# CONTROL OF $CO_2$ CONCENTRATION IN EDUCATIONAL SPACES USING NATURAL VENTILATION

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## ABSTRACT

This paper reports on research carried out to develop natural ventilation control strategies for densely occupied learning spaces with the intention of improving indoor air quality and heating energy consumption. Investigations were carried out for two test cases according to the characteristics given in CIBSE Guide A (2006) and Building Bulletin (BB) 101 (Department for Education, 2006). The performance of these test cases were assessed using dynamic thermal simulation with fixed $CO_2$ set-points, based on which opening dampers are controlled. Improvements to the control strategy are then proposed. The results show that acceptable indoor air quality can be achieved in almost all cases by adopting typical, traditional control strategies. However, energy consumption can be reduced further by applying more advanced control strategies which use two $CO_2$ set-points to regulate the opening sizes in a non-linear, but stepwise manner. Simulation results predict savings in heating energy consumption of at least 30%.

**Key words**: natural ventilation, educational spaces, $CO_2$ concentration control, dynamic thermal simulation, indoor air quality, energy

## 1. Introduction

High running costs of mechanical ventilation in buildings is one of the main reasons which encourage building owners and operators to consider natural ventilation. 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.

According to BB87 (Department for Education, 2003) $CO_2$ concentration can be used as an indicator of Indoor Air Quality (IAQ). $CO_2$ levels in a naturally ventilated building can be controlled either automatically or manually. Results from studies by Griffiths and Eftekhari (2008) and Khatami *et al* (2011) suggest that occupants are often unaware of $CO_2$ levels, and for this reason it is not recommended that $CO_2$ concentration is controlled manually by occupants. Hence introducing automatic control of $CO_2$ concentration in a densely occupied space is often necessary to provide acceptable IAQ. Traditionally, in the control industry, $CO_2$ levels in an occupied space are detected by sensors and, if $CO_2$ levels are greater than the set-point, vents open allowing external air to enter the space until the $CO_2$ level falls below the set-point (CIBSE Guide H, 2009).

In contrast to mechanical ventilation in which ventilation demand can be determined based on occupancy level and easily modulated (Emmerich and Persily, 2001), in naturally ventilated buildings the ventilation performance (and flow rate) are highly influenced by opening sizes. Therefore, to identify optimum natural ventilation control strategies that maintain acceptable IAQ and minimize energy consumption, it is important to understand the effects on the $CO_2$ control of the set-points and the opening area of the vents.

The results of Dounis et al. (1996) and follow up studies of Kolokosta (2003) showed that due to the complexity of natural ventilation, fuzzy control is able to provide an acceptable solution for controlling $CO_2$ concentration in naturally ventilated buildings. According to Shepherd and Batty (2003), fuzzy logic is more beneficial in systems with multivariable input such as internal and external temperature, $CO_2$ level and humidity. For this reason fuzzy logic and rule-based controls are more effective than classical proportional-integral-derivative (PID) controls.

Dounis et al. (1996), Kolokosta (2001), Kolokosta (2003), Jaradat and Al-Nimr (2009) and Hellwig (2010) studied the effect of introducing different $CO_2$ fuzzy control into naturally ventilated buildings. In all these studies, room $CO_2$ concentration was used as the input to a fuzzy controller, and opening area or fan rotation speed were defined as the output of the fuzzy controller. Results of Dounis et al (1996) used simulation to demonstrate the capability of such a system to provide acceptable IAQ. The findings of Kolokosta (2001) showed that fuzzy logic is capable of providing acceptable IAQ. However, in this study and follow up studies by Kolokosta (2003) it is suggested that applying mechanical ventilation during extreme climatic conditions such as winter could be more energy efficient and natural ventilation strategies should only be used during temperate conditions. Results of a study by Hellwig (2010) on the application of $CO_2$ control in an educational space demonstrated unacceptably low temperatures during winter, suggesting that free areas were too large or radiators were not operating as expected.

A further issue to consider, in terms of providing acceptable $CO_2$ control, is the ability of the control strategy to provide stability of opening area (Dounis *et al*. 1996). As the $CO_2$ concentration is very responsive to the flow rate, providing very low or high flow rates can lead to rapid fluctuations of $CO_2$ levels and consequently a higher risk of hunting, whereby opening areas change rapidly leading to poor control and deterioration of components.

Although several studies have been conducted in order to test different $CO_2$ control strategies, high energy consumption or poor performance of proposed $CO_2$ control strategies during extreme external conditions have raised questions over what can be done to improve the performance of the control strategies in order to reduce energy consumption. To minimise the complexity of control strategies and to study the direct effect of inputs (set-points) and outputs (free areas) on IAQ and energy consumption, in this work, the effect of applying control strategies with fixed $CO_2$ set-points and free areas was studied in each set of scenarios.

The aim of this study was to investigate the performance of various $CO_2$ based natural ventilation control strategies that maintain acceptable IAQ whilst minimising heating energy consumption.

