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Improving thermal comfort and indoor air quality through minimal interventions in office buildings

Narguess Khatami^{a,*}, Arman Hashemi^b

^a*Hilson Moran Partnership, Shackleton House, 4 Battle Bridge Lane, London, SE1 2HP, UK*

^b*School of Environment and Technology, University of Brighton, Brighton, BN2 4GJ, UK*

Abstract

High internal heat gain and slow reaction of occupants to overheating have been identified as major contributors to risk of thermal discomfort in offices. This paper reports on the findings of a research programme which investigates the impacts of reducing internal heat gain and introducing automated ventilation strategies into lightweight open plan offices. It is aimed to develop intervention strategies with minimum disruption to occupants in order to improve energy performance thermal comfort and indoor air quality (IAQ). A case study building was selected and dynamic thermal simulation was conducted to test the performance of proposed strategies. The results reveal that tested strategies reduced the risk of overheating and poor IAQ by 64% and 90%, respectively. The energy consumption was also reduced by 2.1% for the best case scenario.

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1. Introduction

Frequent occurrence of overheating and/or overcooling during summers and winters lead to increased thermal discomfort and energy consumption in overglazed poorly insulated lightweight office buildings [1]. Modern open plan offices face higher risk of overheating due to the rather low floor to ceiling height and excessive heat gains from artificial lighting and office equipment [2]. Climate change is also expected to increase the risk of overheating and thermal discomfort in buildings. According to CIBSE KS 03 [3], external air temperatures in the UK is predicted to rise by 4° to 6°C in the next 50 to 80 leading to higher cooling demand and energy consumption in buildings.

* Narguess Khatami. Tel.: +44 (0) 2070893540
E-mail address: NKhatami@hilsonmoran.com

Energy efficient buildings and natural ventilation have been identified as appropriate answers to both increasing energy prices and environmental concerns [4,5]. Moreover, considering the low annual replacement rates of 1-1.5%, it is estimated that around 70% of the existing buildings will still be in use by 2050 [6]. Considering general trend of energy prices, energy efficient retrofit options are becoming more profitable and popular [7]. Retrofitting is therefore an appropriate strategy to improve the performance of existing buildings.

To this end, this paper intends to investigate potentials for improving IAQ, thermal comfort and energy consumption of office buildings by introducing minor and manageable changes to minimise disruptions to the occupants. For the purpose of this assessment, a typical open plan office was selected as the case study building. The building performance in terms of IAQ, thermal comfort and energy consumption was monitored for one year and the results were reported in [8] and [9]. According to the results of previous investigations, high internal heat gain and slow reaction of occupants to thermal discomfort were the two main contributors to overheating. Moreover, according to [9] and [10], occupants are usually unaware of CO₂ concentration and therefore introducing some forms of automatic control in densely occupied zones is essential to maintain acceptable IAQ. Therefore, better IAQ and thermal comfort could potentially be achieved by reducing internal heat gain and automating existing windows coupled with control strategies to maximise the effectiveness of the existing openings. The effects of these new strategies (reducing internal heat gain, automation and control strategies) are explored in this paper.

Nomenclature

T _c	Operative temperature
T _o	External temperature
T _a	Air temperature

2. The case study building

The case study building is situated on a business park located in the UK midlands. The building is a lightweight two-storey commercial building which was originally built in 1992 and was internally refurbished in 2005 to extend the size of the open plan office. This is reflected in the construction of the building envelope which comprises brick and block walls and metal cladding. The case study building is arguably a good representative of lightweight open plan offices with low floor to ceiling height and high internal heat gain. The building is surrounded by similar two storey retrofitted lightweight buildings and open green fields and is oriented 22° clock-wise from the north (Fig. 1).



Fig. 1. Picture of the case study building.

The total building floor area is 1,100 square meters with a densely occupied open plan office located on the first floor. The rest of the spaces, including the training room, which is also used as a meeting room, kitchen, toilets and the warehouse are located on the ground floor (Fig. 2). Heating is provided by a gas-fired central heating system controlled by thermostatic radiator valves. No mechanical cooling is installed and natural ventilation in the 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 a capacity of 0.9 l/s/m² helps to ventilate the open plan office on the first floor. Solar shading is provided through internal vertical fin translucent blinds on all windows and no external shading is provided.

