EFFECTS OF MANUAL AND AUTOMATIC NATURAL VENTILATION CONTROL STRATEGIES ON THERMAL COMFORT, INDOOR AIR QUALITY AND ENERGY CONSUMPTION

Narguess Khatami

School of Civil and Building Engineering,

Loughborough University, UK

n.khatami@lboro.ac.uk

Arman Hashemi

Grenfell-Baines School of Architecture, Construction and Environment,

University of Central Lancashire, UK

ahashemi@uclan.ac.uk

Malcom Cook

School of Civil and Building Engineering,

Loughborough University, UK

malcolm.cook@lboro.ac.uk

Steven Firth

School of Civil and Building Engineering,

Loughborough University, UK

firth@lboro.ac.uk

EFFECTS OF MANUAL AND AUTOMATIC NATURAL VENTILATION CONTROL STRATEGIES ON THERMAL COMFORT, INDOOR AIR QUALITY AND ENERGY CONSUMPTION

Narguess Khatami[1], Arman Hashemi[2,] Malcom Cook[3] & Steven Firth[4]

[1]School of Civil and Building Engineering, Loughborough University, UK, n.khatami@lboro.ac.uk
[2]Grenfell-Baines School of Architecture, Construction and Environment, University of Central Lancashire, UK, ahashemi@uclan.ac.uk
[3]School of Civil and Building Engineering, Loughborough University, UK, malcolm.cook@lboro.ac.uk
[4]School of Civil and Building Engineering, Loughborough University, UK, s.k.firth@lboro.ac.uk

Abstract

Occupants of naturally ventilated buildings can tolerate wider ranges of temperature and Indoor Air Quality (IAQ) if they have more control over their environment. Meanwhile, due to the complexity of advanced natural ventilation (ANV) strategies, introducing some form of automatic control is essential despite the fact that they limit the occupants' control over their environment. Therefore, it is essential to understand the performance of ANV systems and occupants' behaviours in order to identify a balance between automatic and manual controls to enhance the performance of ANV systems while maintaining the occupants' comfort. The aim of the work reported in this paper is to evaluate the effects of a retrofitted ANV system with manual and automatic controls on thermal comfort, indoor air quality and energy consumption in an open-plan office building in the UK. Physical measurements were used to study the building performance in terms of thermal comfort, IAQ and energy consumption. The results revealed that occupants were much more aware about thermal comfort compared to IAQ. Therefore, relying on the occupants to control the ventilation system would considerably increase the risk of poor IAQ in buildings. Moreover, introducing automatic controls did not affect the thermal comfort conditions for those who understood and actively controlled the ANV system, while the situation improved for those occupants who were not active. Results of this study showed that introducing automated natural ventilation helped to reduce energy consumption by 8%.

Key words: Automatic control, manual control, advanced natural ventilation, Indoor Air Quality (IAQ), thermal comfort.

Introduction

Interest in providing thermal comfort and acceptable Indoor Air Quality (IAQ) through natural ventilation is increasing due its lower energy consumption compared to mechanical ventilation systems. According to Allocca, Chen and Glicksman (2003) 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, Moujalled, Cantin and Guarracino 2008 and De Dear 2009) and have lower IAQ expectations compared to air conditioned buildings (Hummelgaard *et al*. 2007).

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, automatic or a combination of both (Martin and Fitzsimmons 2000). Results of Heieslberg (2008) and Khatami, Cook and Hudleston

(2011) showed that occupants are usually very slow to control their thermal environment and react to thermal discomfort too late. At the same time, results of studies by Griffiths and Eftekhari (2008) and Khatami, Cook and Hudleston (2011) suggested that occupants are often unaware of CO_2 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 was found to be essential, results of studies by Ackerly, Baker and Brager (2011) showed that in naturally ventilated buildings, introducing automatic control may eliminate the abovementioned advantages of occupants' control in naturally ventilated buildings and according to Frontczak, Anderson and Wargocki (2012), occupants much prefer manual controls in naturally ventilated buildings. This study therefore intends to compare manual and automatic controls and their effects on the temperature, IAQ, and energy consumptions in office buildings.

For this purpose a typical office building was selected and performance of the building in terms of thermal comfort, IAQ, and energy consumption was studied before and after implementing ANV strategy. Performance of the building after intervention was studied in two different phases. In the first phase, occupants were responsible for controlling the ANV system and in the second phase automatic controls were introduced into the system.

Description of the case study building (CSB) and ANV strategies
The CSB 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 (Fig. 1).