Simplified $CO_2$ control strategies were tested using dynamic thermal simulation (DTS) for two configurations: a densely occupied seminar room; and a classroom. The physical characteristics of the spaces were based on a case study building and information in CIBSE Guide A (2006) and BB101 (Department for Education, 2006). Free areas of ventilation openings were specified based on recommended free areas in BB101, CIBSE Application Manual AM10 (2005) and CIBSE Guide B (2005). Using DTS tools the performance of each proposed option was assessed against BB101 (Department for Education, 2006) criteria for IAQ, i.e. $CO_2$ concentration levels.

The paper is structured into seven sections. The second section describes the case study building, the third section details the methodology used and the simulation results using the typical control strategies are discussed in the fourth section. Results of simulations which used minimum acceptable free areas and maximum acceptable set-points, are presented in the fifth section. The sixth section presents the results obtained using the refined control strategies. All refined control strategies were intended to provide acceptable IAQ while reducing energy consumption. Finally, the conclusions of the study are given in the seventh section.

## 2. Description of the case study building

The case study building (Figure 1) is a retrofitted lightweight two-storey office and warehouse in the West Midlands, UK. For the purpose of this study, one zone of the building (Training Room) was considered as an educational space (Figure 1-c). The main entrance to the building points 22° clockwise away from north. Accommodation on the ground floor comprises a training room, warehouse, toilets and kitchen (Figure 1-c) and an open plan office space is located on the first floor (Figure 1-d). Average external wall and roof U-values for the building are estimated as $0.36 W/m^2K$ and $0.49 W/m^2K$ respectively. The total floor area of the case study building is 1100 $m^2$.

The total floor area of the training room is $47.7m^2$. Four top hung openable windows (each 1m×1m) with a sill height of 0.95m are located on the north west and west north west facades of the room. The maximum opening angle of these windows is 20°. The training room is connected to the warehouse via one internal wall and to a corridor from the second internal wall (Figure 1-c and Figure 2).

Natural ventilation is provided by top hung windows in the training room, kitchen and open plan office. These are located on the north, north-east and north-west facades. Ventilation is enhanced in the open plan office by a balanced supply and extract system with a capacity of 0.9 $l/s/m^2$. Solar control is provided by internal vertical fin translucent blinds on all windows. Gas-fired central heating through wall-mounted radiators heats the building between 06:00 and 18:00 Monday to Friday with a set-point of 20°C.


**Figure 1:** *a) Case study building; b) building in relation to its surrounding; c) ground floor plan; and d) first floor plan*

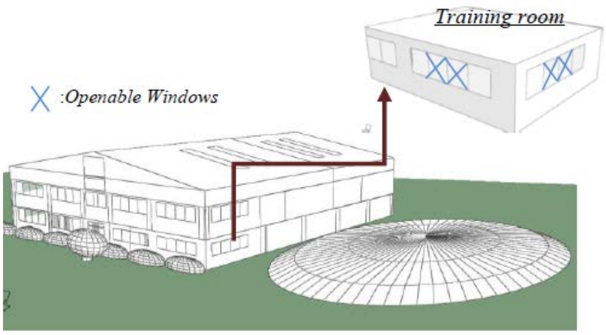


**Figure 2:** *3D model of the case study building and training room*

## 3. Methodology

Dynamic thermal simulations (DTS) of the building were conducted using Integrated Environmental Solutions Virtual Environment software (IES-VE, 2011). The Test Reference Year weather data for Birmingham 2005 (CIBSE, 2008) was used.

Heat gain assumptions for the space are based on typical values for educational spaces given in CIBSE Guide A (2006). Two heat gain scenarios were considered as shown in *Table 1*. Throughout this paper, these are referred to as a "seminar room configuration" and a "classroom configuration". All other physical and geometrical properties of the two scenarios remain identical. In each case, a total heat gain of 90W is assumed for each occupant.

The occupancy profile was derived from information provided in BB101 which states that spaces should be modelled as fully occupied from 9:00 to 15:30 Monday to Friday.

***Table 1****: Internal heat gain of case study spaces*

| Room configuration | People ($m^2$/person) | Lighting ( $W/m^2$) | Equipment ( $W/m^2$) | Total | |
|---|---|---|---|---|---|
| | | | | ($W/m^2$) | ( W) |
| **Seminar room** | 3 = (16 occupants) | 12 | 5 | 47 | 2242 |
| **Classroom (teaching space)** | 1.5 =(32 occupants) | 12 | 10 | 77 | 3674 |

The discharge coefficient for the four windows and the air infiltration of the room were assumed to be 0.62 (Application Manual AM10 2005) and 0.25ac/hr (equivalent to 10 $m^3/(h.m^2)$@50 Pa) specified in CIBSE guide A (2006), respectively.

The BB101 criteria were used in this study as the assessment method for IAQ. According to BB101, the following criteria regarding $CO_2$ 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; NS*
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 BRECSU (2000). Typical heating and hot water energy consumption for this type of building is specified as 79 $kWh/m^2$.

Three typical control strategies referred to as Group A, Group B and Group C (Table 2) were investigated to represent commonly used strategies in buildings of this type. For each group a range of parameter variations were tested. Based on the results of these typical strategies, two refined control strategies were tested (Group 1S and Group 2S).