3. Methodology

Dynamic Thermal Simulation (DTS) was conducted to evaluate and improve thermal comfort, IAQ and energy consumption in the case study building. The accuracy of simulation is highly affected by the inputs and correct setting of computer models is therefore critical to achieve accurate and reliable results. For this reason the results of physical measurements were used to assess the accuracy of DTS model as well as defining a base case model. The base case model was then used to test the effects of different retrofitted options.

3.1. Methods used to define a reasonable base case model

Results of the physical measurements reported in [8] and [9] were used to test the accuracy and reliability of computer models. The results of physical measurements over a period of one year (July 2009-July 2010) were compared with the results of DTS model over a period of one typical year using Typical Reference Year (TRY) 05 weather data for Birmingham. The results were compared in terms of risk of thermal discomfort, IAQ and energy consumption. Thermal comfort, IAQ and energy consumption were assessed as follows:

- Thermal comfort: frequency of the time operative temperature is above 25°C and 28 °C [11]
- IAQ: frequency of occupied period when CO₂ concentration is higher than 1000, 1200 and 1500 ppm [12]
- Energy consumption: comparing the actual and simulated building by reporting monthly and annual gas electricity consumption [13].

Although CIBSE TM 52 [14] suggests assessing thermal comfort in the buildings by using either predicted mean vote (PMV) or adaptive model, traditional method of assessment (reporting frequency of the time when operative temperature is higher than 25°C and 28°C) suggested by CIBSE Guide A [11] was used because, unlike predicted mean vote (PMV) or adaptive model, in this method thermal comfort is not a function of external temperature or occupants' activity levels. IES-VE software programme was used to conduct DTS. The physical geometry and orientation of the case study building were modelled in IES (Fig. 3) according to the actual building information. Construction materials and U-values were specified based on building surveys carried out on site. U-value of 0.44, 0.38, 0.44 and 3.2 W/m²K were used for external walls, roof, ground floor and windows, respectively.

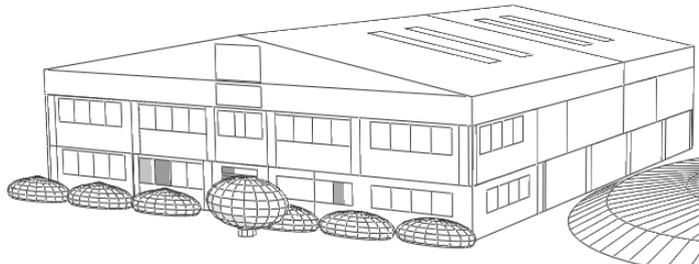


Fig. 2. Model represent the case study building and its surroundings in IES-VE.

Heat gain assumptions were specified based on [11], and the actual building heat gain profile, and were calculated based on proposed methodology in [15] (Table 2).

Table 1. Internal heat gain assumption.

Room type	People (m ² /person)	Lighting (W/m ²)	Equipment (W/m ²)
Open plan office	10	18	14
Training room	3	12	5

Similar to the actual building, natural ventilation was assumed to be provided by top hung openable windows on the north, north-east and north-west facades, each measuring 1.14 m × 0.95 m. Manual controls were specified according to the occupants' thermal comfort and actual occupants' behaviours based on field observations. Table 3 shows opening and closing profiles used to model manual controls in the DTS models.

Table 2. Opening profiles in model represents current building performance.

Training room	Open plan office
	Winter (Jan to Feb & Nov to Dec): Windows linearly open when internal air temperature is in range of 24 °C to 28 °C
Windows linearly open when internal air temperature is in range of 23.5 °C to 27.5 °C	Windows will close if $T_o < 10$ °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 $\Rightarrow > 18$ °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

The case study building was divided into nine zone types including, open plan office, training room, meeting room, warehouse, kitchen, toilets entrance and corridors. This paper reports on the results of simulations in the open plan office and training/meeting room as the two main occupied zones.