(a)   (b)

Figure 1: Case study building

The total building floor area is 1100 m² and a densely occupied open plan office is located on the first floor while a training/meeting room, kitchen, toilets and warehouse are located on the ground floor (Figures 2a and b). 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×1m. Furthermore, a mechanical supply and extract system with 0.9 l/s/m² capacity helps to ventilate the office on the first floor. However, the supply and extract system was disabled when natural ventilation systems were introduced into the building. The open plan office itself is divided into three subzones (Fig. 2b).
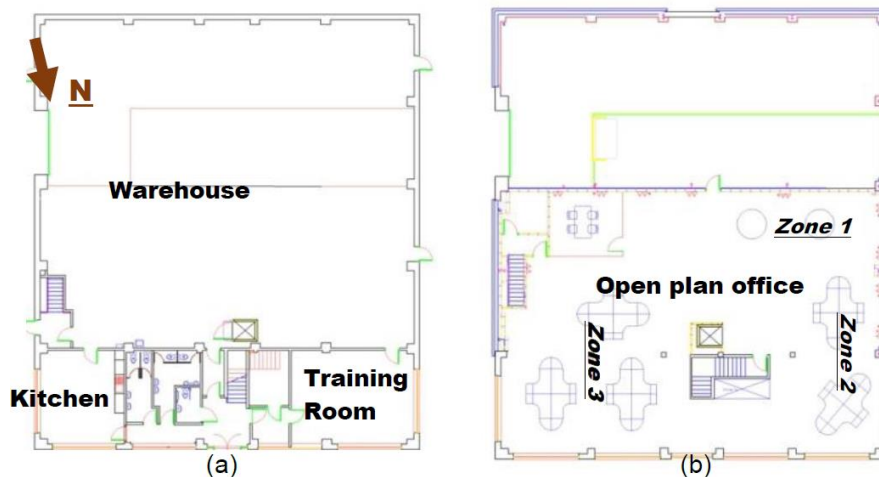
Figure 2: Plan of Case study building

Khatami, Cook and Hudleston (2011) showed that due to high internal heat gains, lightweight structure, and limited ventilation devices, ventilation was ineffective in the CSB before intervention and remedial actions were required to control overheating. For this reason, existing ventilation strategies in the CSB were enhanced by ANV strategy.

According to Lomas (2007) the stack effect is almost always reliable as an existing natural ventilation force; therefore, proposed options took advantage of stack induced ventilation as the main driving force. Implemented options (Fig. 3) included introducing a new series of openings installed on the CSB's roof. These were designed to serve as high level outlets and existing windows as low level inlets to maximize stack effect. A new series of openings were also introduced at the ceiling level by replacing some of the suspended ceiling tiles with openable vents (Fig. 3b). These ceiling vents were designed to connect the open plan office to the unheated, unoccupied roof area (loft) exhausting hot polluted air into the roof space.

Due to the important role of occupants in the success or failure of a natural ventilation strategy (Martin and Fitzsimmons 2000 and Ward, 2004), training was provided after implementing the new ANV strategy. During training, occupants were instructed on how to use the systems. They were instructed to open the ceiling tiles, roof vents, and finally the low level openings (windows), in that order. This was to take advantage of lower/milder temperature and CO_2 concentration levels of the unoccupied roof space which acted as a buffer to reduce energy consumption.

Occupants were asked to take responsibility for controlling the ANV system (e.g opening and closing the windows and roof vents) for six months after installing the ANV systems. The ANV system was then enhanced by introducing automatic controls. Control strategies contained complex algorithms based on the external temperature and occupancy patterns and were designed to monitor and control both CO_2 levels and internal temperatures. Similar to the manual controls, automatic controls activated openings in the following order: ceiling tiles, roof vents, and finally windows, to provide acceptable IAQ while minimising the energy consumption. Details of the control algorithms used are provided in Khatami *et al.* (2013) and SE Controls (2013).
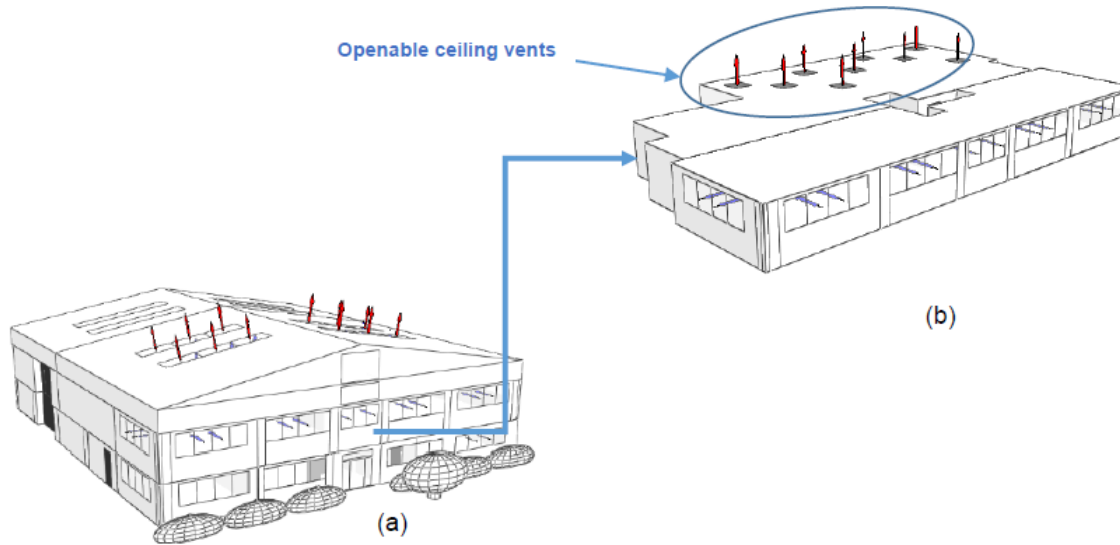
Figure 3: Principle of ANV strategy implemented in refurbishment, whole building (a), first floor open plan office (b)

