criteria is developed based on the methods shown in Table 3-11. For the purpose of the assessment, since this chapter concentrates on the capability of control strategies to provide thermal comfort, in addition to the frequency of discomfort, severity of discomfort is also reported by calculating the number of degree hours of thermal discomfort (Liang, 2012).

This chapter contains five sections. Following the Introduction, Section 7.2, describes the options tested to study different temperature based control strategies. The effects of applying typical control strategies with common set-
points and free areas are then reported in Section 7.3. The fourth section shows the results of models using the refined control strategies. Finally, the findings of this chapter are summarized in Section 7.5.

7.2 Description of options tested

Due to the complexity of natural ventilation and the number of inputs in naturally ventilated buildings as discussed in Section 2.8.2, applying logic-based control strategies is more appropriate for naturally ventilated buildings and for this reason logic-based strategies were developed to control temperature. For the logic-based control strategies in this section, the variable parameter was the temperature set-point, the opening free area or the number of operating hours.

Similar to the previous chapter, the effects of applying two typical control strategies were studied first. Based on the findings of the typical control strategies, some refinements were made to the typical control strategies to improve their efficiency in terms of providing thermal comfort and lower energy consumption.

Some common rules which proposed by BSRIA (1995), CIBSE Guide H (2009), Firth and Cook (2010), Fordham (2000) and BSRIA (2009) were applied to all the tested control strategies as follows:

1. If external temperature is higher than internal temperature, then all the vents will be closed. This was to reduce the risk of introducing hot air into the building (BSRIA, 1995).
2. In order to minimise the risk of draught and demand on the heating system, ceiling tiles were opened first, then roof vents were activated and finally windows were opened (similar approach as Firth and Cook, 2010), therefore the set-points for the ceiling tiles and Roof vents openings were 2K and 1K lower than windows set-points respectively.
3. To minimise the risk of draught if external temperature is less than 10\(^\circ\)C, close the low level openings (windows) (Fordham, 2000).
4. As all low level openings are located on the same elevation, to minimise the risk of draught due to the wind, low level openings should be driven to the safe position during windy days. Therefore, if wind direction is between 0-45° (clockwise from north) and wind velocity is higher than 8 m/s close low level openings (BSRIA, 2009).

5. The effects of applying a range of temperature set-points (20°C to 25°C) were tested in each series of simulations. The minimum set-point (20°C) was specified based on heating set-point and the maximum set-point was specified based on CIBSE guide A (2006).

In addition to the above rules there were some individual rules that were applied to each series as follows:

**Simple Typical (ST):** This series is similar to the typical control strategies in common practice. In this series the internal temperature (Ta) determined the free areas of the openings. By increasing the temperature, free areas linearly increased and vents were fully opened when internal temperature and set-point differences reached +4°C (Firth and Cook, 2010).

**Advanced Typical (AT):** This series is similar to the ST strategies. The deviation between internal temperatures and set-points determined the free areas of the openings, but to minimise unnecessary heat loss, three control modes for Summer, Winter and Mid-season were introduced (Aggerholm, 2003 and Schulze and Eicker, 2013). These three modes, with different set-points, determined the opening sizes. Summer, Winter and Mid-season modes are usually determined based on schedule or external temperature. Since the comfort temperature in naturally ventilated buildings is highly correlated with the external temperature (Humphrey, 2002 and results of section 4.2), in this study the external temperatures were used to specify ventilation modes. Set-points for external temperatures were specified based on recommendations by Fitzgerald (2006) and Aggerholm (2003) and three definitions for external climatic conditions were used as follows, $T_0 < 12^\circ C$, $12^\circ C < T_0 < 18^\circ C$ and $T_0 > 18^\circ C$. These were used to be representative of cold, intermediate (Mid-season) and hot seasons. To specify internal opening set-points (when vents will be open) a similar approach to Schulze and Eicker (2013) was also used;
to minimise risk of overcooling or high energy consumption, ventilation set-points during cold, intermediate and hot seasons were increased by 2K, 1K and 0K respectively.

**Simple Refined (SR):** These strategies were developed based on the AT control strategies and the same internal and external temperature set-points were used, but in these strategies free areas were not only a function of deviation between internal set-point and internal temperature but were also a function of internal/external temperature differences. As it was shown in Section 4.2 due to the light weight structure of the case study building, internal temperatures in the case study building were highly influenced by external temperatures, and providing the same opening regime as the AT control strategies may lead to overcooling in winter and overheating in summer. Therefore, free areas were specified based on the internal/external temperature differences, internal heat gain and temperature differences between internal temperatures and set-points.

As in this building natural ventilation strategies were stack induced, the free areas were a function of temperature differences and the minimum free area required (A), is given by Equation 7-1 (CIBSE Guide B, 2005 and CIBSE AM 10, 2005)

\[
C_d A = \frac{\Phi}{C_c \Delta T} \times \sqrt{\frac{T_i + 273}{2(\Delta T g H_n)}}
\]  

(7-1)

Where,

\(C_d A\): Aerodynamic free area \((\text{m}^2)\)
\(\Phi\): total heat gain \((\text{W})\)
\(C_c\): volumetric capacity of air =1200 \((\text{J/m}^3\text{K})\)
\(\Delta T\): internal/external temperature difference \((\text{K})\)
\(t_i\): Internal Temperature \((^\circ\text{C})\)
\(H_n\): neutral height \((\text{m})\)
Based on equation 7-1 three different free areas for summer, winter and mid-season were identified. For example for a set-point of 23 °C, internal set-points and free areas were calculated in Table 7-1:

<table>
<thead>
<tr>
<th></th>
<th>Internal temperature set-points (Tᵢ)</th>
<th>External temperature set-points (Tₒ)</th>
<th>Low level FA (windows) (m²)</th>
<th>High level FA (roof vents) (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP 23</td>
<td>Summer 23 °C</td>
<td>18 °C</td>
<td>2.3</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Mid-season 24 °C</td>
<td>12 °C</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Winter 25 °C</td>
<td>10 °C</td>
<td>0.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Three opening arrangements were then defined in which the lower limit of opening areas were specified based on results of Equation 7-1 (the minimum required free area) and free areas linearly increased as a function of temperature using equation 7-2 to specify percentage of opening area:

$$opening \ area \ (\%) = \frac{lower \ limit \ of \ opening \ area \ (Equation \ 7-1)}{maximum \ existing \ free \ area} \times 100 \times (Tᵢ - SP) \quad (7-2)$$

Where,

SP= Temperature set-point

**Advanced Refined (AR):** Several studies have shown the importance of night time ventilation and the important effect of operating hours (times when openings are controlled) on temperature control and occupant comfort (BSRIA, 1995, Kolokotroni et al., 2001 and Gayesky, 2010). In addition, due to the regular occupancy pattern and dependency of indoor temperature on internal heat gain in open plan offices, indoor air temperature is usually a function of time and increased throughout the day (Section 4.2.1). Therefore, providing temperature based control strategies which prevent overheating during hot days and take advantage of internal heat gain during cold days to minimise reliance on a heating system and reduce the risk of overcooling, can help to minimise the risk of thermal discomfort and unnecessary energy consumption. Therefore, the variable in this series was operating time, keeping control strategies and free areas the same as the SR control strategies. It should be noted that in this series, similar to the actual building, it was assumed that the working hours were 9:00-17:30 and the building was fully occupied during this period.
In this study, the effects of applying control strategies with four different operating hours were tested as follows:

1. 24 hours (night cooling) which operates the windows depending on internal and external weather conditions regardless of occupancy pattern and natural ventilation systems assumed to be operated even during unoccupied periods. This group could be representative of models with night time ventilation.

2. 08:00-18:30 (Pre and post cooling periods): almost every day there are some occupants present 1 hour before and after working hours¹ and for this reason opening the vents should not cause any problem in terms of safety and security.

3. 09:00-17:30 (full occupancy period): actual working hours in the office and when almost all the occupants are in the case study building (same as SR series)

4. 10:30-17:30 (heat-up period): As suggested by CIBSE Guide A (2006), depending on the size of plant and heating systems, some time is required to heat up a building. The control strategies developed in this study were intended to be retrofitted natural ventilation in the existing buildings and changing the capacity of the plant was not an option. Therefore, this operating schedule tested the effect of delaying the vents opening on both energy consumption and thermal comfort. Delaying the vents opening it enabled the heating system to heat up the case study building. (10:30 was chosen since according to the results of the SR series, internal temperature reached the heating set-point for 90% of the time and heating systems were switched off after 10:30).

Table 7-2 shows the control strategies tested in this chapter.

¹ Working hours in the case study building were 9:00-17:30
Table 7-2: Tested rule based control strategies

<table>
<thead>
<tr>
<th>Type</th>
<th>Summer (To&gt;18ºC)</th>
<th>Mid-season (12 ºC &lt;To&lt;18ºC)</th>
<th>Winter (To&lt;12 ºC)</th>
<th>Opening sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SP</td>
<td>OH</td>
<td>SP</td>
<td>OH</td>
</tr>
<tr>
<td>Simple</td>
<td>SP^1</td>
<td>OH^2</td>
<td>SP</td>
<td>OH</td>
</tr>
<tr>
<td>Typical (ST)</td>
<td>09:00 - 17:30</td>
<td>Same as Summer</td>
<td>Same as Summer</td>
<td>Same as Summer</td>
</tr>
<tr>
<td>Advanced</td>
<td>09:00 - 17:30</td>
<td>Summer +1ºC</td>
<td>Same as Summer</td>
<td>Same as Summer</td>
</tr>
<tr>
<td>Typical (AT)</td>
<td>09:00 - 17:30</td>
<td>Same as Summer</td>
<td>Summer +2ºC</td>
<td>Same as Summer</td>
</tr>
<tr>
<td>Simple</td>
<td>09:00 - 17:30</td>
<td>Summer +1ºC</td>
<td>Same as Summer</td>
<td>Same as Summer</td>
</tr>
<tr>
<td>Refined</td>
<td>24hrs</td>
<td>24hrs to 10:30-17:30</td>
<td>Summer +2ºC</td>
<td>10:30-17:30</td>
</tr>
<tr>
<td>Refined</td>
<td></td>
<td>Function of internal heat</td>
<td>Function of internal heat</td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td></td>
<td>gain and internal/external</td>
<td>gain and internal/external</td>
<td></td>
</tr>
<tr>
<td>Refined (AR)</td>
<td></td>
<td>temperature differences</td>
<td>temperature differences</td>
<td></td>
</tr>
<tr>
<td>Refined</td>
<td></td>
<td>Function of internal heat</td>
<td>Function of internal heat</td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td></td>
<td>gain and internal/external</td>
<td>gain and internal/external</td>
<td></td>
</tr>
<tr>
<td>Refined (AR)</td>
<td></td>
<td>temperature differences</td>
<td>temperature differences</td>
<td></td>
</tr>
</tbody>
</table>

1: SP= internal Set-Point
2: OH= operating hours

To assess the effectiveness of each temperature based control strategy, an adaptive approach was used and frequency of the occupied times when operative temperatures were higher than acceptable level is reported using CIBSE Guide A (2006) and BS EN ISO 7730 (2005) methods (refer to Table 3-11). Moreover severity of thermal discomfort (Liang, 2012) were assessed by calculating degree hours of cold and hot periods using Equations 7-3 and 7-4 and 30 degree hours of thermal discomfort assumed as acceptable. The effects of applying each control strategy on energy consumption were also studied by reporting annual heating consumption in each zone.

Degree hours of Cold period = \( \sum w_f \cdot \text{time for } T_c(\text{actual}) < T_{\text{conf}} \text{ (lower limit)} \) 

(7-3)

Where,

\[ W_f = \text{weighted factor} = T_{\text{conf}} \text{ (lower limit)} - T_c(\text{actual}) \]

\( T_c(\text{actual}) \) = actual operative temperature, and \( T_{\text{conf}} \text{ (lower limit)} \) = minimum comfortable temperature calculated based on equations 2-6 and 2-7

Degree hours of warm period = \( \sum w_f \cdot \text{time for } T_c(\text{actual}) > T_{\text{conf}} \text{ (upper limit)} \) 

(7-4)

Where,

\[ W_f = \text{weighted factor} = T_c(\text{actual}) - T_{\text{conf}} \text{ (upper limit)} \]

\( T_c(\text{actual}) \) = actual operative temperature, and \( T_{\text{conf}} \text{ (upper limit)} \) = maximum comfortable temperature calculated based on equations 2-6 and 2-7.
Chapter 7: Temperature based control strategies

To study effects of applying each control strategy on energy consumption, heating consumption in the open plan office is reported and since there was not any mechanical cooling system the effect of electricity consumption was ignored since the electricity consumption in all models tested were the same.

7.3 Results for typical control strategies (ST and AT series)

7.3.1 Simple typical control strategy (ST series)

Table 7-3 summarises the effects of applying simple typical control strategies in the open plan office. The results confirmed that there is a direct link between window opening temperature set-point, risk of overheating and energy consumption. The results show that increasing the set-point increased the risk of overheating and reduced the heating energy consumption and risk of overcooling (degree hours of cold periods).