3.2. Methods used to test retrofitted options

It was expected to achieve better IAQ and thermal comfort conditions by automating existing windows coupled with appropriate control strategies to maximise the effectiveness of existing openings and minimise energy consumption and internal heat gain by using low cost alternative equipment. The intention was to propose options with minimum disruption to occupants whilst improving the performance of the case study building in terms of thermal comfort, IAQ and energy consumption. Three intervention strategies were therefore suggested as follows:

- Case A, reducing internal heat gain;
- Case B applying typical automation control strategies; and
- Case C, in which cases A and B were combined

Case A: The results of physical measurements and observations showed that there is high internal heat gain (including people, equipment and electric lighting) in the open plan office. As shown in Table 2, lighting systems generated the highest amount of heat. The power density of the lighting system installed in the office is 18W/m² which is 33% higher than good practice benchmarks [13]. In Case A, the effects of replacing existing light bulbs with an energy efficient option (PL-L Polar 36 W/830/4P) were studied. This reduced the lighting power density from 18 W/m² to 13 W/m².

Case B: Effects of introducing automatic temperature and CO₂ window controls were tested in Case B. The control strategies tested in this section were developed based on the typical control strategies reported in [16]. Details of the tested control strategies are as follows: If 22°C < Internal temperature < 26°C, then linearly open the vents until fully opened or If CO₂ > 1000ppm then open 30% of total free area.

Case C: The effects of introducing automatic window controls and reducing internal heat gain, combination of Cases A and B, were tested. Table 4 shows the criteria used to test the effectiveness of cases A, B and C. Similar to the previous section, the effectiveness of proposed options were tested in terms of the thermal comfort, IAQ and energy consumption.

Table 3. Variables which were used to test effectiveness of proposed options

	Assessment criteria
Thermal comfort	% of occupied hours $T_c > 22^\circ\text{C}$ (as target room temperature) [11]
	% of occupied hours $T_c > 25^\circ\text{C}$ (as the temperature in which most of the occupants feel uncomfortable occupants' productivity reduces incrementally by 2% per $^\circ\text{C}$ increase in internal air temperature when the indoor temperature rises above 25°C) [11] and [17]
	% of occupied hours $T_c > 28^\circ\text{C}$ (as the temperature which should try to limit its occurrence)[11]
IAQ	% of occupied hours $\text{CO}_2 > 1000\text{ppm}$ (as target value) [12]
	% of occupied hours $\text{CO}_2 > 1200\text{ppm}$ (as acceptable value in existing buildings) [12]
	% of occupied hours $\text{CO}_2 > 1500\text{ppm}$ (1500 ppm is CO_2 level in which usually all the occupants reported some symptoms of Sick Building Syndrome (SBS) [18]
Energy consumption	Monthly and annual gas and electricity consumption [13]

4. Results and discussions

4.1. Base case validation

Fig. 4 shows the frequency of time when the operative temperature was higher than 25°C and 28°C in different zones of the case study building. Comparing the results of this section with physical measurements shows a 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 Fig. 4 is the average temperature in the open plan office.

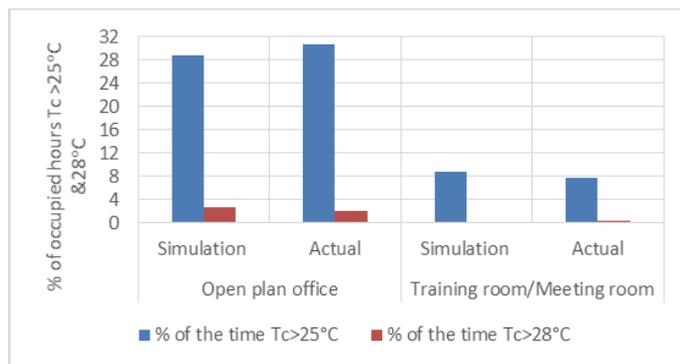


Fig. 3. Frequency of the time when operative temperature is higher than $25^\circ/28^\circ\text{C}$ in both actual building and computer model for the base case

Fig. 4 shows annual heat gain and heat loss in the case study building, positive figures are representative of heat gains while negative figures are representative of heat losses in the building. The results reveal that internal heat gain (from people, equipment and lighting systems) in the open plan office was almost five times more than the heating system during a year (Fig. 4). Between all heat sources in the open plan office, lighting system was found to consume and generate the highest amount of electricity and heat respectively (Table 2). Therefore, improving the lighting system would help to reduce both internal heat gain and electricity consumption.