Methodology

To assess the actual building performance, physical measurements were taken and thermal comfort, IAQ, and energy consumption was evaluated based on BS EN 15251: 2007, CIBSE guide A: 2006 and CIBSE guide F: 2012 methods.

To assess thermal comfort it is possible to use a heat balance or adaptive methods (Djongyang, Tchinda and Njomo 2010). It is believed that thermal comfort is affected by occupants' behavior and expectations in naturally ventilated buildings (Djongyang, Tchinda and Njomo 2010) as well as their past thermal history (De Dear and Brager, 1998). Therefore it is recommended to use an adaptive approach to assess thermal comfort in naturally ventilated buildings.

In an adaptive approach, thermal comfort is assessed based on the mean running outside temperature (T_{rm}) using equations 1 and 2. (British Standard Institute 2007 and Chartered Institution of Building Services Engineers 2006b).

$$T_{comf}= 0.33\ T_{rm}+18.8\ (T_{rm}>10°C) \tag{1}$$

$$T_{comf}= 0.09\ T_{rm}+ 22.6\ (T_{rm}\leq 10°C) \tag{2}$$

Where:

T_{comf}= comfort temperature. According to BS EN 15251 (Chartered Institution of Building Services Engineers 2007) it is assumed that occupants feel comfortable if the indoor operative temperature is in the range of ±3ºC of the calculated comfort temperature;

T_{rm}= running mean temperature for the current day which is weighed with a higher influence of the previous daily mean external temperatures (T_{ed-1}; T_{ed-1}; …) (Nicole *et al.* 2009); and

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

Results of studies by Hummelgaard *et al*. (2007) showed that occupants of naturally ventilated buildings did not only have more tolerance regarding temperature but also had lower IAQ expectations. Although there are different assessment criteria for assessing thermal comfort in naturally and mechanically ventilated buildings, there is a single assessment criteria for IAQ in both naturally and mechanically ventilated buildings. To assess IAQ as suggested by BS EN 15251 (Brit2007, frequency of time when CO_2 concentration was higher than acceptable levels was reported. Acceptable ranges were specified as 1000ppm as the target value (British Standard Institute 2007) and 1200ppm as an acceptable value in existing buildings (British Standard Institute 2007). Above 1500ppm when almost all occupants report some symptoms of Sick Building Syndrome (Petty 2013).

For the purpose of physical measurements, air temperature and CO_2 concentration sensors were installed in the main zones of the open plan office. Data from air temperature sensors were used to calculate Mean Radiant Temperature (MRT). MRT was estimated by using equation 3 which was proposed by Han *et al.* (2007):

$$MRT = R^2 \times Ta - 0.01 \tag{3}$$

Where:

$R^2 = 0.99$; and

Ta= air temperature.

Using the estimated MRT and measured Ta, as suggested in CIBSE (Chartered Institution of Building Services Engineers 2006a), the operative temperature was calculated as the average of Ta and MRT. An external sensor was also installed on the north elevation of the building to estimate T_{rm} and $T_{comfort}$ in the building using equations 1, 2 and 3. As mentioned in section 19 of CIBSE guide F (2012), monthly meter readings were used to assess the energy consumption in the case study building before and after the interventions. Table 1 summarises assessment criteria which were used in this study.

Table 1: Assessment criteria for this study

Criteria	Method	Source
Thermal comfort	heating seasons= % of occupied hours Tc is not in the range of 20-24 Cooling season = % of occupied hours Tc is in in the range of calculated T_{comf} ±3 ºC	BS EN 15251: 2007
IAQ	% of occupied hours CO_2 >1000ppm % of occupied hours CO_2 >1200ppm % of occupied hours CO_2 >1500ppm	BS EN 15251: 2007 Petty,2013
Energy consumptions	Monthly meter reading	CIBSE Guide F:2012

Thermal comfort
Table 2 summarises results of building performance in terms of thermal comfort when the adaptive assessment method was applied. Comparison of occupants' thermal comfort before and after intervention, overall indicated better temperature control after refurbishment as shown by the frequency of thermal discomfort in Table 2 and

temperature variations during 6 months in Figure 4. This is despite summer external temperatures being slightly higher after intervention (Fig. 4).