The typical control strategies used two $CO_2$ set-points (1000ppm and 1200ppm). The value of 1000ppm is based on BB101 criteria and the results of a study by Santamouris et al. (2008). The value of 1200ppm is based on ASHRAE Standard 62.1.2010 (ASHRAE, 2010) in which 1200ppm is considered as the higher acceptable $CO_2$ 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 3).

The following sections describe the control parameters for each of the three typical and two refined control strategies.

**Group A**

In Group A, a maximum free opening area is specified based on rules of thumb given in BB101 which state that the minimum areas for worst-case scenario summer time ventilation for both temperature and $CO_2$ control, is approximately 5% and 2% of floor area in single-sided and cross ventilated rooms, respectively. In the test room under investigation windows are located on one side only; maximum free areas were therefore set to 5% of the floor area. The control strategies used are illustrated in Figure 3.

**Group B**

Group B represents another common practice approach for $CO_2$ based control. A single set-point is defined, similarly to group A (see Figure 3). When this set-point is reached the 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. One reason for this simulation study is to assess whether, in densely occupied spaces such as teaching spaces (classroom configuration in this work), such a small free area can meet BB101 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:

$$Q_{\text{(seminar room)}} = \frac{16 \times 10\ \frac{l}{s}/person}{1000} = 0.16\ (m^3/s) \quad \textbf{(Eq.1)}$$

$$C_d\ A_{\text{(seminar room)}} = Q\sqrt{\frac{Ti+273}{\Delta T\ gh}} = 1.3\ (m^2) \quad \textbf{(Eq.2)}$$

$A_{\text{(seminar room)}}$ =2.1 m² (=4.4% of floor area)

Similarly, the required free area in the classroom configuration was 4.2m$^2$ (8.8% of floor area). The control strategies used are illustrated in Figure 3.

**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 free opening 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 no longer met the BB101 requirements in terms of acceptable IAQ.

**Group 2S**

Group 2S contained the refined strategies based

*Table 2*: *Control strategy groups*

| Type | | Description | Opening sizes |
|---|---|---|---|
| Typical | Group A | Constant opening area during occupied period when $CO_2$ exceeds 1000ppm or 1200ppm. | Maximum opening area is 5% of the floor area (BB101) |
| | Group B | Constant opening area during occupied period when $CO_2$ exceeds 1000ppm or 1200ppm. | Maximum opening area is 1.5% of the floor area (30% of BB101) |
| | Group C | Constant opening area during occupied period when $CO_2$ exceeds 1000ppm or 1200ppm. | Maximum opening area is 4.4% (seminar room) and 8.8% (classroom) of the floor area (AM10) |
| Refined | Group 1S | Opening area during occupied periods is determined by those CO2 set-points from groups A, B and C which gave the best results for IAQ and energy. 1S indicates one-step control. | Opening area is 1.9% to 5% of the floor area |
| | Group 2S | Opening area during occupied periods is determined by those CO2 set-points from groups A, B, C and 1S which gave the best results for IAQ and energy. 2S indicates two-step control. | Opening area is 0.2% to 5.5% of the floor area |

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, the effects of two set-points and two free areas were studied.

## 4. Results for typical control strategies (groups A, B and C)

### 4.1. Seminar room configuration

Table 3 summarises the effect of applying the typical control strategies in the seminar room configuration.

The results of the seminar room simulation showed that acceptable IAQ was achieved in all Group A simulations. $CO_2$ levels rapidly increase as occupants enter the room and rapidly fall when vents open, since opening areas are large in comparison to the floor area. These scenarios led to a consequential increase in heating energy consumption and hunting effect.

Group B simulations did not deliver acceptable IAQ with daily average $CO_2$ 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 because 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 Group C was at least 21% higher than the heating energy consumption benchmark of 79 kWh/m$^2$/year for good practice buildings (BRECSU, 2000).

### 4.2. Classroom configuration

Simulation results of Group A control strategies for the classroom configuration are similar to the seminar room results. When higher set-points are used (e.g. 1200ppm in case A-1), the control strategies could not provide acceptable IAQ (Table 4). When lower set-points (e.g. 1000ppm) are used, acceptable IAQ is achieved; however, heating energy consumption in all group A cases is high in comparison to the typical heating energy consumption proposed in BRECSU (2000). 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 3 and Table 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 Group B strategies, energy consumption was considerably higher for Group C. For 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 3:** *Results for typical control strategies in seminar room*

| ref | | Set-point (ppm) | Free area (% of floor area) | Heating energy consumption (kWh/year/m$^2$) | BB101 Criteria for IAQ, Pass (Y) or Fail (N) | Average $CO_2$ level (ppm) | Maximum daily average $CO_2$ level (ppm) |
|---|---|---|---|---|---|---|---|
| BB101 method | A-1 | 1200 | 5 | 139 | Y | 863 | 1284 |
| | A-2 | 1000 | 5 | 163 | Y | 769 | 1139 |
| | A-3 | 1200 | 5 | 122 | Y | 817 | 1128 |
| | | 1000 | 2.5 | | | | |
| Common practice | B-1 | 1200 | 1.5 | 66 | N | 957 | 1604 |
| | B-2 | 1000 | 1.5 | 75 | N | 891 | 1567 |
| | B-3 | 1200 | 1.5 | 64 | N | 914 | 1581 |
| | | 1000 | 0.75 | | | | |
| AM 10 method | C-1 | 1200 | 4.4 | 116 | Y | 883 | 1309 |
| | C-2 | 1000 | 4.4 | 140 | Y | 813 | 1132 |
| | C-3 | 1200 | 4.4 | 100 | Y | 838 | 1143 |
| | | 1000 | 2.2 | | | | |