The results of this section also showed that, although the criterion that is proposed in CIBSE Guide A (2006) can be used as a starting point, since in this method, effects of overcooling are ignored this method must not be the only assessment criterion. For example as shown in Table 7-3, although 20 °C and 21°C set-points could control the risk of overheating, since by applying either of them, vents opened too early, they increased the risk of overcooling and failed to provide thermal comfort.

<table>
<thead>
<tr>
<th>Assessment criteria</th>
<th>SP20</th>
<th>SP21</th>
<th>SP22</th>
<th>SP23</th>
<th>SP24</th>
<th>SP25</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIBSE Guide A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of occupied hours Tc&gt;25°C</td>
<td>4.0</td>
<td>4.2</td>
<td>4.8</td>
<td>6.8</td>
<td>13.8</td>
<td>29.1</td>
</tr>
<tr>
<td>% of occupied hours Tc &gt;28°C</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Maximum Tc (°C)</td>
<td>30.67</td>
<td>30.68</td>
<td>30.70</td>
<td>30.72</td>
<td>30.76</td>
<td>30.80</td>
</tr>
<tr>
<td>BS EN 15 52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of occupied hours Tc  &gt;T&lt;sub&gt;comfort&lt;/sub&gt;+3 or &lt; T&lt;sub&gt;comfort&lt;/sub&gt;-3</td>
<td>21.7</td>
<td>10.4</td>
<td>4.4</td>
<td>2.2</td>
<td>2.7</td>
<td>4.0</td>
</tr>
<tr>
<td>degree hrs cold period based on T&lt;sub&gt;comfort&lt;/sub&gt;</td>
<td>113.0</td>
<td>58.0</td>
<td>18.3</td>
<td>7.4</td>
<td>6.7</td>
<td>6.5</td>
</tr>
<tr>
<td>degree hrs warm period based on T&lt;sub&gt;comfort&lt;/sub&gt;</td>
<td>15.0</td>
<td>15.3</td>
<td>15.7</td>
<td>16.8</td>
<td>21.8</td>
<td>35.4</td>
</tr>
<tr>
<td>CIBSE Guide F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating Energy Consumption (kWh/m²/year)</td>
<td>52.0</td>
<td>29.4</td>
<td>27.1</td>
<td>26.4</td>
<td>25.9</td>
<td>25.7</td>
</tr>
<tr>
<td>Overall Pass/Fail</td>
<td>F</td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>
The results of this Section are similar to the results of Section 4-2 whereby air temperature rose rapidly when occupants entered the building and since most of the occupants remained in the space during working days, internal heat load remained the same during the different days of a year. Therefore, the internal temperature and the risk of overheating were highly influenced by external temperature. During moderate external conditions (Figure 7-1-a), lower set-points helped to prevent overheating during occupied hours and delayed peak internal temperature. Whereas, during very hot external conditions (Figure 7-1-b), due to the high internal temperature regardless of applying any of the above set-points, vents were fully opened and the natural ventilation strategy performed similarly in all models. This also explains the similar performances of all the models tested in terms of controlling higher temperatures (refer to % of occupied hours when Tc>28°C in Table 7-3).

![Figure 7-1: Effects of different set-points on controlling temperature during typical and hot summer days](image)

7.3.2 Advanced typical control strategy (AT series)

The results of this section showed that introducing different internal set-points based on the external temperature in the AT series instead of introducing single set-points (ST series) throughout a year helped to reduce energy consumption by a maximum of 47% (set-point 20°C) and by a minimum of 2% (c.f. set-points 24°C and 25°C) (c.f. Table 7-3 and Table 7-4).
Chapter 7: Temperature based control strategies

The results of this Section also showed more consistent heating energy consumption and less dependency of the heating energy consumption on the opening temperature set-points when opening set-points are determined by external temperature (AT series). For example, as shown in Table 7-3 and Table 7-4, increasing the internal set-point from 20°C to 25°C in the AT series led to 8% lower energy consumption while increasing the internal set-point from 20°C to 25°C in the ST series led to 50% lower energy consumption.

Since in this series, opening set-points were increased during colder periods when the risk of overcooling is higher, applying AT control strategies helped to prevent the risk of overcooling (compare degree hours overcooling in Table 7-3 and Table 7-4). However, it led to a higher risk of overheating. This could be due to opening the vents earlier in the ST series which helped to prevent overheating more effectively compared to the AT series.

### Table 7-4: Performances of advanced typical temperature control strategies

<table>
<thead>
<tr>
<th>Assessment criteria</th>
<th>SP20</th>
<th>SP21</th>
<th>SP22</th>
<th>SP23</th>
<th>SP24</th>
<th>SP25</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CIBSE Guide A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of occupied hours Tc&gt;25°C</td>
<td>4.0</td>
<td>4.3</td>
<td>4.8</td>
<td>8.5</td>
<td>27.8</td>
<td>42.6</td>
</tr>
<tr>
<td>% of occupied hours Tc&gt;28°C</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Maximum Tc (°C)</td>
<td>30.67</td>
<td>30.68</td>
<td>30.70</td>
<td>30.72</td>
<td>30.75</td>
<td>3.80</td>
</tr>
<tr>
<td><strong>BS EN 15 52</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of occupied hours Tc &gt;T\text{comfort}+3 or &lt; T\text{comfort}-3</td>
<td>7.3</td>
<td>5.3</td>
<td>5.6</td>
<td>2.0</td>
<td>3.2</td>
<td>10.3</td>
</tr>
<tr>
<td>degree hrs cold period based on T\text{comfort}</td>
<td>18.7</td>
<td>7.5</td>
<td>6.9</td>
<td>6.5</td>
<td>6.3</td>
<td>6.2</td>
</tr>
<tr>
<td>degree hrs warm period based on T\text{comfort}</td>
<td>15.1</td>
<td>15.4</td>
<td>15.8</td>
<td>16.9</td>
<td>24.8</td>
<td>92.1</td>
</tr>
<tr>
<td><strong>CIBSE Guide F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating Energy Consumption (kWh/m²/year)</td>
<td>27.4</td>
<td>26.5</td>
<td>26.0</td>
<td>25.6</td>
<td>25.4</td>
<td>25.2</td>
</tr>
<tr>
<td>Overall Pass/Fail</td>
<td>F</td>
<td>P</td>
<td>P</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

### 7.4 Results for refined control strategies (SR and AR series)

#### 7.4.1 Simple refined control strategy (SR series)

The results of this section revealed that among the tested control strategies, the SR series provided the most effective overheating control strategies. This was because in the SR series, free areas were the function of internal/external temperature differences and were modified based on the required flow rates. This can be confirmed by comparing the percentage of the time Tc>25°C in Table 7-3 and Table 7-5. Moreover, comparing the
performances of different models with different set-points in this group (Table 7-5) showed that, due to the higher flexibility that was provided by determining free areas based on required flow rate in the SR series, there was more consistency in providing thermal comfort and energy consumption.

Table 7-5: Performance of simple refined temperature control strategy

<table>
<thead>
<tr>
<th>Assessment criteria</th>
<th>SP20</th>
<th>SP21</th>
<th>SP22</th>
<th>SP23</th>
<th>SP24</th>
<th>SP25</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIBSE Guide A</td>
<td>% of occupied hours $T_c &gt; 25^\circ C$</td>
<td>3.9</td>
<td>4.0</td>
<td>4.0</td>
<td>5.00</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>% of occupied hours $T_c &gt; 28^\circ C$</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Maximum $T_c$ ($^\circ C$)</td>
<td>30.65</td>
<td>30.66</td>
<td>30.67</td>
<td>30.69</td>
<td>30.72</td>
</tr>
<tr>
<td>BS EN 15 52</td>
<td>% of occupied hours $T_c &gt; T_{comfort} + 3$ or $&lt; T_{comfort} - 3$</td>
<td>8.7</td>
<td>3.1</td>
<td>2.0</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>degree hrs cold period based on $T_{comfort}$</td>
<td>37.7</td>
<td>12.6</td>
<td>7.1</td>
<td>6.7</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>degree hrs warm period based on $T_{comfort}$</td>
<td>14.9</td>
<td>15.1</td>
<td>15.2</td>
<td>15.6</td>
<td>16.8</td>
</tr>
<tr>
<td>CIBSE Guide F</td>
<td>Heating Energy Consumption (kWh/m²/year)</td>
<td>28.7</td>
<td>26.8</td>
<td>26.3</td>
<td>25.8</td>
<td>25.5</td>
</tr>
<tr>
<td>Overall Pass/Fail</td>
<td>F</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

Although applying the SR series was effective in controlling overheating, results of this section showed that the risk of overcooling (degree-hours cold period) and heating energy consumption were slightly higher than the AT series.

Further investigation into energy consumption and the risk of overcooling showed that higher energy consumption and the risk of overcooling was more likely to happen during morning times when the control strategy was in Mid-season mode ($12^\circ C < T_o < 18^\circ C$). During mid-season, SR control strategies provided larger free areas than SR series. This helped to control temperature and the risk of overheating more accurately but it increased energy consumption and risk of overcooling (compare energy consumption and free area between 9:00-11:00 in Figure 7-2). The results of this section suggest that introducing different operating hours to control temperature may help to provide further energy savings and reduce the risk of overcooling during early hours of occupied days.
7.4.2 Advanced refined control strategy (AR series):

The results of this series showed a strong relationship between the number of hours in which natural ventilation is operating (operating hours) and occupants’ thermal comfort, while operating hours had the minimal effects on energy consumption. Additionally energy consumption was more affected by set-points rather than operating hours.

In many cases delaying the opening of the vents slightly reduced energy consumption (by a maximum of 0.5%) (refer to Table 7-6); however, a delay in vents opening from 9:00 to 10:30 in models with lower opening set-points, (e.g. AR SP 20°C where heating set-point and opening set-points were close to each other) slightly increased energy consumption (maximum of 1.3%). In these models, since set-points were low, temperature rose above the opening set-points more frequently and therefore vents were opened more frequently and for longer periods. This consequently led to a sharper temperature drop below the heating set-point resulting in the need for more heating and higher energy consumption.
By comparing degree-hours of warm periods in different models in Table 7-6, it can be concluded that opening the vents earlier (e.g. 24hrs and 08:00-18:30) helped considerably in reducing the risk of overheating. It is shown that options tested reduced the risk of overheating by minimum of 30 degree-hours.
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(SP 20°C) and by a maximum of 45 degree-hours (SP 25°C). As shown in Figure 7-3, increasing operating hours during hot summer days of the simulated year firstly helped to reduce indoor temperature during unoccupied periods and prevented overheating during extreme hot conditions; and secondly helped to remove the stored heat in the building to prevent overheating during the next day. However, since the case study building is a light weight structure, night cooling (models with 24hrs operation) was not very effective and it performed similar to the models operating between 08:00-18:30.

![Figure 7-3: Effects of operating hours on temperature control (SP 25°C)](image)

The results of this series also showed that, since overcooling usually occurred during the early hours of the working days, a delay in opening the vents (models with operating hours of 10:30-17:30) helped to reduce the risk of overcooling but increased the risk of overheating during hotter days. Therefore, it can be concluded that by applying different control strategies through a working day makes it possible to reduce the risk of overheating during hotter days by opening the vent earlier and preventing the risk of overcooling by delaying the opening of the vents during moderate and cold days. This was tested and confirmed by testing a series of models in which operating hours were combined and temperature set-points of 20°C to 24°C in models with combined operating hours could pass the assessment criteria. Results of this test can be found in Appendix F.
7.5 Summary

In this chapter the effects of introducing different temperature control strategies into the case study building were tested and their performance investigated in terms of thermal comfort and energy consumption. DTS models were used as the assessment tool to study the effects of applying different control strategies. The findings of this work can be summarised as follows:

- There is a direct link between window opening temperature set-point, risk of overheating and energy consumption. Increasing the opening set-point increased the risk of overheating by up to 90% (AT SP20- AT SP25) and reduced the heating energy consumption by maximum of 50% (ST SP20- ST SP25).

- By introducing different operating modes (Winter/Mid-season/ Summer) based on external temperature, it was possible to minimise the dependency of energy consumption on window opening set-points. For example, when different operating modes were introduced into the AT series, energy consumption only increased by 8% while in the ST series, where there was a single control mode, energy consumption increased by 50%.

- Specifying opening free areas based on internal and external temperature differences in the series provided the best performance in terms of temperature control. Better performance was achieved since free areas were modified based on the required flow rates which helped to minimise dependency of the risk of overheating control on window opening set-points.

- There is a direct link between operating hours and the risk of overheating. For example, activating natural ventilation one hour before and after the full occupancy period helped to reduce the risk of overheating by up to 17%.
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- Very little correlation between energy consumption and operating hours was identified: energy consumption was more affected by the opening set-points rather than operating hours.
8 Building performance after intervention

8.1 Introduction

This chapter describes performance of the case study building after the intervention of natural ventilation system. Several natural ventilation options and control strategies are proposed in Chapters 5, 6 and 7. This chapter describes the refurbishment and retrofitting process and reports on the effects of applying new systems on thermal comfort, IAQ and energy consumption. As discussed in Section 3.4.5 performance of the case study building after the intervention was studied in two phases. In the first phase occupants were asked to take responsibility for controlling the natural ventilation system (e.g. opening and closing the windows and roof vents) for six months after the new systems were installed. The natural ventilation system was then enhanced by introducing automatic controls in the second phase. For this purpose, both qualitative and quantitative studies were conducted and results were compared with the performance of the case study building before intervention (Chapter 4).