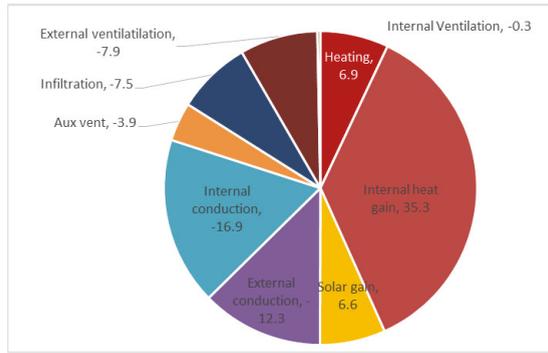


Fig. 4. Annual heat gains and losses in open plan office

The percentages of the occupied hours during which CO₂ concentration was higher than 1000, 1200 and 1500 ppm are shown in Fig. 5. Although for the training room there is a significant difference between measured and simulation predictions, the pattern of CO₂ distribution is similar. CO₂ levels in both computer model and actual measurements fell during hotter periods, as a result of opening windows more frequently, and increased during colder periods. As discussed in [9], CO₂ levels in the case study building were highly influenced by occupancy patterns as well as the vents' positions (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.

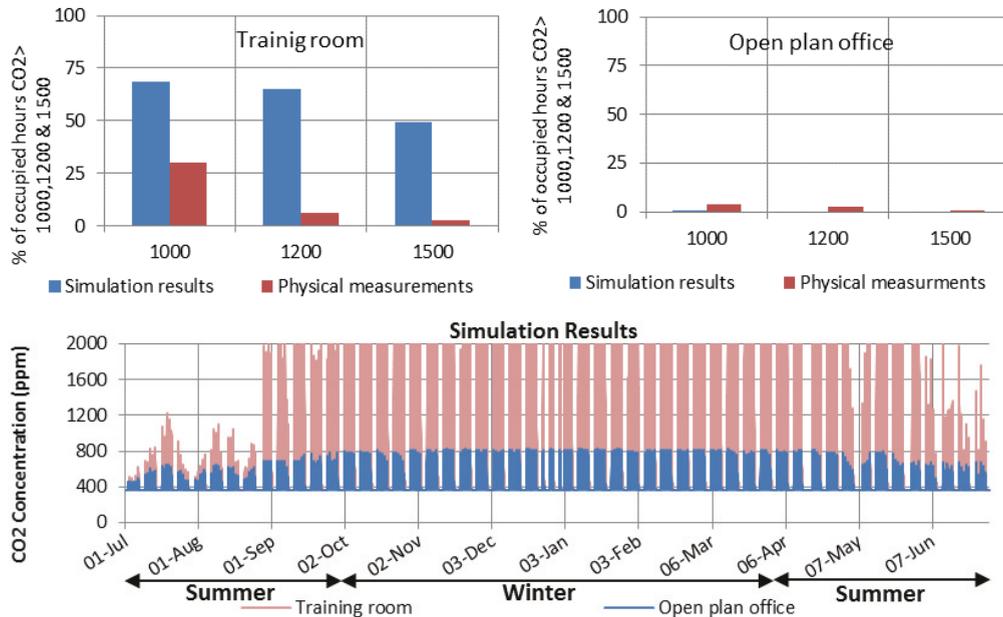


Fig 5. CO₂ concentration in measured and simulated models

Comparison between simulated energy consumption and good practice and typical energy consumption benchmarks showed that similar to actual measurements, simulated energy consumption was between typical and good practice benchmarks (Fig. 6).

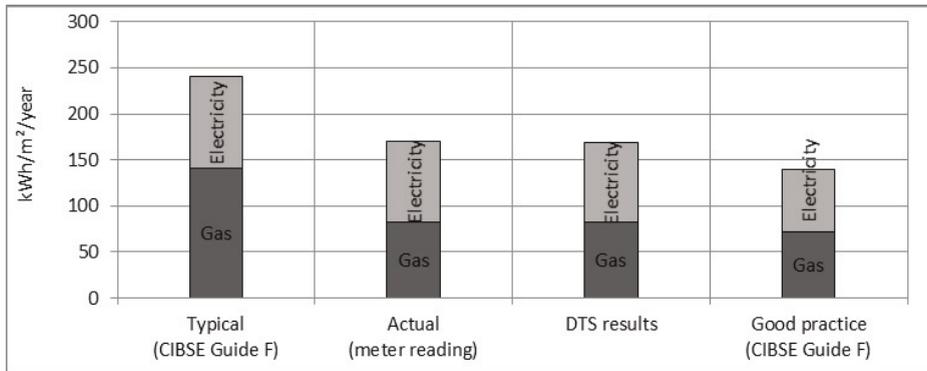


Fig. 6. Comparison of simulated, actual, typical and good practice energy consumption benchmarks.