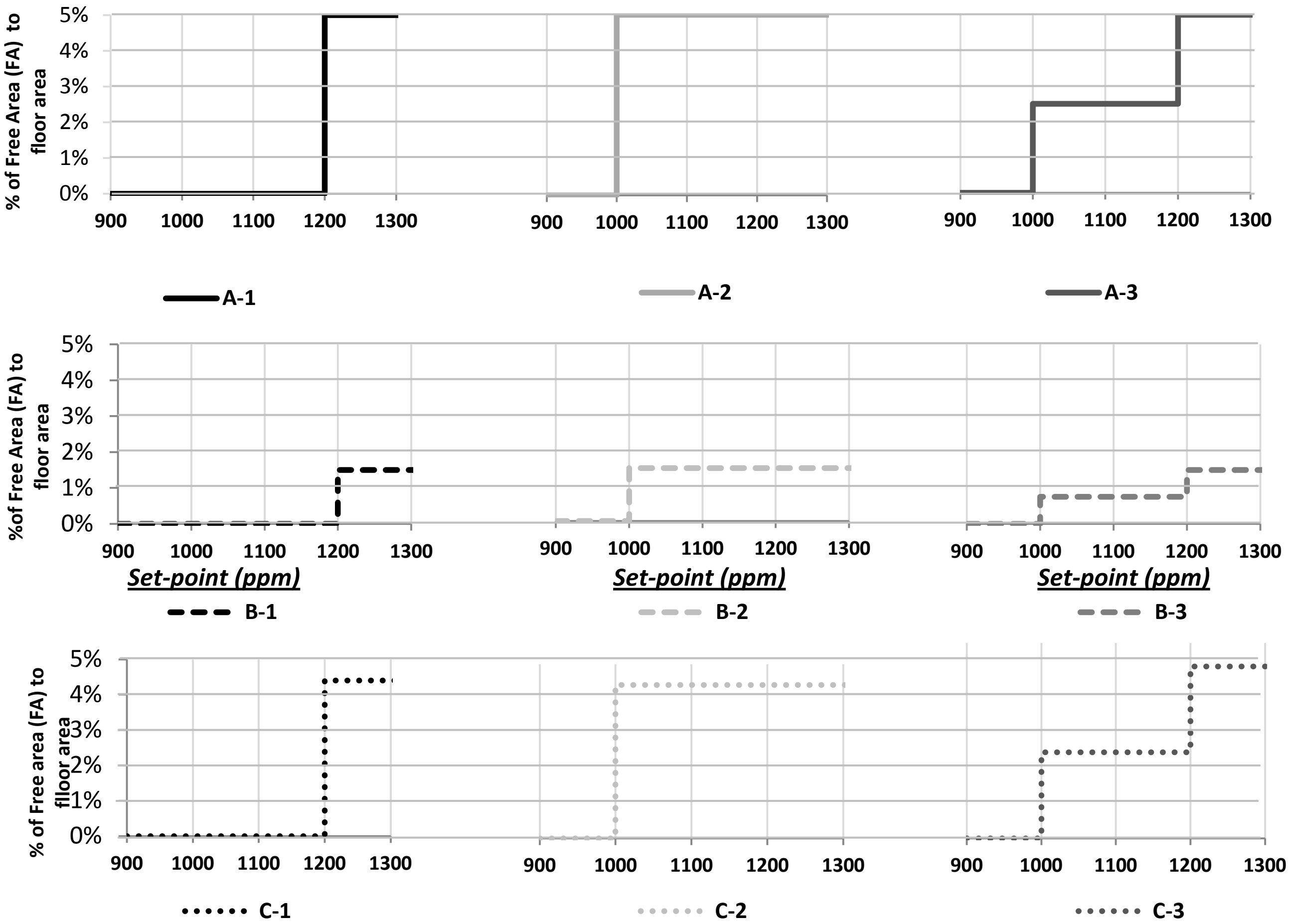


***Figure 3**: Typical control strategies in seminar room*

**Table 4:** *Results for typical control strategies in classroom*

| ref | | Set-point (ppm) | Free area (% of floor area) | Heating energy consumption (kWh/year/m$^2$) | BB101 Criteria for IAQ, Pass (Y) or Fail (N) | Average $CO_2$ level (ppm) | Maximum daily average $CO_2$ level (ppm) |
|---|---|---|---|---|---|---|---|
| BB101 method | A-1 | 1200 | 5 | 172 | N | 1068 | 1548 |
| | A-2 | 1000 | 5 | 184 | Y | 1023 | 1372 |
| | A-3 | 1200 | 5 | 169 | Y | 1015 | 1363 |
| | | 1000 | 2.5 | | | | |
| Common practice | B-1 | 1200 | 1.5 | 88 | N | 1212 | 2618 |
| | B-2 | 1000 | 1.5 | 93 | N | 1155 | 2619 |
| | B-3 | 1200 | 1.5 | 87 | N | 1157 | 2619 |
| | | 1000 | 0.75 | | | | |
| AM 10 method | C-1 | 1200 | 8.8 | 246 | Y | 810 | 1147 |
| | C-2 | 1000 | 8.8 | 281 | Y | 752 | 1021 |
| | C-3 | 1200 | 8.8 | 230 | Y | 766 | 1045 |
| | | 1000 | 4.4 | | | | |

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

High heating energy consumption in both seminar room and classroom configurations suggested that the maximum free areas used in groups A and C were too large for the purpose of controlling $CO_2$, 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.