This chapter contains five sections. Following the Introduction, the commissioning process, including a description of the hardware, software and personnel training, are presented in Section 8.2. The effects of applying manual controls on thermal comfort, IAQ and energy consumption are reported in Section 8.3. The fourth section shows the results of introducing automated natural ventilation options in the case study building. Finally, the findings of this chapter are summarised in Section 8.5.

8.2 Commissioning

Commissioning of natural ventilation includes installing, wiring and programming the required software and hardware (Marjanovic, 2002). Moreover, due to important role of occupants in the success or failure of natural ventilation (Fitzsimmons, 2000 and Ward, 2004) occupants training should also be included as part of the commissioning stage. The following section
describes the actions that were considered for commissioning of the proposed natural ventilation systems in the case study building.

### 8.2.1 Hardware

According to the results of Chapter 5, a combination of automated windows, moveable ceiling tiles, and operable roof vents was the most suitable and practical natural ventilation option for the case study building. Therefore, in the open plan office, existing windows were modified to controllable windows by installing window actuators to control the IAQ and temperature. Suspended ceiling tiles were replaced with automated ceiling vents and two controllable automatic louvres were also installed on the roof to enhance the performance of natural ventilation. In the training room, existing windows were also modified to automated ones to facilitate natural ventilation.

Free areas were specified according to the results of the Roofvent option (Scenario 3) described in Chapter 5. As shown in Figure 8-1, the open plan office and training room were divided into six and one zones respectively.
Figure 8-1: Schematics of wiring and hardware of the project.
Each zone was controlled by a logic based controller which received input data from internal sensors (temperature and CO$_2$) and external sensors (temperature, rain, wind velocity and wind direction) and sent output signals to the actuators and radiator valves based on the control strategies developed in Chapters 6 and 7. Internal sensors and the wall controller were enclosed in the same housing to minimise wiring requirements.

Natural ventilation components were installed after preparing the wiring schematics and specifying the position of hardware (Figure 8-1). High level openings (roof vents) at the roof level$^1$ (Figure 8-2-a), and most of the wiring, were installed over two days (2/07/11 and 1/10/11). Actuators on windows$^2$ and local switches were also installed on 10/12/11 (Figure 8-2-b and Figure 8-2-c). To avoid disruptions for occupants, most of the installations took place during weekends.

![Figure 8-2: One of the installed roof vents (a), local manual switch (b) and actuated window (c)](image)

$^1$Roof vents were manufactured by Powrmatic. According to the guidelines provided by the manufactures, total effective free areas that were provided by roof vents were estimated as 3.1m$^2$, which was 20 cm$^2$ smaller than the required free areas calculated in Chapter 5.

$^2$ SECON24 40 Actuators manufactured by SE Controls were installed on windows. The overall maximum free areas provided by actuators were 43 cm$^2$ and 12 cm$^2$ smaller respectively than the calculated free areas for the low level openings in the open plan office and windows in training room respectively.
Next to each actuator there was a manual switch which allowed occupants to open and close the windows manually and override automatic control at any stage (Figure 8-2-b).

Motorised ceiling tiles and radiator values were installed during a working day (21/12/11) and since all the cables were installed, motorised ceiling tiles (Figure 8-3-a) and radiator valves (Figure 8-3-b) were installed in less than 2 hours. Radiator valves were installed and integrated with the existing central heating system in the building and aimed to provide local on/off control on each individual radiator. Since the radiator valves were connected to the wall controller with a local temperature sensor, they provided better local control than the existing heating control system in the case study building with a single sensor for the whole office.

As shown in Figure 8-4 wall controllers were also installed to provide automatic control for the system. The wall controllers comprised an LCD screen which displayed CO$_2$ level, internal/external temperature and RH. Since, according to the results of Section 4.3, occupants were unaware of the IAQ, wall controllers were enhanced with a traffic light CO$_2$ level indicator to inform and educate the occupants about IAQ.$^1$

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$^1$ CO$_2$<100ppm = green; 1000 ppm<CO$_2$<1200 ppm=amber, CO$_2$ >1200 ppm = red
8.2.2 Software

The controller algorithm (software) was designed based on the results of the developed temperature and CO₂ based control strategies described in Chapters 6 and 7 and were coded by electronic engineers at SE Controls. This led to the development of a new product called NVLogIQ (Figure 8-4). A brochure of this product can be found in Appendix G.

Control strategies included CO₂ and temperature control strategies. CO₂ control only operated during occupied hours while temperature control operated 24/7. According to the results of Section 7.4.2 different temperature based control strategies were used during the working day. To reduce the risk of overheating on hotter days, vents opened earlier and to prevent the risk of overcooling and minimise risk of excessive energy consumption, opening the vents was delayed during moderate and cold days.

Some minor modifications were applied to the original developed control strategies and fixed 5% free areas were set to ease implementation of control strategies in the case study building. Although a 5% fixed free area was larger than the minimum identified required free areas (3%) as it is shown in Appendix
H, based on the DTS results energy consumption did not increase and energy consumption increased only by 1.5%. CFD results presented in Appendix H, also showed that by introducing a fixed minimum 5% of actuator chain, the risk of draught was negligible.

8.2.3 Occupant training

Once every four months, staff forums take place in the case study building. This opportunity was used for staff trainings. Training was conducted twice in June 2011 (one month before intervention) and February 2012 (eight months after intervention). The training aimed to educate the occupants as to how use the new systems and discuss the logic behind the new systems.

To encourage the occupants to be more proactive and increase their awareness of their working environment, in addition to training, fleeces and sweatshirts were provided for each occupant and cold and hot drinks were supplied.

8.3 Building performance after intervention – manual control

Physical measurements were used to assess thermal comfort, IAQ and energy consumption. During this period, all hardware except wall controllers and motorised ceiling tiles were installed in the open plan office. During this period natural ventilation systems purely relied on the occupants’ manual controls and the ceiling tiles were fully opened.

Since ventilation options in the training room and warehouse remained the same as before intervention, only results of building performance in the open plan office are reported here. Moreover, due to concerns expressed by the building manager, questionnaires were not distributed at this stage.

8.3.1 Thermal comfort

Both adaptive and heat balance approaches were used to study the risk of thermal discomfort in the case study building. In both methods, risk of thermal discomfort was evaluated by calculating the percentage of time when operative temperature or PMV were not within comfortable ranges and the
Chapter 8: Building performance after intervention

frequency of discomfort was reported in each method. Moreover, the percentage of occupants who felt thermally uncomfortable was predicted by calculating PPD and P (refer to Equation 3-2 and Section 2.4.1) and maximum values were reported to show the worst conditions. Results of PPD and P can be found in Appendix I.

Comparison of occupants’ thermal comfort before and after intervention showed improved temperature control after refurbishment, even though external temperatures were slightly higher in 2011 (after intervention) (Figure 4-2 and Figure 8-5). According to the results of this section introducing new natural ventilation strategies helped to reduce the risk of overheating by a maximum of 70% (in the R&D area) and by a minimum of 13% (in the Accounts area) (Table 8-1). It should be noted that according to the results of the questionnaire before intervention (Section 4-3), occupants of the R&D were the most dissatisfied occupants and occupants of the Accounts area were the most satisfied ones. The results suggest that occupants of the R&D area who were the most dissatisfied occupants before intervention, responded to the new strategies more actively after intervention and better temperature controls were provided in this area. The occupants of Accounts area, who were the most satisfied, had the little intention to change their working environment. Therefore, when natural ventilation relied only on the manual controls by the occupants, they controlled natural ventilation less actively making the NV strategies less effective in the Accounts area.

Table 8-1: Thermal comfort in the case study building after intervention with manual control

<table>
<thead>
<tr>
<th>Method</th>
<th>Criteria</th>
<th>Before intervention</th>
<th>After intervention (manual control)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Main office</td>
<td>Accounts</td>
</tr>
<tr>
<td>Heat balance</td>
<td>1. % of occupied hours PMV in not in the range of ±0.5</td>
<td>37.2%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>2. Maximum PPD (Predicted Percentage Dissatisfied)</td>
<td>72%</td>
<td>74%</td>
</tr>
<tr>
<td>Adoptive</td>
<td>1. % of occupied hours Tc&gt;25°C</td>
<td>26.6%</td>
<td>28.2%</td>
</tr>
<tr>
<td></td>
<td>2. % of occupied hours Tc is not in the range of calculated T_comf ±3 °C</td>
<td>6.2%</td>
<td>9.1%</td>
</tr>
<tr>
<td></td>
<td>3. Maximum P (predicted daily discomfort)</td>
<td>22%</td>
<td>31%</td>
</tr>
</tbody>
</table>

1 as shown in Table 4-4 only 33% of them were dissatisfied
Comparing the results of building performance before and after intervention (c.f. Figure 8-5, Figure 4-2) showed that, before refurbishment there was more temperature variation in different areas of the office and air temperature in R&D was usually 1-2 °C higher than other areas, whereas after refurbishment there was more consistency in temperature throughout the open plan office.

Figure 8-5: Air temperature in open plan office during the time enhance natural ventilation were controlled manually

The results of this section also showed that, after intervention, natural ventilation helped to shift the occurrence of peak temperatures from occupied to unoccupied periods which helped to prevent the risk of overheating. This can be seen in Figure 8-6-a and Figure 8-6-b which illustrate temperature and CO₂ concentration on two similar days in relation to the external weather conditions. It also shows the slower reaction to overheating in the Account area where as a result of delaying opening the vents internal temperature was higher than the other zones.

The results of this section also revealed that, in terms of controlling internal temperature, manually controlled natural ventilation performed better during hotter days. During hotter days, occupants reacted to the internal temperatures faster and tried to control the temperature more actively resulting in more effective temperature control. Overall, results of this section showed
that air temperature at the beginning of the working day is very important. For example as shown in Figure 8-6-b and Figure 8-6-d on 27/9/11 and 7/7/11, although at 9am internal temperatures on both days were the same, because external temperature was higher on 27/9/11, occupants opened both high and low level openings at the beginning of the working day. However, on 7/7/11 they waited until the internal temperature reached 25°C (when they felt it was hot) and opened the openings later. This delay in opening the windows and Roofvents led to higher internal temperatures on that day (Figure 8-6-c).

![Figure 8-6: Temperature and CO2 concentration in two similar days before and after intervention](image)

**Figure 8-6: Temperature and CO2 concentration in two similar days before and after intervention**

### 8.3.2 CO2 concentration and IAQ

To assess IAQ, the percentages of the occupied time when CO2 concentrations were higher than 1000 ppm, 1200 ppm and 1500 ppm were reported.
Table 8-2 summarises the results of this section. Comparing the results of the building performance before intervention, when the supply and extract system was activated, and after intervention when natural ventilation relied on occupants’ manual control, showed considerably poorer IAQ after intervention. For example, percentages of the occupied time when CO₂ concentration was higher than 1000 ppm and 1200 ppm were increased by 76% and 50% respectively after intervention.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Open plan office (before intervention)</th>
<th>Open plan office (manual control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of occupied hours CO₂&gt; 1000ppm</td>
<td>3.8%</td>
<td>15%</td>
</tr>
<tr>
<td>% of occupied hours CO₂&gt; 1200ppm</td>
<td>2.8%</td>
<td>5.5%</td>
</tr>
<tr>
<td>% of occupied hours CO₂&gt; 1500ppm</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Maximum recorded</td>
<td>1690</td>
<td>1800</td>
</tr>
</tbody>
</table>

Although after intervention, more control options were provided, occupants controlled the openings based on their thermal comfort. This could have occurred as they are either less sensitive about IAQ conditions or unaware of it. For this reason CO₂ concentration was considerably lower during hotter days (compare CO₂ level during cold and hot seasons in Figure 8-7). The results of this section suggested that, since there was little intention by the occupants to control windows to improve IAQ, it is rather risky to only rely on manual controls to provide acceptable IAQ.

![Figure 8-7: CO₂ concentration before and after intervention](image-url)
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CO₂ patterns during occupied hours shown in Figure 8-6-b and Figure 8-6-d suggested the high dependency of CO₂ concentration on the opening positions. According to the results, CO₂ concentration suddenly dropped or rapidly rose by opening or closing the openings. Therefore CO₂ concentration can potentially be used as an indicator of the position of openings in densely occupied spaces with a constant occupancy pattern and large opening sizes.

### 8.3.3 Energy Consumption

Since guidelines provide energy benchmarks for a year and this part of the study was conducted for 6 months, energy consumption was not compared with benchmarks and it was only compared with the actual energy consumption before intervention for the same period of time (July to January).

The results showed that introducing enhanced natural ventilation into the case study building helped to reduced electricity consumption by 2%. Lower electricity consumption could have occurred as a result of disabling supply and extract systems. Moreover, since during summertime, enhanced natural ventilation system could control overheating more effectively, occupants used their desk fan less frequently.