In terms of energy consumption, the results revealed good agreement between measured data and computer predictions (Fig. 7). Simulated electricity consumption was slightly lower than the actual electricity consumption (1%) which may be due to several reasons including the possible operation of some equipment during unoccupied periods. Moreover, according to the results, the actual gas consumption was 0.6% higher than the simulations. A possible explanation for this is the higher external temperatures in Birmingham TRY 05 weather data during winter compared to the actual measurements on site (Fig. 7).

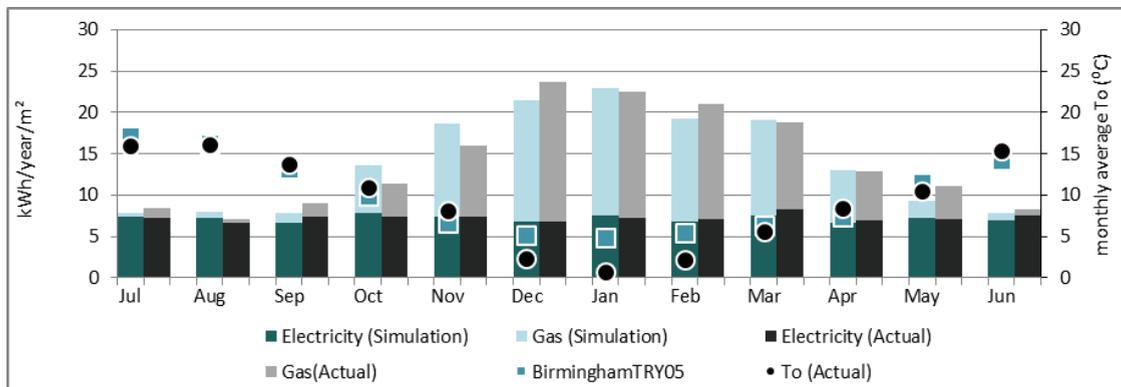


Fig. 7. Monthly measured and simulated energy consumption

4.2. Tested scenarios

The risk of overheating was assessed by reporting the frequency of thermal discomfort in the open plan office and training room. The results of adopting any of the tested scenarios (Case A, B and C) revealed a reduced risk of thermal discomfort (Fig. 8). Although these minimal changes helped to reduce the occurrence of overheating by a maximum of 65%, none of them met thermal comfort requirement of 5% suggested by [11]. It should be mention that according to [11] in naturally ventilated buildings it is acceptable to have operative temperature (T_c) of higher than 25 °C for up to 5% of occupied periods. 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 (Fig. 8). Due to applying manual controls during very hot conditions and lower internal heat gains, Case A was more effective than Case B in controlling peak temperatures (% of occupied hours $T_c > 28^\circ\text{C}$); however, it was still higher than acceptable conditions suggested by [11].