Table 2: Effects of automatic and manual control on thermal discomfort

Criteria	Before intervention			After intervention (Manual control)			After intervention (Automatic control)		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
% of occupied hours Ta is not in comfortable range	18%	9.1%	6.5%	7%	7.2%	4.8%	5%	3.0%	3.1%

Table 2 shows that introducing manually controlled ANV helped to reduce the risk of thermal discomfort by a maximum of 60% (in Zone 1) and by a minimum of 21% (in Zone 2). It is while according to the results of a questionnaire before intervention, occupants of the Zone 1 were the most dissatisfied occupants while occupants of Zone 2 were the most satisfied people (Khatami, Cook and Hudleston 2011). The results showed that occupants of the Zone 1 who were the most dissatisfied occupants, responded to the new strategies more actively after intervention and better temperature controls were provided in this area. The occupants of Zone 2, who were the most satisfied, had the least 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 Zone 2.

Comparing the results of building performance for manual and automatic controls showed that introducing automatic control was more effective in Zone 2 as it decreased the risk of thermal discomfort by 58%. This was due to the little intention of occupants of Zone 2 to control their indoor environment when natural ventilation systems relied on manual controls. Therefore, introducing automatic control was more effective in this zone. This was while introducing automatic control in the Zone 1, where occupants were more active, was less effective and the risk of thermal discomfort reduced by only 28.5%.
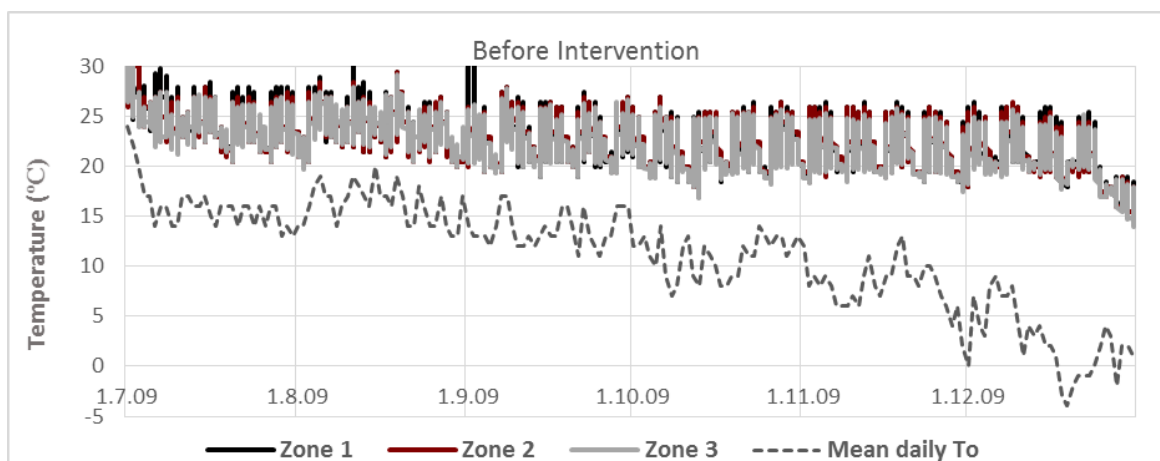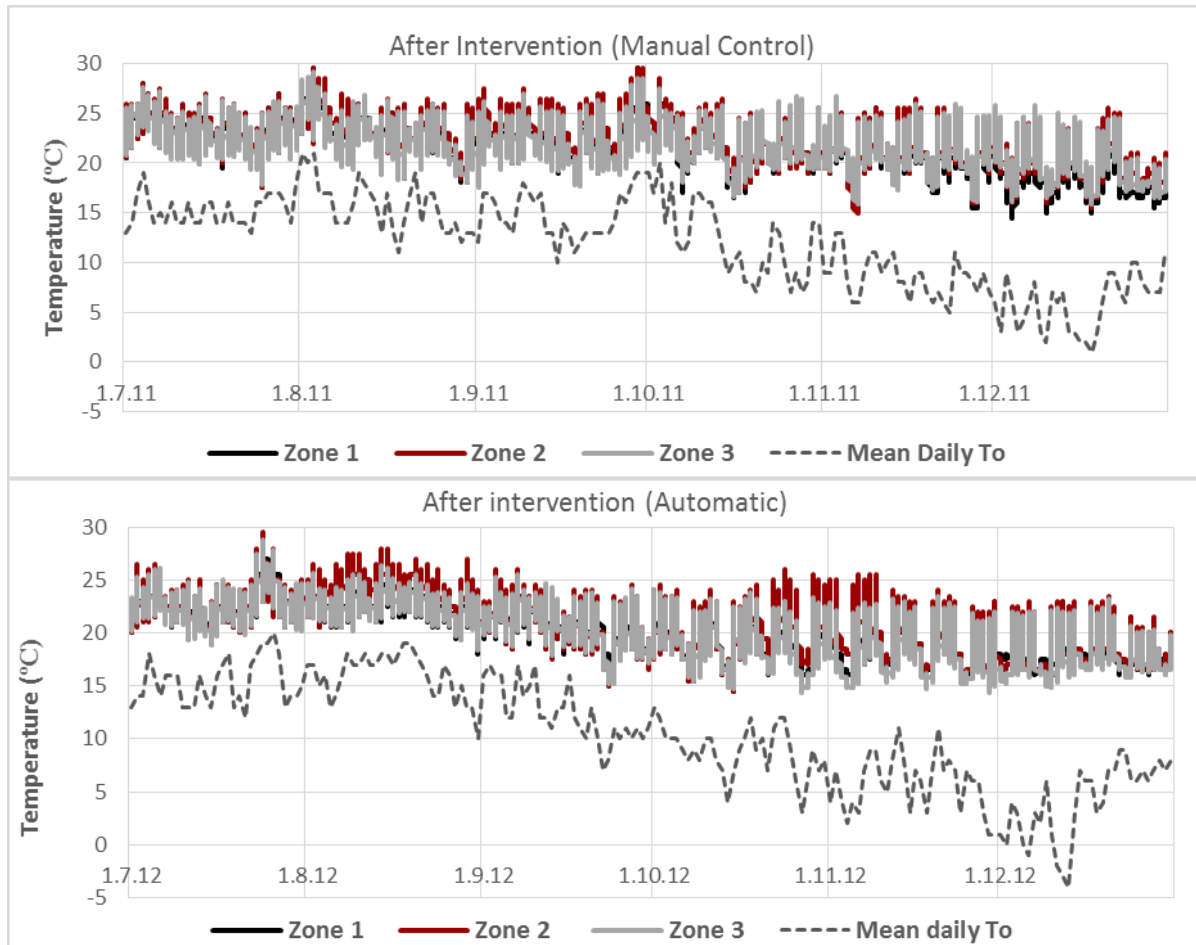
Figure 4: Internal and external temperature variation during the testing period