Gas consumption was also reduced by 7.5% since disabling supply and extract systems helped to reduce room ventilation rate, and consequently heating demand reduced. Furthermore, as discussed in Section 4.2, before
intervention there was a risk of overheating even during cold seasons, and occupants needed to open windows. By applying advanced natural ventilation strategies, overheating was controlled more effectively, and for this reason, during heating seasons, occupants needed to open the windows less frequently. Opening the window less frequently during winter also helped to reduce heating demand.

Further investigations on energy consumption during occupied and unoccupied periods in the case study building showed that although energy consumption considerably reduced during occupied hours (36%), it increased by 11% during unoccupied periods (Figure 8-9). This may have occurred as a result of using uncontrolled ceiling tiles which were always open. The open ceiling tiles connected the heated zone of the open plan office to the unheated zone of the roof space, which increased heating demand. Results of this section suggested that introducing some form of controls are required to minimise heating demand during unoccupied hours.

![Figure 8-9: Energy consumption before intervention and after intervention with manual control during occupied and unoccupied hours](image)

**8.4 Building performance after intervention – automatic control**

To assess building performance after intervention (automated natural ventilation), both objective and subjective assessments were conducted by using physical measurements and questionnaires as shown in Chapter 4. Thermal comfort, IAQ and energy consumption were assessed in the case study building.
8.4.1 Physical Measurements

Similar to Sections 8.3 and 4.2, physical measurements were conducted to examine thermal comfort by using heat balance and adaptive approaches. IAQ was assessed by measuring the frequency of time when IAQ was not acceptable. Energy consumption was also studied by comparing gas and electricity consumption with benchmarks and energy consumption before intervention.

Since the function of the warehouse changed to the canteen and the meeting rooms and they were not occupied for almost 7 months, physical measurements were only conducted in the open plan office and training room.

8.4.1.1 Thermal Comfort

Table 8-3 summarises the results of building performance in terms of providing thermal comfort when both heat balance and adaptive assessment methods were applied. Results of this section showed that, introducing automatic control provided a considerably better overheating control when both adaptive and heat balance approaches were applied. Comparing the results of automated natural ventilation with building performance before intervention, showed that the risk of overheating reduced by a maximum of 95% (R&D area) and by a minimum of 41% in the Training room (Table 8-3).
### Table 8-3: Thermal comfort in the case study building after intervention with automatic control

<table>
<thead>
<tr>
<th>Method</th>
<th>Criteria</th>
<th>Before intervention</th>
<th>After intervention (Manual control)</th>
<th>After intervention (Automatic control)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Main office</td>
<td>Accounts</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Heat balance</td>
<td>1. % of occupied hours PMV in not in the range of ±0.5</td>
<td>37.2%</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>2. Maximum PPD (Predicted Percentage Dissatisfied)</td>
<td>72%</td>
<td>74%</td>
<td>88%</td>
</tr>
<tr>
<td>Adoptive</td>
<td>1. % of occupied hours Tc&gt;25°C</td>
<td>26.6%</td>
<td>28.2%</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>2. % of occupied hours Tc is not in the range of calculated T&lt;sub&gt;comf&lt;/sub&gt; ±3 °C</td>
<td>6.2%</td>
<td>9.1%</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>3. Maximum P (predicted daily discomfort)</td>
<td>22%</td>
<td>31%</td>
<td>49%</td>
</tr>
</tbody>
</table>

Comparing the results of building performance for manual and automatic controls showed that introducing the automatic control was more effective in controlling thermal discomfort in the Accounts area as it decreased the risk of thermal discomfort by 60%. This was due to the little intention of occupants in the Accounts area to control their indoor environment when natural ventilation systems relied on manual controls. Therefore, introducing the automatic control was more effective in this zone. This was while introducing the automatic control in the R&D area, where occupants were more active, was less effective and the risk of thermal discomfort reduced by only 26%. However, it is necessary to study the effects of providing automatic controls on occupants’ perception on thermal comfort, as automatic controls may lead occupants to feel that they have little or no control over their working environment. This will be addressed in Section 8.4.2.
When the performance of the case study building with manual and automatic controls was studied, similar performances were recorded during extreme external conditions (c.f. Figure 8-11-a and Figure 8-11-c). When natural ventilation relied only on manual controls, since during hot days, occupants opened the vents as soon as they entered the office (Figure 8-11-a), the case study building performed similarly to when automated controls were installed (Figure 8-11-c).

Although building performance during hot days was similar, introducing automatic controls during typical summer days was more effective. As discussed in Section, 4.2.1 and 8.3.1 occupants reacted to overheating slowly and therefore introducing automatic control helped to prevent overheating and kept internal temperature within a comfortable range. This can be seen by comparing Figure 8-11-b and Figure 8-11-d which shows building performance during two similar typical summer days with and without automatic control.
Results showed that although introducing automatic controls considerably helped to reduce the risk of overheating, it also increased the risk of overcooling (Figure 8-12). The following reasons were identified as the causes of this problem:

1. New radiator valves were incompatible with some of the existing radiators. For this reason, new valves did not control the radiator and some of them remained off continuously.

2. Opening the vents to control IAQ during winter led to introducing cooler temperature into the indoor environment and caused a temperature drop. This could be improved if bottom hung windows were introduced. Introducing bottom hung windows facilitate a mixture of hotter lighter hotter internal air with cool denser external air.
3. Comparing daily external temperature during wintertime, illustrated in Figure 8-5 and Figure 8-10 showed that when the effect of automatic controls were studied (2012) external temperature was lower than previous years (2009-2011) which increased the risk of overcooling.

![Figure 8-12: Frequency of overheating and overcooling in the case study building](image)

### 8.4.1.2 CO₂ Concentration and IAQ

To assess the effects of introducing the automated natural ventilation system on IAQ, the frequency of occurrence of CO₂ concentration exceeding 1000 ppm, 1200 ppm and 1500 ppm, as well as the maximum recorded CO₂ concentration, were reported.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Before intervention</th>
<th>After intervention (manual control)</th>
<th>After intervention (automatic control)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open plan office</td>
<td>Training room</td>
<td>Open plan office</td>
</tr>
<tr>
<td>% of occupied hours CO₂&gt; 1000ppm</td>
<td>3.8%</td>
<td>30.2%</td>
<td>15%</td>
</tr>
<tr>
<td>% of occupied hours CO₂&gt; 1200ppm</td>
<td>2.8%</td>
<td>6.1%</td>
<td>5.5%</td>
</tr>
<tr>
<td>% of occupied hours CO₂&gt; 1500ppm</td>
<td>0.5%</td>
<td>2.8%</td>
<td>0%</td>
</tr>
<tr>
<td>Maximum recorded</td>
<td>1690</td>
<td>2000</td>
<td>1800</td>
</tr>
</tbody>
</table>

Results of this section showed that introducing automatic controls instead of relying on occupants to control IAQ, significantly helped to reduce the risk of poor IAQ. The results of this Section also showed that introducing automatic controls in more crowded zones, such as the training room was more effective.
For instance introducing automatic controls in the training room helped to reduce the frequency of the time when CO\(_2\) concentration was higher than 1000 ppm by 50% (Table 8-4) while comparing the same figure in the open plan office showed a reduction of 25% (Table 8-4).

Comparing the results of the performances of the case study building before and after intervention (c.f. Figure 4-4 and Figure 8-13) showed that, before introducing automatic controls, there were considerable variations in CO\(_2\) concentrations in the open plan office and training room, whereas after refurbishment there was more consistency in the CO\(_2\) levels throughout the case study building in different zones with different occupancy densities. Similar to the performance of the case study building pre-intervention, the CO\(_2\) concentration was lower during the summer time, when openings were more likely to be opened to provide thermal comfort.

![Figure 8-13: CO\(_2\) concentration in the case study building with automated natural ventilation system](image)

Comparing the results of the building performance before intervention (when supply and extract ventilation was activated) with when automated natural ventilation was introduced, showed the frequency of the time CO\(_2\) concentration was higher than 1000 ppm increased by 66% and the frequency
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of the time CO$_2$ concentration was higher than 1200 ppm reduced by 47% (Table 8-4). The results of this section suggested introducing a lower CO$_2$ opening set-point could help to achieve the 1000 ppm target. However, as discussed in Section 8.2.2, the minimum free areas that opening actuators could provide was 5%. It is while according to the results of DTS simulations in Section 6.5, reducing opening set-points and keeping the free area as 5% could increase the energy consumption and the risk of hunting.

The effects of applying a lower first set-point was also tested in the actual building. As shown in Figure 8-14, on 27/11/12 the first set-point reduced to 900 ppm (with ±50 ppm interval), while the opening set-point on 28/11/12 remained as 1000 ppm (with ±50 ppm interval). Although IAQ was slightly better on 27/11/12, as free areas were the same on both days, windows opened and closed several times on 27/11/12 suggesting introducing lower set-points could increase the risk of the hunting effect. This confirmed the results of computer simulations discussed in Section 6.5.

Further investigations showed that during cold periods (when external temperature< 10°C), low level openings (windows) were kept closed and ventilation mainly relied on high level openings which helped to prevent the risk of draught. At the same time during rainy days, to prevent rain ingress, roof vents were also kept closed. Therefore, during cold rainy days IAQ deteriorated and internal temperature increased. Figure 8-15 illustrates internal and external temperatures and CO$_2$ concentration during a cold rainy day. During this day, since neither high nor low level openings opened, CO$_2$ concentration reached almost 1500 ppm. These results suggested that
introducing a new rule into the control strategies is required. This was to make sure that, regardless of external temperature, if CO\textsubscript{2} concentration reached a high set-point (e.g. 1500ppm) then vents open for a short period to minimise the risk of high CO\textsubscript{2} concentration.

![Figure 8-15: CO\textsubscript{2} level and indoor air temperature during a rainy cold day](image)

**8.4.1.3 Energy consumption**

Energy consumption in the case study building after intervention was evaluated based on the meter readings and compared with good practice and typical energy consumption benchmarks as well as energy consumption before intervention. Total energy consumption was 157 kWh/m\textsuperscript{2}/year which was almost 12% higher than good practice benchmarks and 36% less than typical energy consumption for this building type. The results of this Section also showed that compared to the energy consumption before intervention, gas and electricity consumption reduced by 9.6% and 4.5% respectively.

Both gas and electricity consumptions were less than typical gas and electricity consumption. Compared with good practice benchmarks, although as a result of introducing an automatic advanced natural ventilation system, gas consumption was only 4% higher than gas consumption in good practice benchmarks, electricity consumption in the case study building was still 18% higher than good practice electricity consumption (Figure 8-16). As mentioned in Section 4.2.3, electric lightings and equipment were the main consumers of electricity in the case study building and since both equipment and artificial lighting systems almost remained the same, electricity consumption remained
higher than good practice benchmarks. Results of this Section suggested that in a building without an air-conditioning system, to meet the level of good practice benchmarks, introducing natural lighting strategies is essential.

**Figure 8-16: Energy consumption in the case study building after intervention**

Disabling supply and extract fans and lowering demand for using desk fans (due to better temperature control) helped to reduce electricity consumption by 4.5%. Comparing gas consumption before and after intervention, showed around 9.6% lower gas consumption after refurbishment even during the months when external temperatures were lower (c.f. gas consumption and external temperature during November and December in Figure 8-17).

**Figure 8-17: Monthly energy consumption before and after intervention**
8.4.2 Questionnaire

The questionnaires were completed by 36 participants representing 95% of regular occupants. More than 80% of the participants spent more than 30 hours/week in the case study building.

Results of the questionnaire confirmed the results of physical measurements and revealed that occupants who worked in the Accounts area were the most passive ones. For instance during winter time, 37% of them never attempted to control their working environment. This was while those occupants who worked in the Main office and R&D were more active as 80% of them made some adjustments to their working environment.

The results of the questionnaire also showed that, although natural ventilation strategies provided more control options, since automated natural ventilation was a new system, at least 75% of the occupants in each zone assumed that they had little or no control over their thermal environments. As shown in Figure 8-18, occupants of R&D, where conventional natural ventilation control options (such as windows) did not exist, felt that they had the least control over their thermal environments.

![Figure 8-18: Percentage of those occupants who felt they had little or no control over their thermal environments](image)

The results of the questionnaire also showed that, those occupants who worked in the R&D and Accounts areas had the best and the worst

---

1 In R&D natural ventilation control option was ceiling tiles while in the Accounts and Main office areas natural ventilation was controlled by automated windows.
understanding respectively regarding how the natural ventilation systems were operating in the case study building.

### 8.4.2.1 Temperature

Post intervention, occupants were asked to evaluate and describe their workplace in terms of temperature in both summer and winter. Figure 8-19 compares the occupants’ mean votes based on the ASHRAE 7-point thermal sensation scale in winter and summer in different areas of the case study building for pre and post intervention. As can be seen in Figure 8-19 and Table 8-3, similar to the results of the physical measurements, occupants’ sensation regarding internal temperatures significantly improved and mean vote temperatures in both winter and summer fell within the comfort range and this results agree with the results of physical measurements (Table 8-3).