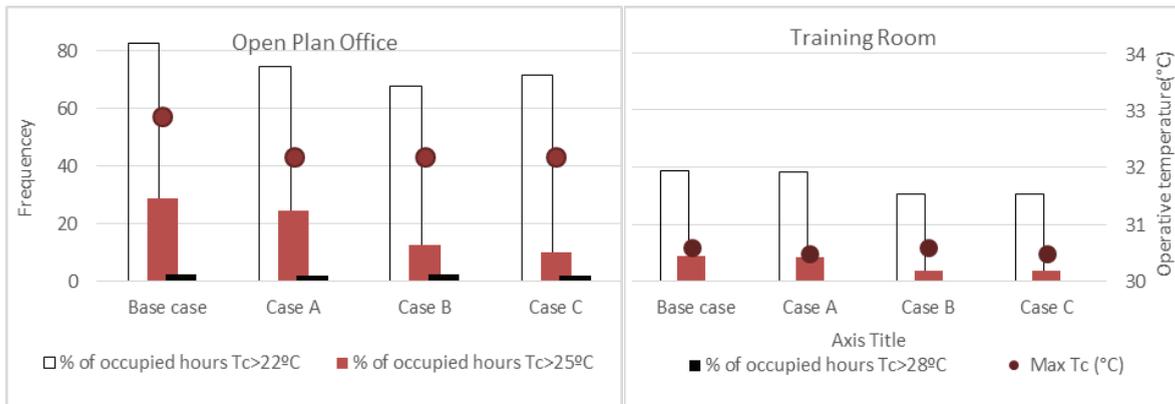


Fig. 8. Thermal comfort performance in tested scenarios

Further studies were carried out in the open plan office where significantly higher risk of overheating was identified. Fig. 9 illustrates the frequency of overheating (the time when operative temperature is higher than 25°C and 28°C) in summer (May to August), winter (January, February, November and December) and mid-season (March, April, September and October). According to the results, there has been high risk of overheating in winter, summer and mid-season period prior to introducing the abovementioned scenarios. As shown in in Fig. 9, although reducing internal heat gain and introducing automatic controls help to reduce risk of overheating during winter and mid-season, summer overheating is still a serious issue and operative temperatures of above 25 °C and 28 °C were recorded in the open plan office. Considering all windows in the case study building are located on only one side of the building (i.e. single sided ventilation), it is evident that the existing openings cannot provide adequate ventilation for the current heat gain in the open plan office.

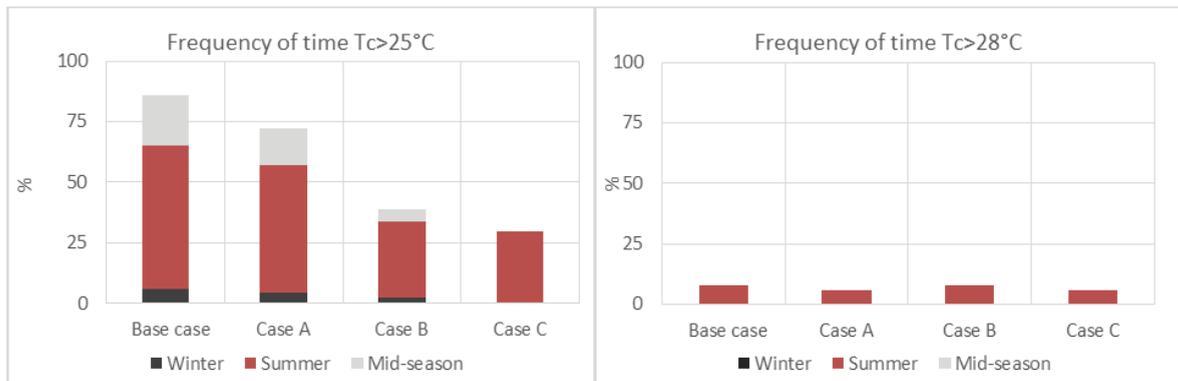


Fig. 9. Frequency of thermal discomfort during summer, winter and mid-season

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 combined with appropriate automation strategies were able to provide acceptable thermal comfort conditions and there was therefore no need for larger opening sizes. The results of DTS models also showed that introducing automatic control (Cases B and C) in the training room was effective in terms of controlling CO₂ concentration and helped to reduce risk of poor IAQ by 90% (Fig. 10, % of occupied hours CO₂>1000ppm). This is while reducing internal heat gain in Case A slightly deteriorated IAQ as windows were opened less frequently. Results of previous studies by Khatami et al. [8,9], showed that occupants usually open the 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 used by the occupants. This explains the reason for slightly higher CO₂ concentrations in Case A compared with the base case. It should be noted that 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 in the office.

