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# On the Use of Windcatchers in Schools: Climate Change, Occupancy Patterns, and Adaptation Strategies

A. Mavrogianni D. Mumovic

The Bartlett School of Graduate Studies, University College London, UK

## Key Words

Schools · Post occupancy evaluation · Thermal modeling · Building regulations · Ventilation rates · Indoor air quality · Climate change · Overheating

## Abstract

Advanced naturally ventilated systems based on integration of basic natural ventilation strategies such as cross-ventilation and stack effect have been considered to be a key element of sustainable design. In this respect, there is a pressing need to explore the potential of such systems to achieve the recommended occupant comfort targets throughout their lifetime without relying on mechanical means. This study focuses on use of a windcatcher system in typical classrooms which are usually characterized by high and intermittent internal heat gains. The aims of this paper are 3-fold. First, to describe a series of field measurements that investigated the ventilation rates, indoor air quality, and thermal comfort in a newly constructed school located at an urban site in London. Secondly, to investigate the effect of changing climate and occupancy patterns on thermal comfort in selected classrooms, while taking into account adaptive potential of this specific ventilation strategy. Thirdly, to assess performance of the

ventilation system using the newly introduced performance-based ventilation standards for school buildings. The results suggest that satisfactory occupant comfort levels could be achieved until the 2050s by a combination of advanced ventilation control settings and informed occupant behavior.

## Introduction

There is compelling scientific evidence that our climate is changing and it is considered “very likely” that human-induced greenhouse gas emissions have been the dominant cause of the observed changes [1]. In addition, a set of research studies indicate that there is a direct link between indoor air quality (IAQ) and the occupants’ physical and psychological well being [2–4]. As a result, the interest towards the design of low-energy buildings of enhanced environmental performance has grown exponentially among professionals dealing with the built environment.

Natural ventilation is attaining wide acceptance nowadays as a low-carbon design strategy. During winter, a minimum ventilation rate is required in order to satisfy IAQ standards, whereas higher air-flow rates are needed during summer to deliver the desired cooling effect [5].

However, as average UK temperatures can be expected to increase between 2.0°C and 3.5°C over the next 50–80 years [6], the effectiveness of these strategies will be limited.

In particular, as indicated by previous studies [7–11], the application of natural ventilation in school buildings presents a significant challenge. Schools are characterized by exceptionally high internal heat gains of intermittent character, which form a hugely decisive factor of their thermal metabolism. This could be further exacerbated as current trends in school design include the improved access to Information and Communication Technology (ICT) equipment across the curriculum. Moreover, the problem could be compounded by the increased length and density of occupation as schools are encouraged to develop as focal points for a range of community services [12].

It is possible that the above factors might render the control of the classroom indoor climate by passive means difficult in the future. To avoid the use of mechanical ventilation or HVAC systems, which further contribute on greenhouse gas emissions, the existing and future potential for the application of natural ventilation must be evaluated.

In the UK context, substantial public funds will be invested for a massive program of rebuilding and refurbishing of school buildings, entitled “Building Schools for the Future”, which is expected to transform radically the schools estate in England and Wales in the next 15 years [13]. Undoubtedly, this funding framework offers an excellent opportunity for integrating sustainable design strategies into the decision making process of school building. The goals of this program are underpinned by Building Bulletin 101 (BB101), which sets a series of performance criteria in relation to the ventilation rates, indoor air quality, and thermal performance of newly built schools [14], as means of compliance with the revised Parts F and L2 of the UK Building Regulations [15,16]. The raised standards of the newly adopted Regulations are expected to reduce the emissions of new and existing buildings and meet the UK’s target of a 80% CO<sub>2</sub> emission reduction by 2050.

The key objectives of the present study were as follows:

(a) To provide evidence of the in-use performance of a typical classroom configuration with single-side ventilation provided by manually operated windows in conjunction with an advanced windcatcher system. To achieve this, a series of winter and summer measurements of indoor environmental variables and a summer thermal comfort questionnaire survey were carried out. Compliance with the existing performance

standards in relation to ventilation rates and IAQ was also assessed.