![Figure 8-19: Occupants’ description about temperature in winter and summer](image)

Table 8-5 provides more details on the occupants’ temperature perception compared with physical measurements. In this Table, “-3” and “-2” are considered as overcooled and “+2” and “+3” are regarded as overheated. Moreover, April to September was assumed as summer time and October to March was considered as winter time.

Comparisons between subjective and objective responses showed that both series of data followed the same pattern although higher deviation between objective an subjective responses were recorded post intervention (compare results in Table 4-4 and Table 8-5). Prior to the intervention, due to the extremely hot conditions, the majority of occupants had similar thermal sensation and described it as too hot. It is while, due to more moderate conditions of post intervention, each individual occupant described her/his
thermal sensation differently and since number of participants was limited, response of each individual could affect the total percentage. For example in the R&D area there were only 12 occupants and even if one of them described the thermal condition as too hot, it meant that, 8.3 percent of them felt their working environment was too hot. It is while

Comparing the results of this section with occupants’ characteristics confirmed the results of studies by Rijal et al (2007). Based on the results of the questionnaires, 37% of the occupants of the Accounts area were categorised as passive and therefore they described their thermal environment as too hot or too cold more frequently than other areas.

Physical measurements predicted a higher risk of overcooling in the R&D area. At the same time, based on the results of the questionnaire, occupants of the R&D area assumed they had the least control over their environment. However, since they were more active and understood the system better, overcooling and overheating in R&D were reported less frequently. Findings of this section confirmed the results of Section 8.3.1 in which it was concluded that, since the R&D area used to have the worst thermal conditions before intervention, occupants in this zone responded to the new system (natural ventilation) more actively.

Table 8-5: Comparison of subjective and objective responses regarding temperature

<table>
<thead>
<tr>
<th></th>
<th>OVERHEATING</th>
<th>OVERCOOLING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OBJECTIVE</td>
<td>SUBJECTIVE</td>
</tr>
<tr>
<td></td>
<td>Heat balance</td>
<td>adaptive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main office</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>8.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Winter</td>
<td>3.3%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Accounts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>14.1%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Winter</td>
<td>6.4%</td>
<td>1.2%</td>
</tr>
<tr>
<td>R&amp;D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>5.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Winter</td>
<td>1.0%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Effects of temperature on the occupants’ productivity after intervention were also assessed. According to the results of the questionnaire, less than

---

1 Characteristics in terms of passive and active
18% and 11% of the participants believed that their productivity was decreased due to the uncomfortable air temperature in winter and summer respectively (Figure 8-20). Comparing the results of this section with the results of similar assessments before intervention, revealed that the percentage of those occupants who felt temperature had a negative effect on their productivity was reduced by up to 75%, (refer to Figure 4-8 and Figure 8-20). The results of this Section also showed that although introducing automated natural ventilation increased the risk of over cooling during winter, it did not affect occupants’ perceived productivity.

Figure 8-20: Effects of air temperature on participants’ productivity post intervention

Occupants were also asked to rate the temperature stability in both winter and summer. The results of the questionnaire after intervention showed that, during winter and summer respectively only 14% and 20% of the occupants felt air temperatures varied during a working day. Compared to the results of questionnaires before intervention when more than 55% of occupants felt that temperature was unstable, considerable improvements were recorded after intervention.

8.4.2.2 Air movement

Figure 8-21 shows the mean value of air movement rated by occupants in different areas of the building. Although ventilation was provided by low and high level openings and windows were opened more frequently after intervention, occupants did not complain about air movements; and compared to the results of the questionnaire before intervention, they were more satisfied with the air movement.
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8.4.2.3 Air quality:

Participants were also asked to assess IAQ in terms of humidity and air freshness. There was generally good agreement between data obtained from RH sensors and the results of the questionnaires. Occupants felt their working environment was drier during winter which was confirmed by the RH measurements. Compared to the results of the questionnaires before intervention, they felt air was slightly drier in summer which was also confirmed by the results of the actual measurements (Figure 8-22 and Appendix I). This could be explained by the higher ventilation rates in which outside dry cold air (low water content) was mixed with inside warm air (lower RH% and higher water content) which reduced the average RH in the case study building.

As shown in Figure 8-23 in terms of air freshness, occupants of the Main office and the R&D area felt that air freshness and IAQ compare to the summer deteriorated during winter. This is in contrast with the results of the pre-intervention survey in which occupants felt freshness deteriorated during summer. More realistic perception of occupants regarding air freshness after intervention could occur due to introducing the traffic light CO₂ level informer. Introducing the CO₂ level traffic light helped to increase occupants’ awareness of IAQ.
Results of this Section also confirm that occupants of the Main office and the R&D areas had an overall better awareness and understanding as to how the natural ventilation systems were operated in the case study building and they were therefore more conscious about their environment. On the other hand the occupants of the Accounts area felt air freshness deteriorated during summer which is in contrast with measured data.

The effect of IAQ on occupants’ productivity was also rated by participants and similar to the effects of temperature on occupants’ productivity, more than 70% of occupants believed that IAQ had no effect on their productivity. This showed that, although IAQ slightly deteriorated after intervention it did affect the occupants’ productivity.

### 8.4.2.4 Noise level

According to the results of the questionnaire, although by introducing natural ventilation, windows were opened more frequently, neither external noise nor generated noise by operating actuators were disruptive and the majority of the occupants described the noise level as neutral (Figure 8-24).
8.4.2.5 Occupants’ satisfaction and thermal Comfort

Occupants were also asked to rate their satisfaction in terms of temperature, IAQ and overall comfort both in winter and summer. The results of this section showed that overall satisfaction of occupants was improved by introducing automated natural ventilation. Moreover, IAQ, temperature and overall satisfaction rates followed similar patterns and were similar in both seasons (refer to Figure 8-25).

![Figure 8-25: Occupants comfort perception in winter and summer](image)

Results of this section showed that, for the examined parameters, the percentage of dissatisfied occupants was reduced considerably (maximum of...
80%) and the percentage of those occupants who rated the examined parameters as neutral and satisfied was increased after intervention.

Occupants were also asked to rate their thermal comfort. Comparison of the results of this section with maximum PPD (predicted percentage of dissatisfied occupants using heat balance method) and P (proportion of occupants who are not comfortable using adaptive method) values in Table 8-7 shows that although the heat balance approach slightly overestimated the risk of thermal discomfort during summer, it provided a better prediction regarding occupants’ thermal comfort. This is despite the fact that the building was naturally ventilated. However, it should be noted that when P values (adaptive approach) were calculated, the effects of overcooling were ignored and P values were only calculated based on overheating. This was while actual and subjective responses from occupants showed that there were risks of overcooling in all tested zones. Based on the results of this Section it is suggested to include the risk of overcooling in the prediction of dissatisfied occupants when adaptive methods are applied.

The results showed that occupants of the Accounts area were the most uncomfortable occupants post intervention (Table 8-7). Moreover compare to the results of pre intervention (Table 4-4), the Accounts area is the only zone in which occupants’ perception regarding thermal comfort deteriorated after intervention. This is in contrast with the results of the pre-intervention survey in which occupants of the Accounts area were the most satisfied occupants. As discussed in Section 4.3.1 before intervention those occupants who worked in the Accounts area had more control options, it seems that by introducing automated windows instead of conventional windows, occupants of the Accounts area felt they lost their control over their environment. On the other hand before intervention occupants of the other zones had little control over their environment, introducing more control options after intervention helped them to feel more comfortable compared to the occupants of Accounts area. Another explanation maybe that the occupants of the Accounts area preferred higher temperatures and were more sensitive to lower temperatures and since after intervention overall temperature were decreased, they felt uncomfortable.
It could be concluded that in order to increase occupants’ satisfaction, providing a moderate condition, shown in Table 8-3, was insufficient and it was necessary to increase occupants’ engagement in controlling natural ventilation.

Table 8-6: Comparing occupants’ thermal comfort based on subjective and objective studies

<table>
<thead>
<tr>
<th>% of Uncomfortable occupants</th>
<th>OBJECTIVE</th>
<th>SUBJECTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heat balance (PPD)</td>
<td>Adaptive (P)</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>Max</td>
</tr>
<tr>
<td><strong>Main office</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>42.9%</td>
<td>15.0%</td>
</tr>
<tr>
<td>Winter</td>
<td>30.5%</td>
<td>10.0%</td>
</tr>
<tr>
<td><strong>Accounts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>50.9%</td>
<td>19.5%</td>
</tr>
<tr>
<td>Winter</td>
<td>26.1%</td>
<td>13.3%</td>
</tr>
<tr>
<td><strong>R&amp;D</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>50.9%</td>
<td>16.0%</td>
</tr>
<tr>
<td>Winter</td>
<td>26.1%</td>
<td>10.8%</td>
</tr>
</tbody>
</table>

8.5 Summary

The effects of introducing manual and automated natural ventilation into the case study building were reported in this chapter. Quantitative and qualitative studies were conducted to assess building performance in terms of IAQ, thermal comfort and energy consumption following the intervention. Table 8-7 summarises the results of this chapter.

Table 8-7: Building performance before intervention

<table>
<thead>
<tr>
<th>Temperature:</th>
<th>Before intervention (Measured)</th>
<th>After intervention (Measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open plan' office</td>
<td>30.8% of annual occupied hours Tc&gt; 25 °C</td>
<td>3.7% of annual occupied hours Tc&gt; 25 °C</td>
</tr>
<tr>
<td>Max = 31.24°C</td>
<td>Max = 28.9°C</td>
<td></td>
</tr>
<tr>
<td>CO₂ level:</td>
<td>Training room</td>
<td>32% of annual occupied hours Co₂&gt; 1000ppm</td>
</tr>
<tr>
<td>Max = 2000ppm</td>
<td>Max = 2000ppm</td>
<td></td>
</tr>
<tr>
<td>Energy consumption:</td>
<td>Whole building</td>
<td>171(kWh/year/m²)</td>
</tr>
</tbody>
</table>

1 These values are generated based on average temperature in the open plan office
Findings of this chapter can be summarised as follows:

- Introducing either the automatic or manual controlled natural ventilation system helped to reduce the risk of overheating. However, the automated design performed better since it could prevent overheating more effectively. According to the results of this chapter, the risk of overheating reduced by a minimum of 13% (manual control in the Accounts area) and by a maximum of 95% (automatic control in the R&D area).

- Introducing the automatic control rather than relying on manual control in crowded zones such as the training room was very effective and helped to reduce the risk of poor IAQ by 50%.

- Comparing gas consumption before and after intervention showed 9.6% lower gas consumption after refurbishment. By applying natural ventilation strategies, overheating was controlled more effectively and for this reason during heating seasons, occupants needed to open the windows less frequently. Opening the windows less frequently during winter helped to reduce heating demand.

- The results showed that introducing automated natural ventilation into the case study building helped to reduce electricity consumption by 4.5%. Lower electricity consumption could have occurred as a result of disabling the supply and extract systems. Moreover, during summertime, the enhanced natural ventilation system could control overheating more effectively. Therefore, there was lower demand for using desk fans.

- Occupants’ sensation regarding internal temperatures significantly improved post intervention and the mean vote temperatures of 1.85 before intervention reduced to 0.34 after intervention.

- Thermal discomfort was reported less frequently by those occupants who were more active and understood the system better (occupants of the R&D area). Therefore, it is highly recommended to educate the occupants and increase the occupants’ involvement and engagement in the process of controlling natural ventilation.
• Improving the thermal comfort also helped to improve the occupants’ perception regarding IAQ. For example after intervention the measured building performance in the open plan office showed poorer IAQ, but because thermal comfort was improved the occupants assumed that IAQ was also improved.
9 Conclusions

This research has investigated the options for retrofitted natural ventilation and control strategies for lightweight occupied office buildings. Natural ventilation options and control strategies were proposed for an existing lightweight office building in order to:

1. Improve thermal comfort,
2. Improve IAQ; and
3. Reduce energy consumption.

A typical lightweight office building was selected and the performance of this case study building was evaluated using physical measurements, computer simulation and questionnaire surveys. Based on the actual building performance before intervention, several natural ventilation options and control strategies were tested using DTS and CFD models. The best options were then used to refurbish the building and the performance of the case study building before and after refurbishment were compared.

According to the results, the implemented natural ventilation system reduced the risks of thermal discomfort by 80% (Aim 1) and poor IAQ 60% (Aim 2). The energy consumption was also reduced by 9% (Aim 3). Moreover the results of the questionnaire surveys revealed that the occupants’ perceptions regarding thermal comfort and IAQ were considerably improved after intervention/refurbishment. According to the results the percentage of dissatisfied occupants reduced by 80% after intervention (Aims 1 and 2).

9.1 Main findings

The stack induced natural ventilation was found to be the best option to provide thermal comfort and acceptable IAQ in the case study building. This suggest this option can be suitable for densely occupied spaces with high internal heat gain and lightweight structure (e.g. open plan offices) without compromising energy consumption. However, wind induced ventilation options, in which stack and wind effects have opposite flow directions,
provided better IAQ in zones with high internal heat gains while it significantly (31%) deteriorated thermal comfort in those areas.