The results of this study revealed that when natural ventilation relied on occupants' manual control, it provided a better temperature control during hotter days (Figures 5a and b). During hot days, internal temperature at the beginning of occupied hours was usually high and occupants reacted to the internal temperatures faster and tried to control the temperature more actively resulting in more effective temperature control. It was while during milder days (Fig. 5b) occupants waited until internal temperature reached to 25°C-26 °C when they opened the vents. Delaying in opening the windows and high level openings led to higher internal temperature in moderate days (Figures 5a and b). Results from this section suggest that air temperature at the beginning of the working day is an important parameter to consider if occupants are responsible for control of the natural ventilation system.

Similar performances were recorded during extreme external conditions when the performance of the CSB with manual and automatic controls were compared (refer to Figures 5a and c). Both controls helped to shift the occurrence of peak temperatures from the occupied to the unoccupied periods which helped to prevent the risk of overheating. It should be noted that since the CSB has a lightweight structure, night cooling provided by automatic control was not very effective. Therefore the rapid reaction of occupants provided a similar effect to automatic control during hot days.

Although the building performance during hot days was similar, during milder summer days, introducing automatic control was more effective. As suggested by Heiselberg

(2008) and Khatami, Cook and Hudleston (2011), occupants reacted to overheating slowly and therefore introducing automatic control helped to prevent overheating and kept internal temperature within comfortable ranges (refer to Figures 5b and d).