***Table 5**: Results showing the effect of one-step control strategy in seminar room configuration (Group 1S)*

| | Ref | Set-point (ppm) | Free area (% of floor area) | Heating energy consumption (kWh/year/$m^2$) | BB101 Criteria for IAQ, Pass (Y) or Fail (N) | Average $CO_2$ level (ppm) | Maximum daily average $CO_2$ level (ppm) |
|---|---|---|---|---|---|---|---|
| **Effect of FA[1]** | 1S.SR.BC[2] (C-1) | 1200 | 4.4 | 116 | Y | 884 | 1309 |
| | 1S.SR.FA - 3% | 1200 | **3**[3] | 79 | Y | 931 | 1335 |
| | 1S.SR.FA -2% | 1200 | **2** | 59 | Y | 999 | 1458 |
| | 1S.SR.FA -1.9% | 1200 | **1.9** | 57 | N | 1005 | 1515 |
| **Effect of SP[4]** | 1S.SR.SP- 1100 | **1100** | 1.9 | 63 | N | 966 | 1505 |
| | 1S.SR.SP-1000 | **1000** | 1.9 | 70 | N | 928 | 1500 |
| | 1S.SR.SP- 900 | **900** | 1.9 | 77 | N | 895 | 1499 |
| | 1S.SR.SP- 800 | **800** | 1.9 | 85 | Y | 856 | 1491 |
| | 1S.SR.FA -2%[5] | 1200 | 2 | 59 | Y | 999 | 1458 |
| | 1S.SR.SP6-1300 | **1300** | 2 | 54 | N | 1037 | 1540 |

**Table 6:** *Results showing the effect of one-step control strategy in classroom configuration (Group 1S)*

| | ref | Set-point (ppm) | Free area (% of floor area) | Heating energy consumption (kWh/year/$m^2$) | BB101 Criteria for IAQ, Pass (Y) or Fail (N) | Average $CO_2$ level (ppm) | Maximum daily average $CO_2$ level (ppm) |
|---|---|---|---|---|---|---|---|
| **Effect of FA** | 1S.CR.BC1 (A-2) | 1000 | 5 | 184 | Y | 1022 | 1372 |
| | 1S.CR.FA-4.7% | 1000 | **4.7** | 168 | Y | 1034 | 1373 |
| | 1S.CR.FA-4.5% | 1000 | **4.5** | 159 | Y | 1059 | 1413 |
| | 1S.CR.FA-4.3% | 1000 | **4.3** | 143 | N | 1059 | 1519 |
| **Effect of SP** | 1S.CR.SP1-900 | **900** | 4.3 | 148 | N | 1022 | 1519 |
| | 1S.CR.SP2-800 | **800** | 4.3 | 155 | N | 919 | 1519 |
| | 1S.CR.SP3-700 | **700** | 4.3 | 167 | N | 845 | 1519 |
| | 1S.CR.FA2-4.5% | 1000 | 4.5 | 159 | Y | 1041 | 1413 |
| | 1S.CR.SP-1100 | **1100** | 4.5 | 156 | Y | 1065 | 1492 |
| | 1S.CR.SP-1200 | **1200** | 4.5 | 149 | N | 1089 | 1538 |

### 5.1. Seminar room configuration

Model C-1 with free area equivalent to 4.4% of floor area and set-point of 1200ppm was chosen as the base case, since this strategy had provided acceptable IAQ with lowest heating energy consumption in the typical control strategies.

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 showed 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 (case reference 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 (c.f. Table 3 and Table 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, because 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 appear to be more important than the set-points in providing acceptable IAQ. Although reducing the set-points from 1200ppm to 800ppm 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 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.

[1] FA= Free Area
[2] 1S.SR.BC= one-step control. Seminar Room. Base Case
[3] Red text 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

### 5.2. Classroom configuration

Similar to seminar room configurations 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 base case model.

In the classroom configuration, 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.SP1100) (Table 6). 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 4 and Table 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 showed 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 controling $CO_2$ concentration as minimum required free area was not delivered (1S.CR.SP3-700). 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, especially in densely occupied spaces such as classrooms.

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

The results of this section were developed based on the best control strategies identified in the Group 1S series. Minimum free areas and set-points from Group 1S which provided acceptable IAQ were 2% of the floor area and 1200ppm 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 configuration the same set-point was used for the maximum set-point (1200ppm).