Considering the slow reaction of occupants to overheating and their unawareness of CO$_2$ concentration levels, automatic controls were found to be necessary to provide acceptable IAQ and thermal comfort in the case study building. In this respect, the results suggested that in order to provide acceptable IAQ, it is possible to either provide larger free areas with higher CO$_2$ concentration set-points or to introduce smaller free areas with lower CO$_2$ set-points. However, the latter minimised the risks of the hunting effect and cold draughts, providing better comfort for the occupants. Introducing automatic controls significantly reduced the risk of poor IAQ by 60%.

Temperature based control strategies were developed in order to provide thermal comfort. Control strategies contained several rules based on external temperature, internal heat gain, internal temperature and time of day. In these strategies the free areas were the function of internal and external temperature differences, different opening set-points depending on external temperature and time of the day determined the vent’s position. The control strategies prevented the risk of overheating during hotter and moderate days by earlier opening of the vents. They also prevented the risk of overcooling by delaying the opening of the vents during colder days.

Proposed strategies in this study can be ranked from minor refurbishment options, such as improving electric lighting systems, to major refurbishments in which fully automated advanced natural ventilation options were proposed. Table 9-1 summarises the proposed options and their impacts on the performance of the case study building. It should be noted that apart from the results of the minor option, which was developed based on the results of computer models, presented information in this table was collected from the actual building and based on the physical measurements.
### Table 9-1: Refurbishment options

<table>
<thead>
<tr>
<th>Level of intervention</th>
<th>Description</th>
<th>Risk of thermal discomfort (frequency of occupied hours Tc&gt;25°C)</th>
<th>Risk of Poor IAQ (frequency of occupied hours CO₂ concentration&gt;1200 ppm)</th>
<th>Energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Open plan office</td>
<td>Training room</td>
<td>Open plan office</td>
</tr>
<tr>
<td><strong>Before intervention</strong></td>
<td></td>
<td>30.8%</td>
<td>7.7%</td>
<td>2.8%</td>
</tr>
<tr>
<td>(Physical measurements)</td>
<td></td>
<td><img src="improve_lighting.png" alt="Lighting System" /></td>
<td><img src="improve_natural_ventilation.png" alt="Natural Ventilation" /></td>
<td><img src="improve_natural_ventilation.png" alt="New Openings and Manual Control" /></td>
</tr>
<tr>
<td><strong>Minor refurbishment</strong></td>
<td>Improving artificial lighting system</td>
<td>24.7%</td>
<td>8.5%</td>
<td>0%</td>
</tr>
<tr>
<td>(Computer model)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Intermediate intervention</strong></td>
<td>Improving natural ventilation by introducing new high level opening and manual control</td>
<td>19.6%</td>
<td>N/A</td>
<td>5.5%</td>
</tr>
<tr>
<td>(Physical measurements)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Major refurbishment</strong></td>
<td>Improving natural ventilation by introducing new high level opening and advanced automatic control</td>
<td>3.7%</td>
<td>4.5%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
9.2 Occupancy surveys

The results discussed in the thesis indicate that due to high internal heat gains, the lightweight structure and limited ventilation devices, ventilation was ineffective in the case study building and remedial action was required to control overheating during hot seasons. During summer, more than 60% of occupants described their thermal condition as uncomfortable. The worst thermal condition was reported in the R&D area where there were no ventilation devices and occupants therefore did not have any control over ventilation. In this zone more than 80% of occupants were uncomfortable.

Comparison of the indoor air temperature during unoccupied periods (e.g. weekends) both in winter and summer periods indicate that indoor air temperature is highly influenced by external temperature. However, in highly occupied spaces where internal heat gains are high, air temperature rises rapidly when occupants enter the room. In these areas, although occupants feel uncomfortable due to high air temperatures, they are slow to react to these conditions. Moreover, the results showed that occupants adjust openings based on thermal comfort and have little intention to open the vents based on IAQ which resulted in high CO₂ concentration during moderate and cold days.

For the above reasons, the existing natural ventilation system (windows and doors) in the case study building was enhanced by introducing new top level openings. Two control strategy types of manual and automatic controls were tested and were compared with each other and with the results of building performance before intervention. Introducing enhanced natural ventilation using either manual or automatic control significantly improves occupants’ thermal comfort in the case study building and the risk of thermal discomfort was reduced by a minimum of 13% and a maximum of 95%.

The work has shown that manually controlled natural ventilation systems appear to perform better during hotter days compared to the moderate summer days. It was concluded that occupants react to the internal temperatures more actively in an attempt to control the internal temperatures during hotter days.
Manual controls may, however, be less effective during moderate summer days due to the delayed reaction of the occupants in controlling the vents (e.g. windows). Automatic control systems are therefore more effective during such days.

Occupants of those areas of the case study building where thermal comfort was relatively poor before intervention (R&D area) responded to the manual natural ventilation systems more actively. In contrast, occupants of the zones in which they were more comfortable before intervention used manual control less often. Therefore, it could be argued that the previous thermal experiences of the occupants' of a zone in buildings with manually controlled natural ventilation systems should be regarded as an additional criteria to the historiced external temperature to determine comfortable temperature.

Automatic controls are more effective in spaces where occupants are less active and have little intention to change their thermal environments (e.g. opening the vents to prevent overheating). According to the results of this study, introducing automatic natural ventilation systems could reduce the risk of thermal discomfort by 60% in such areas.

Although after intervention, more control options were provided, when the enhanced natural ventilation was controlled manually, occupants were much more responsive to their thermal discomfort compared to poor IAQ. This is similar to the results of building performance before intervention. For this reason, the risk of unacceptable IAQ increased during colder seasons. This is because they either avoided adjusting openings to avoid thermal discomfort in cold weather or they were less aware of the IAQ conditions.

Compared to natural ventilation systems, mechanical supply and extract systems could provide better IAQ in terms of CO₂ concentration levels. However, natural ventilation systems can reduce the energy consumption in buildings. The natural ventilation system monitored in this work reduced the gas and electricity consumption by 9.6% and 4.5% respectively.

In terms of identifying suitable assessment methods to study the risk of thermal discomfort, the results of this study also showed that there was good
agreement between the static PMV calculation methods and the results of the questionnaire for the naturally ventilated spaces where control options were limited or activity levels were high. Moreover, the results confirmed that the adaptive approach provides better prediction for areas with more environmental manual control options. Results also showed that, since in automated naturally ventilated building occupants felt their controls have been limited, PMV slightly overestimated risk of thermal discomfort while the adaptive approach underestimated the risk of discomfort.

The results also indicated that indoor air temperature has the most significant effect on occupants’ overall comfort which can enhance their perceived productivity.

9.3 Proposed natural ventilation options

Internal heat gains in the open plan office generated almost five times more heat than the heating system during a year. Therefore, minimising internal heat gain would help to minimise the risk of overheating. For example, according to the results of DTS models, introducing minor changes such as installing energy efficient light bulbs in the open plan office reduced the risk of overheating by 64%.

Introducing additional high level openings helped to control the risk of overheating in areas with high internal heat gains (e.g. the open plan office). The risk of overheating (overheating defined as the percentage of occupied hours operative temperature was higher than 25°C) was reduced by a minimum of 74% (Windcatcher in Scenario 1) and by a maximum of 88.5% (Stack ducts in Scenario 2). However, since internal heat gain in the open plan office was high, there was always an upward flow due to the stack effect. For this reason, the Stack ducts and Roofvent options, in which the wind effect reinforced the stack effect and increased the upward air movement, performed better. Whereas for the Two ducts and the Windcatchers cases, when the wind speed was low or internal temperature was high (and stack effect was the dominant force), the wind effect opposed upward air movement caused by the stack effect and reduced the ventilation rate.
The results of CFD simulations showed that the problems caused by opposing wind and stack effects could be minimised if ventilation ducts were directly connected to the open plan office. This would allow for the fresh air to be delivered directly into the open plan office. However, by connecting the ducts directly to the open plan office, opening sizes were limited to the cross section area of the ducts. Moreover, this increased the risk of draught, costs and structural load on the roof.

Although all natural ventilation options tested in this study provided acceptable IAQ, the Two ducts and Windcatcher options provided slightly better IAQ. The results showed that the risk of poor IAQ increased during colder periods when, to prevent the risk of draught, low level openings were less likely to be opened and natural ventilation was mainly operated by the high level openings. In the Windcatcher and Two ducts cases openings were located on the walls of the ducts, therefore, when the wind heated the ducts, a positive pressure field was formed around the windward side and negative pressure field around the opposite side (leeward side). Thus, fresh air entered the building from the openings located in the positive pressure region and exited through openings located on the opposite low pressure side.

### 9.4 Proposed strategies for control of natural ventilation

The results of models with variable set-points suggested that the size of the openings appears to be more important than the set-points in providing acceptable IAQ in naturally ventilated buildings. Very small openings are less likely to be able to deliver acceptable IAQ as they cannot provide adequate flow rates which, in turn, make the set-points ineffective even if they are set to a very low value to open the vents earlier.

The relationships between the opening area and energy consumption in CO2 based control strategies are sometimes unclear. If adequate free opening area is not provided, it may lead to higher energy consumption, because vents need to open more frequently in order to control CO2 concentration, leading to higher energy consumption. For example, in some simulations, although both
models used identical set-points, energy consumption increased by 10% in a model with 25% smaller opening size.

Introducing new increments into the conventional CO$_2$ based control strategies enables the upper set-point to be increased. This helps reduce the heating energy consumption whilst improving the average IAQ. For example in both the seminar room and classroom configurations, energy consumption was reduced by almost 16% while IAQ was improved because introducing the additional increment enabled an upper set-point of 1400ppm to be used.

There is a close relationship between the vent opening temperature set-points, the risk of overheating and the energy consumption. The results showed that, in options tested in this study, increasing the opening temperature set-point by 5ºC increased the risk of overheating by a maximum of 90% and reduced the heating energy consumption by a maximum of 50%.

The results also suggested that in order to achieve more consistency in temperature control, it was necessary to specify different operating modes based on the external temperature and regulate the size of opening based on the internal and external temperature differences and internal heat gains as well as the time of the day. These helped to adjust the free areas based on the required flow rates which minimised the risk of thermal discomfort and unnecessary energy consumption.

### 9.5 Limitation of the research and suggestion for further works

As discussed in the literature review, based on the results of several studies, occupants of naturally ventilated buildings feel more comfortable in a wider ranges of temperatures (de Dear and Brager, 1998; Nicol and Humphreys, 2002; Wagner et al. 2007; Moujalled et al. 2008; de Dear, 2009) and have lower IAQ expectations compared to air conditioned buildings (Hummelgaard et al., 2007), since they feel they have more control over their
environments. Therefore it is recommended to assess thermal comfort in naturally ventilated buildings based on an adaptive approach.

However, results of this study in Chapters 4 and 8 and other studies by Heiesberg (2008) and Griffiths and Eftekhar (2008) suggest that providing automatic controls are required in order to protect both building and occupants from undesired internal and external conditions. Although introducing some forms of automatic control is essential, automatic controls limit the occupants’ control over their environment. The results of this study (Section 8.4.2) showed that in the automated naturally ventilated building, the heat balance approach overestimates the risk of discomfort while the adaptive approach underestimates the risk of discomfort in such buildings. However, this needs to be studied in a wider range of buildings with a larger number of participants in order to gain confidence that this assessment approach for automated naturally ventilated buildings are appropriate or not.

The results of the questionnaire after implementing the automated natural ventilation system showed that more than 75% of the occupants in each zone felt they had little or no control over their thermal environments. This is despite the fact that several control options were provided and on several occasions occupants were told they could override the automatic control. A possible explanation for this was that the retrofitted system was a new system and occupants were unfamiliar with it. Therefore, it is necessary to conduct a questionnaire survey again to see if occupants’ perception regarding the controls has been improved after one year of intervention. Moreover, it is necessary to identify ways to increase the level of occupant engagement and awareness of the automated natural ventilation systems. This helps to improve occupants’ comfort and identify a balance between the automatic control, which is essential, and manual control strategies, which is desired, by the occupants.

Although introducing automatic controls considerably helped to reduce the risk of overheating, it slightly increased the risk of overcooling. This issue needs to be addressed. A possible solution for this problem is combining existing motorised ceiling tiles with a heat recovery system or to temper the air
which enters to the open plan office through the motorised ceiling tiles. The effects of this can be tested using CFD simulations.

Based on the results of actual building performance discussed in Section 8.3 and studies by Eftekhar and Marjanovic (2003), Darum (2004) and Calvino et al. (2004), it is expected that a better performance with more consistency can be achieved if existing rule based control strategies proposed in this study are combined with fuzzy logic systems. The control strategies developed in this study (Chapters 6 and 7) can be used as “fuzzy expert rules” in new fuzzy logic systems.

The control strategies and advanced natural ventilation systems developed in this study are capable of improving energy performance, indoor air quality and thermal comfort of/in non-domestic buildings such as offices and educational buildings. The system is expected to have better performance in buildings with high thermal mass since “pre-cooling” and “cool down” periods will be more effective in such buildings. This needs to be studied in more detail using either computer simulation or physical measurements.
References


References and publications


Chao, J., Mu,X., Xue, Y., Li, F., Li, W., Lin ,C-H.,Pei,J., and Chen,Q. 2014, A modified tracer-gas-concentration decay method for ventilation rate measurements in large, long, and narrow spaces, Indoor and Built Environment, 23, 1012-1020


References and publications


**Publications**

**Referred journal**


**Referred conferences**


Appendix A: Typical natural ventilation control strategies

The following section describes common control strategies that are proposed by different guidelines including CIBSE Guide H (2009) and BSRIA (1995).