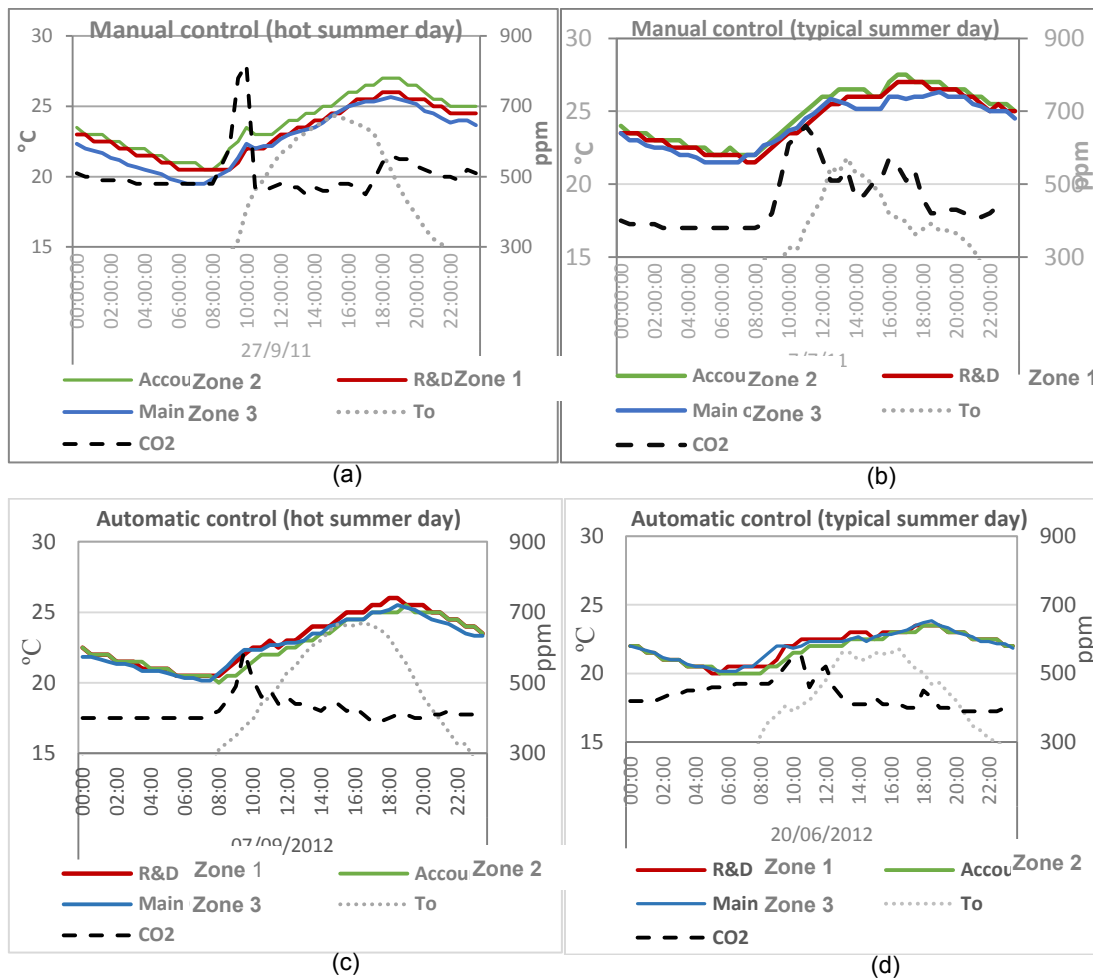

Figure 5: Effect of applying automatic control on temperature control during hot and typical summer days

CO_2 concentration and IAQ

Table 3 summarises the results of this section. Comparing the results of the building performance before intervention (when supply and extract ventilation was activated) with manual control showed considerably poorer IAQ after intervention. According to the physical measurements, the percentage of the occupied time when CO_2 concentration was higher than 1000 and 1200 ppm was significantly increased after intervention.

Table 3: IAQ before and after intervention (manual and automatic controls)

Criteria	Before intervention	After intervention (Manual control)	After intervention (Automatic control)
% of occupied hours CO2> 1000ppm	1%	15%	6.4%
% of occupied hours CO2> 1200ppm	0%	5.5%	0.8%
% of occupied hours CO2> 1500ppm	0%	%0.5	0

Although after intervention more control options were provided, occupants controlled the openings mainly based on their thermal comfort as they were less aware of IAQ conditions. For this reason, CO_2 concentration was considerably lower during hotter periods (Fig. 6).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 rely only on manual controls to provide acceptable IAQ.
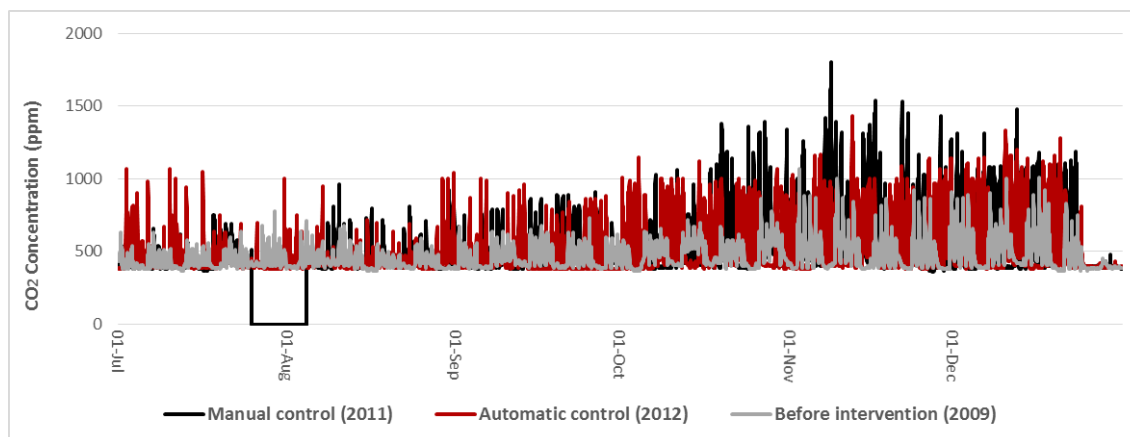

Figure 6: CO_2 concentration before and after intervention

Introducing automatic controls significantly helped to reduce the risk of poor IAQ. Automated natural ventilation controls reduced the amount of time when CO_2 concentration was higher than 1200ppm by 85%. Although when compared to the manual controls, automatic control provided better IAQ conditions, supply and extract systems proved to be more effective than both manual and automatic controls in controlling CO_2 concentration in the open plan office.