The set-point for the first increment was set to 1000ppm according to BB101in both room configurations. The size of the first free area in the base case was set to half of the maximum free area, similar to the typical control strategies discussed in section 4 (A-3, B-3, and 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 scenarios. This reduced the heating energy consumption by almost 16% in both rooms while IAQ was improved through a reduced average $CO_2$ concentration (see Tables 5, 6 and 7).

Increasing either the first set-point or the 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.

The results of this section have shown that in control strategies with more increments for 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 4).

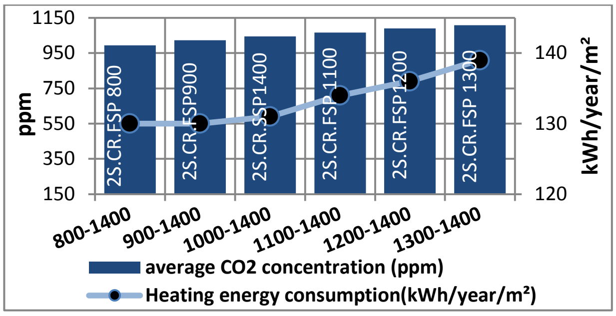


**Figure 4:** *Effect of increasing second set-point on energy consumption and IAQ*

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-2.7% in Table 7).

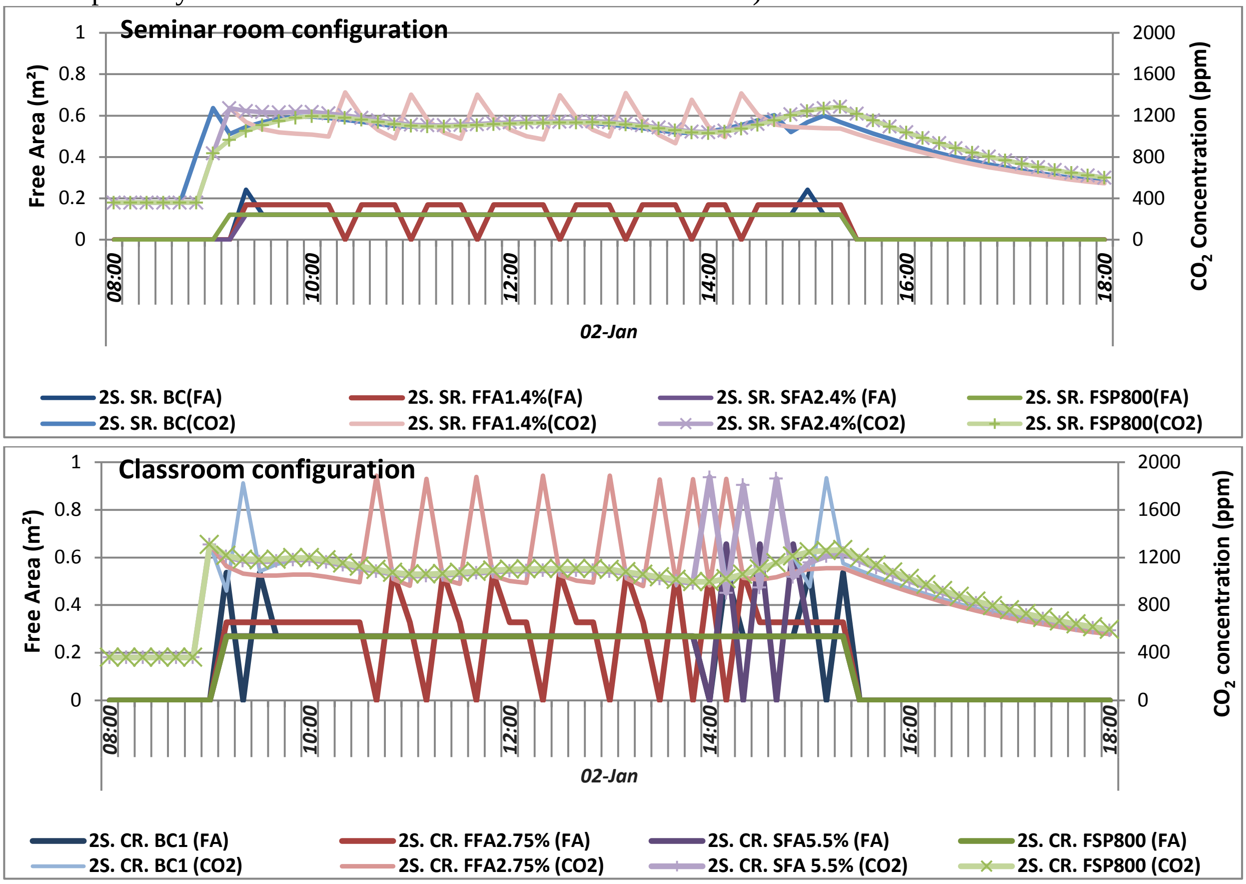


**Figure 5:** *Effect of control strategies with similar performance on $CO_2$ concentration and free area*

Similar performance of (2S. SR. BC1), (2S. SR. FSP800), (2S. SR. FFA1.4%) and (2S. SR. SFA2.4%) models for the seminar room configuration and (2S. CR. FSP800), (2S. CR. FFA2.75%) and (2S. CR. SFA5.5%) for the classroom configuration, in terms of providing acceptable IAQ (see Table 7), showed that it is possible to achieve similar IAQ when $CO_2$ levels are controlled either by introducing lower set-points and thus earlier opening of the vents ((2S. SR. BC1) and (2S. SR. FSP800)), or by providing larger free areas and delaying the opening of the vents ((2S. SR. FFA1.4%) and (2S. SR. SFA2.4%)). Introducing larger opening areas resulted in a rapid increase in the flow rate and consequently a sudden drop in $CO_2$ concentration which led to a higher risk of draught and hunting (compare the effect of free area on $CO_2$ concentration in model (2S. CR. BC1), (2S. CR. FSP800), (2S. CR. FFA2.75%) and (2S. CR. SFA5.5%) shown in Figure 5). Similar behaviour was observed for the classroom configuration.