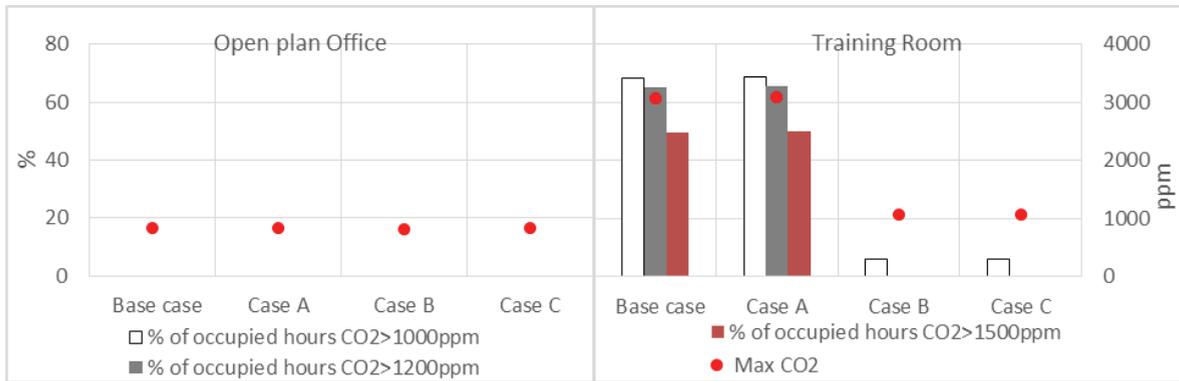


Fig. 10. IAQ in tested scenarios

Energy consumption figures showed that, compared to the base model, Case A performed the best and reduced energy consumption by 2.1% (Fig. 11) while Case B performed the worst and increased energy consumption by 1.4%. In all cases energy consumption was higher than good practice benchmarks but it was lower than the benchmarks for typical buildings [13]. Gas consumption slightly increased in all cases while electricity consumption reduced in Cases A, and C, and remained the same in Case B (Fig. 11). The results of DTS models also revealed that in Case A, as a result of installing low energy 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.

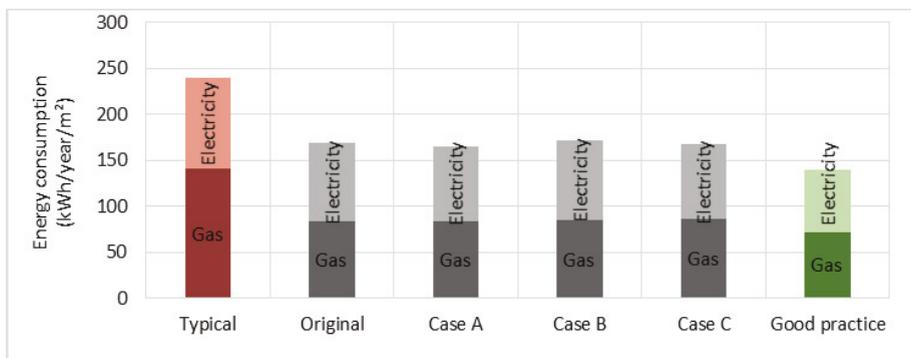


Fig. 11. Gas and electricity consumptions in models with lower ventilation demand

5. Conclusions

This paper investigated the effects of reducing internal heat gain and introducing automated windows on thermal comfort, indoor air quality and energy consumption in office buildings using dynamic thermal simulation. The following could be concluded based on the results of this research:

In typical lightweight office buildings with high internal heat gain and manually controlled natural ventilation, there is high risk of thermal discomfort during winter and summer. Moreover, due to poor indoor air quality in densely

occupied zones, such as training and meeting rooms, introducing some form of control to minimize risk of poor IAQ is essential.

Introducing automated windows (rather than relying on occupants to control the openings) along with reduced internal heat gain can potentially reduce the risk of overheating in office buildings by 64% and improve IAQ in highly occupied environments by 90%.

Although reducing internal heat gain and introducing automatic control help to reduce the risk of overheating, open plan offices may still face a high risk of overheating, especially during summer and mid-season. Increasing ventilation rate by introducing more openings and/or further reduction of internal heat gain may help to address this issue. In this respect, provision of new openings into the open plan office (e.g. high level openings [8]) and/or enhancement of user controls [19] may improve natural ventilation performance and thermal comfort consequently.

Although reducing internal gain by for example, installing low energy lighting systems, reduce the risk of overheating and electricity consumption, such strategies may increase heating requirements during winter offsetting the savings in terms of energy consumption.

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