CO_2 levels during occupied hours illustrated the high dependency of CO_2 concentration to the opening positions (Fig. 5). According to the results, CO_2 concentration dropped suddenly or rose rapidly by opening or closing the openings. Therefore it could be argued that CO_2 concentration can be used as an indicator of the vents status (open/closed) in densely occupied spaces with constant occupancy patterns and large opening sizes.

Energy Consumption
The results of the study showed that introducing automatic natural ventilation into the CSB helped to reduce electricity consumption by 5%. Lower electricity consumption could have occurred as a result of disabling the supply and extract systems. Moreover, since during summertime, the ANV system controlled overheating more effectively, occupants used desk top fans less frequently (Fig. 7).

Gas consumption was also reduced by 11.5% since disabling the supply and extract system reduced the ventilation rate and associated heating demand. Furthermore, as discussed by Khatami, Cook and Hudleston (2011), before intervention there was a risk of overheating even during cold seasons and occupants needed to open windows even during winter. By applying ANV strategies, overheating was controlled more effectively and for this reason during heating seasons, occupants needed to open the windows less frequently which also helped to reduce heating demand.

Comparing energy consumption for manual and automatic natural ventilation systems showed reductions of 2% and 3% in gas and electricity consumption respectively. The results in this section suggest that both manual and automatic controls have similar effects on the energy consumption in naturally ventilated office buildings where there is no form of mechanical cooling systems.
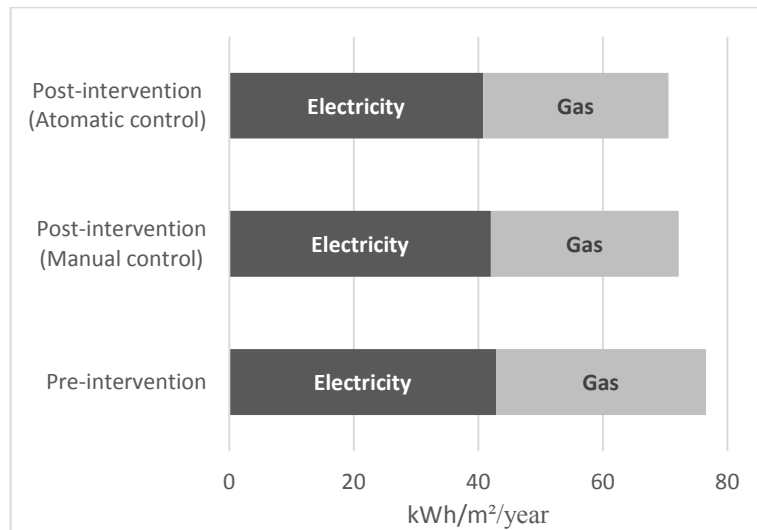

Figure 7: Monthly energy consumption before and after intervention

Conclusions

This study used monitoring to evaluate the effects of applying manual and automatic control to natural ventilation systems on thermal comfort, IAQ, and energy consumption in a typical office building in the UK.

The work has shown that manually controlled natural ventilation systems appear to perform better during hotter days as occupants react to the internal temperatures more actively in an attempt to control the internal temperatures. 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.

Based on the results of this study occupants of those areas of the CSB where thermal comfort was relatively poor before intervention (Zone 1) responded to the manual NV systems more actively. Therefore, it could be argued that the previous thermal experiences of the occupants' of a zone in buildings with manually controlled NV systems should be regarded as an additional criteria to the historic exteral 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 before it reaches to high temperatures). According to the results of this study, introducing automatic NV systems could reduce the risk of thermal discomfort by 60% in such areas.

Occupants seem to be much more responsive to their thermal discomfort compared to poor IAQ increasing the risk of unacceptable IAQ during colder seasons. This is because they may either avoid adjusting openings to avoid discomfort in cold weather or they are less aware of the IAQ conditions. Introducing automatic controls significantly reduced the risk of poor IAQ by 85%.

Compared to NV systems, mechanical supply and extract systems could provide better IAQ in terms of CO_2 concentration levels; however, NV systems can reduce the energy consumptions in buildings. The NV system monitored in this work reduced the gas and electricity consumptions by 11.5% and 5% respectively.

Acknowledgments

References
ACKERLY, K., BAKER, L. and BRAGER, G., 2011, Window Use In Mixed Mode Buildings: A Literature Review, Center For The Built Environment (CBE), Berkley.