Opening the vents earlier (e.g. when $CO_2$ concentration reached 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%, energy consumption reduced by 63%, 21% and 55% compared to cases A-1, B-1 and C-1 respectively in the seminar room, and by applying 2S.CR.FFA-2% in the classroom configuration, energy consumption was reduced by 35% and 51% compared with A-2 and C-2 respectively. However, energy consumption increased by 23% compared to case B-1. It should be noted 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).

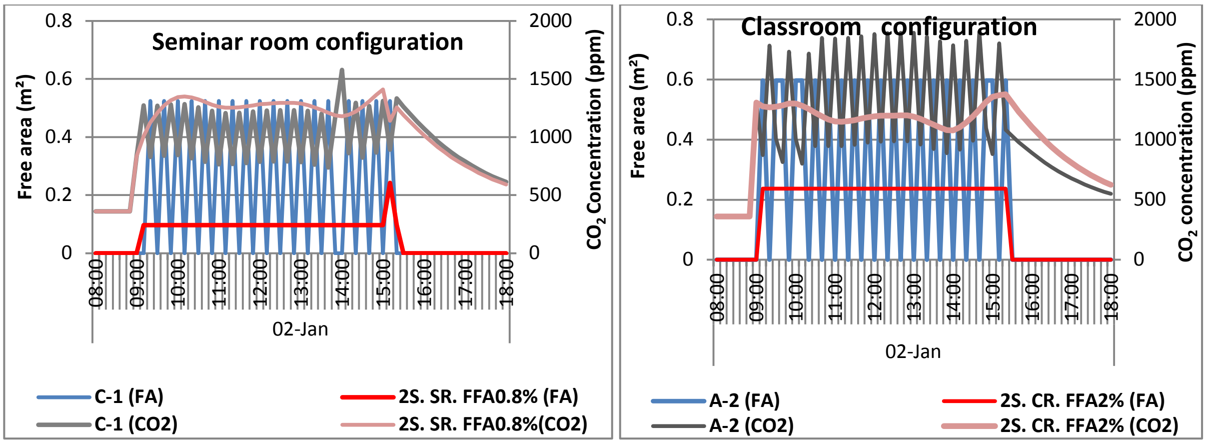


**Figure 6:** *Hunting effect in the best refined and typical control strategy*

**Table 7:** *Results for two-step control strategies in classroom and seminar room[6] (Group 2S)*

| | Seminar room configuration | | | | | | | Classroom configuration | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ref | Set-point (ppm) | FA= % of floor area | Heating energy consumption (kWh/year/m²) | BB101 Criteria for IAQ, Pass (Y) or Fail (N) | Average $CO_2$ Level (ppm) | Maximum daily average $CO_2$ Level (ppm) | Ref | Set-point (ppm) | FA= % of floor area | Heating energy consumption (kWh/year/m²) | BB101 Criteria for IAQ, Pass (Y) or Fail (N) | Average $CO_2$ Level (ppm) | Maximum daily average $CO_2$ Level (ppm) |
| Second set point | 2S. SR. BC1*[7] | 1000 / 1200 | 1 / 2 | 56 | Y | 950 | 1473 | 2S. CR. BC1** | 1000 / 1200 | 2.25 / 4.5 | 147 | Y | 1032 | 1423 |
| | 2S. SR. SSP[8]1300 | 1000 / 1300 | 1 / 2 | 52 | Y | 970 | 1475 | 2S. CR. SSP[9]1300 | 1000 / 1300 | 2.25 / 4.5 | 138 | Y | 1037 | 1426 |
| | 2S. SR. SSP1400 | 1000 / 1400 | 1 / 2 | 49 | Y | 985 | 1490 | 2S. CR. SSP1400 | 1000 / 1400 | 2.25 / 4.5 | 131 | Y | 1045 | 1465 |
| | 2S. SR. SSP1500[10] | 1000 / 1500 | 1 / 2 | 49 | N | 991 | 1544 | 2S. CR. SSP1500 | 1000 / 1500 | 2.25 / 4.5 | 124 | N | 1057 | 1533 |
| First set point | 2S. SR. FSP1300 | 1300 / 1400 | 1 / 2 | 49 | N | 1053 | 1530 | 2S. CR. FSP1300 | 1300 / 1400 | 2.25 / 4.5 | 139 | N | 1107 | 1593 |
| | 2S. SR. FSP1200 | 1200 / 1400 | 1 / 2 | 48 | Y | 1027 | 1500 | 2S. CR. FSP1200 | 1200 / 1400 | 2.25 / 4.5 | 136 | N | 1090 | 1503 |
| | 2S. SR. FSP1100 | 1100 / 1400 | 1 / 2 | 48 | Y | 1005 | 1490 | 2S. CR. FSP1100 | 1100 / 1400 | 2.25 / 4.5 | 134 | Y | 1067 | 1465 |
| | 2S. SR. SSP1400 | 1000 / 1400 | 1 / 2 | 49 | Y | 985 | 1490 | 2S. CR. SSP1400 | 1000 / 1400 | 2.25 / 4.5 | 131 | Y | 1045 | 1465 |
| | 2S. SR. FSP900 | 900 / 1400 | 1 / 2 | 52 | Y | 958 | 1490 | 2S. CR. FSP900 | 900 / 1400 | 2.25 / 4.5 | 131 | Y | 1022 | 1465 |
| | 2S. SR. FSP800* | 800 / 1400 | 1 / 2 | 57 | Y | 923 | 1479 | 2S. CR. FSP800*** | 800 / 1400 | 2.25 / 4.5 | 130 | Y | 994 | 1465 |
| First free area | 2S. SR. FFA-0.6% | 800 / 1400 | 0.6 / 2 | 46 | N | 976 | 1510 | 2S. CR. FFA-1.8% | 800 / 1400 | 1.8 / 4.5 | 118 | N | 1005 | 1501 |
| | **2S. SR. FFA-0.8%[11]** | **800 / 1400** | **0.8 / 2** | **52** | **Y** | **947** | **1491** | **2S. CR. FFA-2.0%** | **800** / 1400 | **2** / 4.5 | **124** | **Y** | **998** | **1489** |
| | 2S. SR. SSP1500 | 1000 / 1500 | 1 / 2 | 49 | N | 991 | 1544 | 2S. CR. SSP1500 | 1000 / 1500 | 2.25 / 4.5 | 124 | N | 1057 | 1533 |