Temperature based control strategies

In this control strategy internal and external temperatures regulate the position of openings, for this purpose the following parameters should be specified when temperature based control strategies are designed:

- Indoor air temperature set-point
- Maximum acceptable external wind speed
- Minimum acceptable indoor temperature (low temperature set-point)
- Minimum acceptable external temperature (low temperature set-point)

Figure A-1 describes the actions which should be followed to implicate a temperature based control strategy in a naturally ventilated building (Priolo, 2002). In this type of control strategy according to the internal temperature it is identified if it is necessary to activate natural ventilation or not, then based on external climatic condition (e.g. high or low external temperature) vents position is modified to protect the building from undesired climatic conditions.
Figure A-1: Temperature based control strategies control strategy
Appendix A

Indoor pollution based control strategies

In this method indoor air quality is measured by CO\textsubscript{2} and/ or air quality sensors. Comparisons of actual CO\textsubscript{2} or indoor air quality index and set-points, specifies the requirements for natural ventilation and natural ventilation is controlled by opening and closing regime of openings. Vent position could be modified based on external temperature, wind velocity/ direction or rain (Guarracino et.al 2003).

As a result of high cost of CO\textsubscript{2} sensors, in some projects infrared detectors are installed. Infrared detectors are cheaper and can operate by low power batteries removing the need for wiring; however, infrared sensors usually perform better in rooms with low occupancy variations (Guarracino et al. 2003). Heieslberg (2008) reported successful examples of applying infrared detectors instead of CO\textsubscript{2} sensors.

Temperature and CO\textsubscript{2} based control strategies

In this strategy, vents positions are specified based on both internal temperature and CO\textsubscript{2} concentration in a building and are modulated based on external weather condition (wind velocity, wind direction, external temperature, etc)(CIBSEGuideH, 2009).

Figure A-2 and Figure A-3 show control strategies that are usually used to control overheating and high CO\textsubscript{2} level. The first one is proposed by BSRIA, (1996) and the second one is suggested by CIBSE Guide H (2009). Both of them are similar and can be used for the purpose of natural ventilation. However, the proposed strategies by BSRIA (1995) (Figure A-2) is more likely to be used in hot seasons and pre-cooling (night cooling) option has been considered in this strategy; whereas CIBSE strategy (Figure A-3) can be used in both hot and cold seasons during occupied periods and night cooling has not been considered in it.
Figure A-2: BSRIA temperature and co2 level based control strategy (BSRIA, 1995)
Night cooling

Night cooling strategies take advantage of low night time external temperature. Since usually there are not any occupants in the building, there is lower risk of drought and occupants’ dissatisfaction due to high ventilation rate. However, control strategies should be designed in a way to minimize risk of overcooling and overheating for the next day. Security is another parameter which should be provided by applying night cooling control strategies (BSRIA, 1995 and BSRIA, 1998b).

The following algorithm (Figure A-4) is a classic night cooling strategy proposed by BSRIA (1998b).

Figure A-3: CIBSE temperature and CO₂ level based control strategy
Figure A-4: Classic night cooling control strategy
Advanced night cooling strategy based on internal heat gain of the building

This strategy is known as pre-cooling strategy and it is based on generated internal heat gain during daytime. In this method internal heat gain and requirement of night cooling are affected by the number of occupied hours during which internal temperature is above the internal temperature set-point. Ventilation is activated during night time until when internal temperature reaches to the specified internal temperature set-point and similar to previous control strategies, external weather conditions are used to modulate the opening positions. If night cooling is accompanied with mechanical ventilation the optimum usage of night cooling should also be considered (Figure A-5) (BSRIA, 1996).

Advanced night cooling strategy based on the thermal capacity of buildings’ fabrics

In advanced night cooling strategy external mean temperature is calculate between 12:00 to 17:00. In case, outside air temperature is above set-point, internal air temperature is higher than external air temperature and outside conditions (rain, wind speed and etc) are in favour, natural ventilation is activated to reach acceptable condition (Figure A-6) (BSRIA, 1995).
Figure A-5: Advanced night cooling control strategy 1 (BSRIA, 1995)
Figure A-6: Advanced night cooling control strategy 2 (BSRIA, 1995)
Appendix B: Building satisfaction questionnaire

Building satisfaction questionnaire which was distributed before intervention

<table>
<thead>
<tr>
<th>Personal Workspace</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. In a typical week, how many hours do you spend in your workspace?</td>
</tr>
<tr>
<td>☐ 10 or less</td>
</tr>
<tr>
<td>2. In which area of the building is your workspace located?</td>
</tr>
<tr>
<td>☐ Accounts</td>
</tr>
<tr>
<td>☐ Other, Please specify: .................................................</td>
</tr>
<tr>
<td>3. Are you near an exterior wall (within 4.5 meters)?</td>
</tr>
<tr>
<td>☐ Yes</td>
</tr>
<tr>
<td>4. Are you near a window (within 4.5 meters)?</td>
</tr>
<tr>
<td>☐ Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. How would you describe typical working conditions in the office in Winter?</td>
</tr>
<tr>
<td>☐ Too cold</td>
</tr>
<tr>
<td>☐ Uncomfortable during the day</td>
</tr>
<tr>
<td>☐ Interferes with your productivity</td>
</tr>
<tr>
<td>☐ Overall satisfaction</td>
</tr>
<tr>
<td>7. How would you describe typical working conditions in the office in Summer?</td>
</tr>
<tr>
<td>☐ Too hot</td>
</tr>
<tr>
<td>☐ Uncomfortable during the day</td>
</tr>
<tr>
<td>☐ Interferes with your productivity</td>
</tr>
<tr>
<td>☐ Overall satisfaction</td>
</tr>
<tr>
<td>8. Is the air movement in Summer too draughty?</td>
</tr>
<tr>
<td>☐ Yes</td>
</tr>
<tr>
<td>9. Air quality in Winter</td>
</tr>
<tr>
<td>☐ Very poor</td>
</tr>
<tr>
<td>☐ Very good</td>
</tr>
<tr>
<td>☐ Smelly</td>
</tr>
<tr>
<td>☐ Interferes with your productivity</td>
</tr>
<tr>
<td>☐ Overall satisfaction</td>
</tr>
<tr>
<td>10. Air quality in Summer</td>
</tr>
<tr>
<td>☐ Very poor</td>
</tr>
<tr>
<td>☐ Very good</td>
</tr>
<tr>
<td>☐ Smelly</td>
</tr>
<tr>
<td>☐ Interferes with your productivity</td>
</tr>
<tr>
<td>☐ Overall satisfaction</td>
</tr>
<tr>
<td>11. Noise level in Winter</td>
</tr>
<tr>
<td>☐ Very loud</td>
</tr>
<tr>
<td>☐ Soft</td>
</tr>
<tr>
<td>☐ Interferes with your productivity</td>
</tr>
<tr>
<td>☐ Overall satisfaction</td>
</tr>
<tr>
<td>12. Noise level in Summer</td>
</tr>
<tr>
<td>☐ Very loud</td>
</tr>
<tr>
<td>☐ Soft</td>
</tr>
<tr>
<td>☐ Interferes with your productivity</td>
</tr>
<tr>
<td>☐ Overall satisfaction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Which of the following do you personally adjust or control in your workspace? (check all that apply)</td>
</tr>
<tr>
<td>☐ Window</td>
</tr>
<tr>
<td>☐ Operable ceiling tile</td>
</tr>
<tr>
<td>☐ Portable heater</td>
</tr>
<tr>
<td>☐ Portable fan</td>
</tr>
<tr>
<td>☐ Door to interior space</td>
</tr>
<tr>
<td>☐ Other, Please specify: .................................................</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>General Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. Please estimate how your job performance is increased or decreased by the environmental conditions in this building (e.g., thermal, lighting, acoustics, cleanliness):</td>
</tr>
<tr>
<td>Decreased:</td>
</tr>
<tr>
<td>9. Please provide any additional comments or recommendations about your personal workspace or building overall:</td>
</tr>
</tbody>
</table>
Appendix B

Building satisfaction survey which was distributed after intervention: Please note that although layout of the open plan office remained the same occupants of R&D were replaced with occupants of marketing and maintenance. For this reason in this questionnaire R&D area changed to maintenance and marketing.
Appendix C: Different construction types used in the IES model

This appendix illustrates construction types that were defined in the IES simulations. In this table relevant construction types are highlighted by red lines.

Table C-1: External wall and ground floor types

<table>
<thead>
<tr>
<th>Type 1:</th>
<th>Type 2:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External wall</strong></td>
<td><img src="image1" alt="Type 1: External wall" /></td>
</tr>
<tr>
<td><strong>Ground</strong></td>
<td><img src="image3" alt="Type 1: Ground" /></td>
</tr>
</tbody>
</table>
Table C-2: Internal partition and ceiling/floor types

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Type 1:</th>
<th>Type 2:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal partition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal ceiling/floor</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Appendix C
Appendix D: Details of calculated PPD and P values for different zones of the case study building before intervention

Figure D-1: PPD values which were calculated based on heat balance approach (before intervention)

Figure D-2: RHs that were used in calculation of PPD
Figure D-3: P Values which were calculated based on adaptive approach (before intervention)
Appendix E: Manual controls tested by DTS models

Manual controls and occupants’ adaptive actions, such as opening and closing windows, have a direct impact on the overall energy consumption of buildings (Roaf et al., 2009). Results of Menezes et al. (2012) studies (reviled that occupants behaviour in general and application of manual control in particular is one of the main causes of discrepancies between the results of physical measurements and simulations. Based on the observation and results of Griffiths and Eftekhar (2008) studies occupants are usually unaware of CO₂ concentration and usually open the windows based on thermal discomfort. For this reason for purpose of this study, it was assumed that occupants open the windows based on thermal discomfort. Traditionally, in the field of building simulation, fixed schedules are defined for window opening and closing patterns often based on differences between internal and external temperature, to represent occupants’ behaviour in naturally ventilated buildings (Borgeson and Brager, 2008). In recent years, a number of factors have been identified as important issues for determining occupants’ manual control in naturally ventilated buildings which were discussed in chapter 2. The only zones of the building in which occupants have some sort of control over temperature are the open plan office, the training room and the kitchen (Figure 3-2). As the kitchen is usually used for short periods only, occupants’ behaviour in the kitchen does not have a significant effect on the building’s total heating energy consumption and thermal behaviour and considering size of training room (4% of total floor area), effects of applying more advanced manual control strategies in open plan office were tested. It should be noted that test scenarios defined based on observation and literature review. Table E-1 summarises the tested options and Figures E-1 and E-2 shows the effect of applying tested options on risk of thermal discomfort and heating energy consumption.
Appendix E

Table E-1: Tested manual control options

<table>
<thead>
<tr>
<th>Test No</th>
<th>Control</th>
<th>Reference</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC1</td>
<td>Ta&gt;24 °C fully open the windows</td>
<td>As suggested by Haldi and Robinson (2008) occupants open the windows when they feel thermally uncomfortable. 24°C is specified based on calculated comfortable temperature for the CSB (Khatami et al., 2011) and actual behaviour of occupants in CSB</td>
<td>Lower risk of thermal discomfort Higher energy consumption</td>
</tr>
<tr>
<td>MC2</td>
<td>Windows linearly open when internal air temperature is in range of 24 °C to 27 °C</td>
<td>To minimise above mentioned problematic impacts as suggested by Marjanovich (2002) fuzzy logic affected</td>
<td>More realistic results but, higher energy consumption and lower risk of thermal discomfort in winter</td>
</tr>
<tr>
<td>MC3</td>
<td>Winter (Jan to March &amp; October to Dec): Windows linearly open when internal air temperature is in range of 24 °C to 28 °C Summer (April to September): Windows linearly open when internal air temperature is in range of 24 °C to 27 °C</td>
<td>As suggested by Rijal et al. (2008) and Borgerson and Brager (2008) occupants opened the windows differently during summer and winter</td>
<td>High risk of energy consumption and lower risk of thermal discomfort during mid-season</td>
</tr>
<tr>
<td>MC4</td>
<td>Winter (Jan to Feb &amp; Nov to Dec): Windows linearly open when internal air temperature is in range of 24 °C to 28 °C Summer (May to September): Windows linearly open when internal air temperature is in range of 24 °C to 27 °C Spring Autumn: (March to April &amp; October) If external temperature =&gt;18°C Windows linearly open when internal air temperature is in range of 24 °C to 27 °C If external temperature &lt;18 °C Windows linearly open when internal air temperature in range of 24 °C to 28 °C</td>
<td>As suggested by Rijal et al. (2008) and during midseason windows more likely to be open and closed and depending on therefore, a new series of control proposed during mid-season in which based on external temperature it is assumed to open de building based on winter or summer schedule Midseason set point was specified as 18 °C (Aggerholm, 2003 and Fitzgerald, 2006)</td>
<td>Acceptable results but slightly lower risk of thermal discomfort</td>
</tr>
<tr>
<td>MC5</td>
<td>Same as MC4 but if To &lt;10 °C or external wind velocity &gt; 8 m/s close the windows</td>
<td>According to Haldi and Robinson (2008) occupants open the windows when they fell thermally uncomfortable and close it in case of feeling draft or cold temperature. In this series it is assumed that if wind velocity is higher that 8m/s (BSRIA, 2009) windows or external temperature is less than 10°C (Fordham, 2000) occupants will close the windows</td>
<td>it provided more acceptable results and was used as base case model</td>
</tr>
</tbody>
</table>
Appendix E