ALLOCCA, C., CHEN, Q., and GLICKSMAN, L.R., 2003, 'Design Analysis of Single-Sided Natural Ventilation,' Energy And Buildings, 35(8), pp. 785–795.

BRITISH STANDARD INSTITUTION, 2007, EN 15251: Indoor Environmental Input Parameters For Design And Assessment Of Energy Performance Of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting And Acoustics, British Standards Institute, London.

CHARTERED INSTITUTION OF BUILDING SERVICES ENGINEERS, 2006a, Comfort, Knowledge Series Ks6, Chartered Institution Of Building Services Engineers, London.

CHARTERED INSTITUTION OF BUILDING SERVICES ENGINEERS, 2006b, CIBSE Guide A: Environmental design, Chartered Institution of Building Services Engineers, London.

CHARTERED INSTITUTION OF BUILDING SERVICES ENGINEERS, 2012, Guide F: Energy Efficiency in Buildings, Chartered Institution of Building Services Engineers, London.

DE DEAR, R. and BARGER, R.J., 1998, 'Towards An Adaptive Model of Thermal Comfort And Preference,' Ashrae Transactions, 104(1), pp.145-167.

DE DEAR, R., 2009, 'The Theory Of Thermal Comfort In Naturally Ventilated Indoor Environments - "The Pleasure Principle",' International Journal of Ventilation, 8(3), pp. 243-250.

DJONGYANG, N., TCHINDA, R. and NJOMO, D., 2010, 'Thermal Comfort: A Review Paper,' Renewable and Sustainable Energy Reviews, 14, pp. 2626-2640

FRONTCZAK,M., ANDERSON R.V., and WARGOCKI,P., 2012, 'Questionnaire Survey On Factors Influencing Comfort With Indoor Environmental Quality In Danish Housing,' Building And Environment, 50, pp. 56-64.

GRIFFITHS, M. and EFTEKHARI, M., 2008, 'Control of CO_2 In A Naturally Ventilated Classroom,' Energy And Buildings, 40(4), pp. 556-560.

HAN, J., ZHANG, G., ZHANG, Q., ZHANG, J., LIU, J., TIAN, L., ZHENG, C., HAO, J., LIN, J., LIU, Y. and MOSCHANDREAS, D.J., 2007, 'Field Study On Occupants' Thermal Comfort And Residential Thermal Environment In A Hot-Humid Climate Of China,' Building And Environment, 42(12), pp. 4043–4050

HEIESLBERG, P., 2008, 'Characteristics of Natural and Hybrid Ventilation Systems,' AWBI, H.B., Ventilation Systems: Design and Performance, Taylor & Francis, Oxon.

HUMMELGAARD, J., JUHL, P., SÆBJÖRNSSON, K.O., CLAUSEN, G., TOFTUM, J., and LANGKILDE, G., 2007, 'Indoor Air Quality and Occupant Satisfaction In Five Mechanically And Four Naturally Ventilated Open-Plan Office Buildings,' Building And Environment, 42(12), pp. 4051-4058.

KHATAMI, N., COOK, M.J. and HUDLESTON, N., 2011, 'Opportunities For Improving Environmental Performance of Retrofitted Lightweight Offices In Temperate Climates, Roomvent 2011,' The 12th International Conference On Air Distribution In Room, Trondheim.

KHATAMI, N., COOK, M. J., FIRTH S.K. and HUDLESTON, N., 2013, 'Control of Carbon Dioxide Concentration In Educational Spaces Using Natural Ventilation,' International Journal of Ventilation, 11(4), pp. 339-352.

LOMAS, K.J., 2007, 'Architectural Design of An Advanced Naturally Ventilated Building Form,' Energy And Buildings, 39, pp. 166–181.

MARTIN, A. and FITZSIMMONS J., 2000, Making Natural Ventilation Work (GN 7/2000). BSRIA, Bracknell.

MOUJALLED, B., CANTIN, R. and GUARRACINO, G., 2008, 'Comparison Of Thermal Comfort Algorithms In Naturally Ventilated Office Buildings,' Energy And Buildings, 40(12), pp. 2215-2223.

NICOL, J.F. and HUMPHREYS, M. A., 2002, 'Adaptive Thermal Comfort and Sustainable Thermal Standards For Buildings,' Energy And Buildings, 34(6), pp. 563-572.

PETTY, S.E., 2013, Forensic Engineering: Damage Assessments For Residential and Commercial Structures, Florida, CRC Press.

SE CONTROLS, 2013, NVLogiQ™ Room Controller <http://www.secontrols.com/assets/uploads/NVLogiQ_Room_Controller.pdf> retrieved on March 10, 2014.

WARD, I., 2004, Energy and Environmental Issues for the Practising Architect: A Guide to Help at the Initial Stage of Design, Thomas Telford Publishing, London.