| | 2S. SR. FFA-1.2% | 1000 / 1500 | 1.2 / 2 | 53 | N | 973 | 1518 | 2S. CR. FFA-2.5% | 1000 / 1500 | 2.5 / 4.5 | 128 | N | 1051 | 1509 |
| | 2S. SR. FFA- 1.4%* | 1000 / 1500 | 1.4 / 2 | 58 | Y | 957 | 1485 | 2S.CR.FFA-2.75%*** | 1000 / 1500 | 2.75 / 4.5 | 131 | Y | 1051 | 1486 |
| | 2S. SR. FFA-1.6% | 1000 / 1500 | 1.6 / 2 | 63 | Y | 942 | 1473 | 2S. CR. FFA- 3.0%* | 1000 / 1500 | 3 / 4.5 | 135 | Y | 1048 | 1463 |
| Second FA | 2S. SR. SSP1500 | 1000 / 1500 | 1 / 2 | 49 | N | 991 | 1544 | 2S. SR. SSP1500 | 1000 / 1500 | 2.25 / 4.5 | 124 | N | 1057 | 1533 |
| | 2S. SR. SFA-2.2% | 1000 / 1500 | 1 / 2.2 | 56 | N | 953 | 1505 | 2S CR SFA-5%* | 1000 / 1500 | 2.25 / 5 | 136 | N | 1044 | 1533 |
| | 2S. SR. SFA-2.4%* | 1000 / 1500 | 1 / 2.4 | 57 | Y | 941 | 1488 | 2S. SR. SFA-5.5%** | 1000 / 1500 | 2.25 / 5.5 | 148 | Y | 1036 | 1498 |

6 Models with the same shaded colour showed changes in each model were conducted based on the previous same colour row
7 * or ** or *** = models with similar performance
8 2S.SR.SSP= 2Step. Seminar Room. Second set-point
9 2S.CR.SSP= 2Step. Classroom. Second set-point
10 Effects of reducing the first set-point in 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.
11 Model with the best performance.

## 7. Conclusions

$CO_2$ levels, as an indicator of IAQ in naturally ventilated spaces, depend on the $CO_2$ control strategies employed. The aim of this study was to investigate the effects of fixed $CO_2$ set-points and fixed free areas on IAQ and energy consumption. In the proposed control strategies, vents were opened earlier than they are in typical control strategies but with smaller free areas.

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

- 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 ECON 19 (BRECSU, 2000).
- The results of this study showed that determining the minimum free area is more important than determining the lower set-point in a single-step control strategy. 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.
- 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.
- The relationship between the opening area and energy consumption is 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 $CO_2$ concentration leading to higher energy consumption. For example, in some simulations, although both models used identical set-points, energy consumption increased by 10% in models which used 25% smaller opening sizes.
- Introducing additional increments into the traditional 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.
- 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, use of vents with larger areas, even if they are not opened as early as vents with smaller areas, increases the risk of hunting effect and draught.
- In more densely occupied spaces, earlier opening of the vents (using a lower set-point) with smaller free opening areas, helps to provide better IAQ and reduced energy consumption. It also helps to control the hunting effect more effectively because, when smaller free areas were used, $CO_2$ concentration was less likely to fall or increase rapidly.

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