Figure E-1: Effects of tested manual control options on risk of overheating in open plan office

Figure E-2: Effects of tested manual control options on heating energy consumption
Appendix F: Temperature based control strategies with combined operating regimes

Based on the results of the section 7.4, it was be concluded that by applying different control strategies through a working day makes it possible to reduce risk of overheating in hotter days by early opening the vents and prevent risk of overcooling by delaying in opening the vents during moderate and cold day therefore series of simulations were conducted in which operating hours tested in section 7.4.2 combined and following operating hours were applied into each model:

Table F-1: Operating hours in model with combined operating strategies

<table>
<thead>
<tr>
<th>Operating hours</th>
<th>Low level openings</th>
<th>High level openings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night cooling</td>
<td>Only operated during summer mode (e.g.(T_o&gt;18^\circ C)) and due to the security reasons maximum free areas limited to 10%</td>
<td>Only operated during summer mode (e.g.(T_o&gt;18^\circ C)) and due to the location of vents security reasons did not cause any restrictions</td>
</tr>
<tr>
<td>Pre-cooling</td>
<td>During Summer mode (e.g.(T_o&gt;18^\circ C)) operated normally. Due to the high risk of overheating even during cold and moderate seasons (e.g.(T_o&lt;18^\circ C)) minimum ventilation was provided(^{20})</td>
<td>During Summer mode (e.g.(T_o&gt;18^\circ C)) operated normally. Due to the high risk of overheating even during cold and moderate seasons (e.g.(T_o&lt;18^\circ C)) minimum ventilation was provided</td>
</tr>
<tr>
<td>Heat up</td>
<td>CO(_2) control + During Summer mode (e.g.(T_o&gt;18^\circ C)) operated normally. Due to the high risk of overheating even during cold and moderate seasons (e.g.(T_o&lt;18^\circ C)) minimum ventilation was provided</td>
<td>CO(_2) control + During Summer mode (e.g.(T_o&gt;18^\circ C)) operated normally. Due to the high risk of overheating even during cold and moderate seasons (e.g.(T_o&lt;18^\circ C)) minimum ventilation was provided</td>
</tr>
<tr>
<td>Full occupancy</td>
<td>CO(_2) control + temperature control operate normally</td>
<td>CO(_2) control + temperature control operate normally</td>
</tr>
<tr>
<td>Cool-down</td>
<td>During Summer mode (e.g.(T_o&gt;18^\circ C)) operated normally. Due to the high risk of overheating even during cold and moderate seasons (e.g.(T_o&lt;18^\circ C)) minimum ventilation was provided</td>
<td>During Summer mode (e.g.(T_o&gt;18^\circ C)) operated normally. Due to the high risk of overheating even during cold and moderate seasons (e.g.(T_o&lt;18^\circ C)) minimum ventilation was provided</td>
</tr>
<tr>
<td>Night cooling</td>
<td>Only operated during summer mode (e.g.(T_o&gt;18^\circ C)) and due to the security reasons maximum free areas limited to 10%</td>
<td>Only operated during summer mode (e.g.(T_o&gt;18^\circ C)) and due to the location of vents security reasons did not cause any restrictions</td>
</tr>
</tbody>
</table>

\(^{20}\) Minimum ventilation Set-points and free areas were specified according to winter mode (refer to equation 7-1 and 7-2)
Table F- 2: Results of models with combined operating strategies

<table>
<thead>
<tr>
<th>Assessment criteria</th>
<th>SP20</th>
<th>SP21</th>
<th>SP22</th>
<th>SP23</th>
<th>SP24</th>
<th>SP25</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CIBSE Guide A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of occupied hours Tc &gt;25°C</td>
<td>3.15</td>
<td>3.23</td>
<td>3.23</td>
<td>4.60</td>
<td>5.13</td>
<td>38.73</td>
</tr>
<tr>
<td>% of occupied hours Tc &gt;28°C</td>
<td>0.52</td>
<td>0.56</td>
<td>0.52</td>
<td>0.56</td>
<td>0.56</td>
<td>0.77</td>
</tr>
<tr>
<td>Tc Maximum (°C)</td>
<td>29.81</td>
<td>29.84</td>
<td>29.85</td>
<td>29.88</td>
<td>29.89</td>
<td>29.96</td>
</tr>
<tr>
<td><strong>BS EN 15 92</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of occupied hours Tc &amp; T&lt;sub&gt;comfort&lt;/sub&gt;+3 or &amp; T&lt;sub&gt;comfort&lt;/sub&gt;-3</td>
<td>8.19</td>
<td>3.19</td>
<td>2.02</td>
<td>2.02</td>
<td>2.06</td>
<td>5.69</td>
</tr>
<tr>
<td>° hrs cold period based on T&lt;sub&gt;comfort&lt;/sub&gt;</td>
<td>30.02</td>
<td>12.20</td>
<td>7.03</td>
<td>6.65</td>
<td>6.35</td>
<td>6.20</td>
</tr>
<tr>
<td>° hrs warm period based on T&lt;sub&gt;comfort&lt;/sub&gt;</td>
<td>9.79</td>
<td>10.30</td>
<td>10.31</td>
<td>10.90</td>
<td>11.17</td>
<td>40.00</td>
</tr>
<tr>
<td><strong>CIBSE Guide F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating Energy Consumption (kWh/m²/year)</td>
<td>28.93</td>
<td>26.87</td>
<td>26.00</td>
<td>25.6</td>
<td>25.5</td>
<td>25.2</td>
</tr>
<tr>
<td><strong>Overall Pass/Fail</strong></td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>F</td>
</tr>
</tbody>
</table>
Appendix G: Brochure of NVLogIQ

NV LogIQ™ Room Controller

Features:
The NV LogIQ™ Room Controller has been designed to offer an effective, efficient and user-friendly solution for adaptive natural ventilation applications that is easily integrated into a new or refurbished building.

The NV LogIQ™ Room Controller can be used as a standalone system or networked to give individual room control with global common signals such as wind, rain and security closing.

All within a small wall-mounted enclosure, the NV LogIQ™ Room Controller has integrated sensors, switches and a backlit LCD display that offers the following facilities without the need for separate sensors within the room:

- CO2 monitoring and level display
- Temperature monitoring and level display
- Humidity monitoring and level display
- User control via inbuilt switches with ten increments of operation
- Output signal for external devices such as central heating control etc.
- Lock out function to prevent misuse
- Time clock for strategy and security closing
- Vent position/open output signal
- Fresh air ‘morning start’ setting
- Intuitive menu for setpoint adjustment via a security dongle
- Continuous data logging for performance analysis

The NV LogIQ™ Room Controller is supplied with a pre-programmed natural ventilation control algorithm developed in partnership with Loughborough University’s Building Energy Research Group.

Applications

The strategy was formulated by modelling hundreds of comparable scenarios in both education and commercial buildings in conjunction with industry-recognized methods and data collected from natural ventilation projects installed over several years by SE Controls.

Requirements for regulations such as BB101 (internal environment for schools) and CIBSE Guides A have heavily influenced the design of the algorithms.

Dynamic Thermal Simulation models (DTS) and Computational Fluid Dynamics (CFD) were used to analyse the effectiveness and efficiency of the algorithm.

The system controls room CO2 levels to a variable profile ensuring that Indoor Air Quality (IAQ) is optimised. The temperature control strategy increases the ventilation rate before internal temperature escalates and becomes uncontrollable. There are multiple temperature control strategies based on external temperature, and occupancy, which provide appropriate temperature control throughout the year.

A night purge strategy cools the building for a fresh start and can provide prolonged daytime cooling in buildings with sufficient thermal mass.

All settings are adjustable from standard or after the initial ‘learning’ period of occupancy.

Data logging is essential for pre or post occupancy performance analysis; the controller is capable of 3 months’ recording of sensor readings and operation signals, and is downloadable using a dongle.

Version 2.1

Tel: +44 (0)1543 44 30 60  www.secontrols.com  Fax: +44 (0)1543 44 30 70
Appendix G

**NV LogIQ™ Room Controller**

**Technical Data**

- **Power**: 24v DC
- **Supply**: 0-10v and O5Link
- **Output**: 0-10v and O5Link
- **Real time clock battery average life 10 years**
- **Environment**
  - **Rating**: IP20
  - **Humidity Range**: 10 to 90% non-condensing
  - **Storage**: -20 to +50°C
  - **Operating temp**: -10 to +50°C
- **Miscellaneous**
  - **Dimensions**: 160 x 105 x 37 mm
  - **Dia**: 20mm top entry with cap and 58mm x 36mm rear entry

**NV LogIQ™ with CO2**

- **Part Number**: NCS 0001 0001

**NV LogIQ™ without CO2**

- **Part Number**: NCS 0001 0002

*CE CERTIFIED*

Compliant to applicable regulations.
Appendix H: Effects of introducing control strategies with minimum fixed free area of 5%

Results of DTS models:
This section compares the results of the case study building performance before intervention (results of section 4), optimum and actual designs. Optimum design was developed based on the findings of this study in Chapters 5, 6 and 7, natural ventilation strategy developed based on Roofvent option Scenario 3 (Chapter 5), \(\text{CO}_2\) based control strategies specified based on 2S. SR. FFA-0.8% (Chapter 6) and temperature based control strategies were defined based on COMBINATION SP22 (Appendix F). In the practical design, due to practical limitations some modification were made on optimum design, control strategies defined based on described control strategies in Appendix F and ventilation strategies specified based on Roofvent option Scenario 3.

Table H-1: Results of computer simulation for building performance before intervention, optimum design and practical design

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Before intervention</th>
<th>Optimum</th>
<th>practical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open plan office</td>
<td>Training room</td>
<td>Open plan office</td>
</tr>
<tr>
<td>Thermal comfort</td>
<td>% of occupied hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_c&gt;25^\circ\text{C})</td>
<td>28.8% 8.8%</td>
<td>3.2% 2.2%</td>
<td>3.8% 2.7%</td>
</tr>
<tr>
<td>% of occupied hours (T_c) is not in the range of calculated (T_{\text{comf}} \pm 3^\circ\text{C})</td>
<td>11.1% 17.5%</td>
<td>4.9% 11.7%</td>
<td>6.3% 13%</td>
</tr>
<tr>
<td>IAQ</td>
<td>% of occupied hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{CO}_2&gt;1000\text{ppm})</td>
<td>0.1% 68.5%</td>
<td>7% 30%</td>
<td>4% 25%</td>
</tr>
<tr>
<td>% of occupied hours (\text{CO}_2&gt;1200\text{ppm})</td>
<td>0% 65%</td>
<td>0% 4.2%</td>
<td>0% 3.5%</td>
</tr>
<tr>
<td>% of occupied hours (\text{CO}_2&gt;1500\text{ppm})</td>
<td>0% 49%</td>
<td>0% 0.01%</td>
<td>0% 0%</td>
</tr>
<tr>
<td>Energy</td>
<td>Total (kWh/m²/year)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>169.1</td>
<td>156</td>
<td>158.2</td>
</tr>
</tbody>
</table>
Results of CFD models:

This CFD models were run to study the effects of introducing 5% free area on draught and internal temperature for this reason two sets of model were set. Boundary and initial conditions were almost the same but in the first series it was assumed that radiators were operating and in the second series it was assumed that internal temperature reached to 20 °C (heating set-point) and radiators were not operating, following assumptions were also made in both models:

- External temperature= 10°C as temperature control lower limit
- Wind velocity= 8 m/s as maximum acceptable velocity
- Wind direction= 22 from north as wind direction which creates the maximum $\Delta C_p$ between low level openings and roof vents
- Free area= 5% of total opening size as minimum free area which could be sent to the actuators by power supply.

As shown in both models air speeds never exceed 0.3m/s. According to CIBSE guide A (2006), air speed of 0.3 m/s is acceptable and there is less likely to cause draught
5% opening, CO\textsubscript{2} control, heating on

Figure H-1: CFD results for model with minimum 5% free area (when heating system assumed to be on)
Figure H-2: CFD results for model with minimum 5% free area (when heating system assumed to be off)
Appendix I: Details of calculated PPD and P values for different zones of the case study building after intervention

Figure I-1: PPDs which were calculated based on heat balance approach (after intervention/manual control)

Figure I-2: RHs that were used in calculation of PPDs

Figure I-3: P values which were calculated based on adaptive approach (after intervention/manual control)
Figure I-4: PPD s which were calculated based on heat balance approach (after intervention/automatic control)

Figure I-5: RHs that were used in calculation of PPD

Figure I-6: P values which were calculated based on adaptive approach (after intervention/manual control)