(b) To investigate how the effect of the given ventilation strategy can be affected by global warming and changes in occupancy patterns and what steps are needed for its future successful application and optimization. Parametric analysis of thermal conditions using modeling software was used to assess the impact of changing climate and occupancy trends on overheating.

## Materials and Methods

### *Description of the Case Study Building*

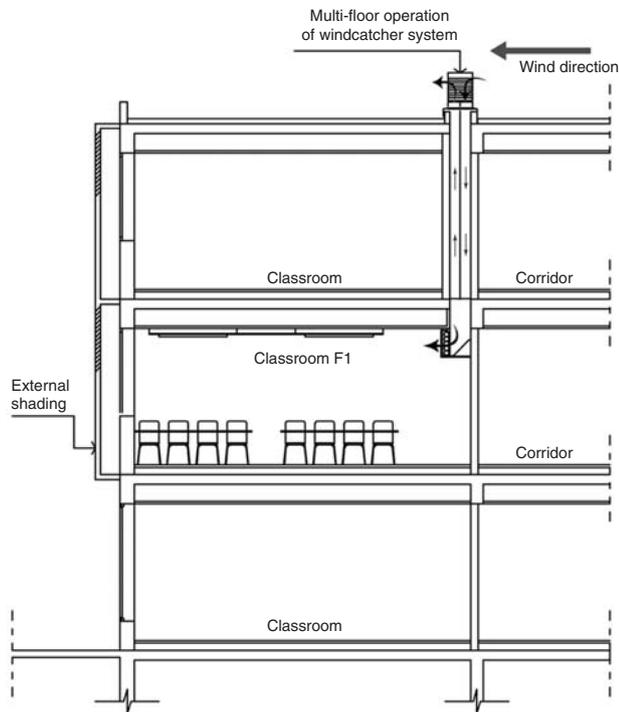
The case study building is a 1500 place secondary school, located at an urban site facing a busy road. The construction project was completed in 2005. The one-to three-storey building volumes are arranged around a central landscaped courtyard. It includes learning areas, a main hall, as well as recreational and dining facilities, which are shared with the community. The majority of the classrooms have a similar interior layout. The ventilation strategy in the first room (F1) is illustrated in Figure 1. It relies on both three manually operated windows located on the south-east facing side of the room and the wind and buoyancy driven split-duct roof mounted windcatcher system (Monodraught, Figure 2) located on the other side of the room. During the winter monitoring the Monodraught was the only operational system as all manually operated windows were locked to reduce the heating costs. The second room (F2) is located on the ground floor and is south-west oriented. It is characterized by high heat gains from computers. In principle, the ventilation strategy for this room is identical to the previous one. Although the same size as the previous room (the floor area), this room is deeper and characterized by higher ceilings. An underfloor heating system is installed in most classrooms.

### *Post Occupancy Evaluation*

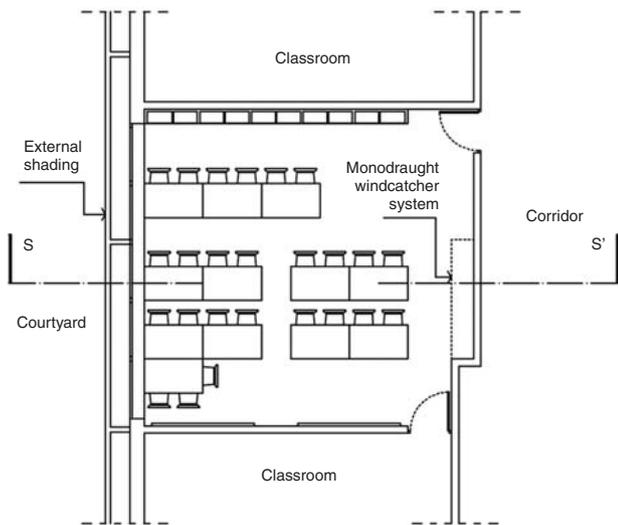
The post occupancy evaluation process consisted of two separate stages:

(a) A monitoring approach was developed to investigate the key performance parameters assessing if the design provided adequate thermal comfort and IAQ in *winter*.

(b) A combined approach including both monitoring and an occupant comfort questionnaire survey was used



(a) Section S-S'



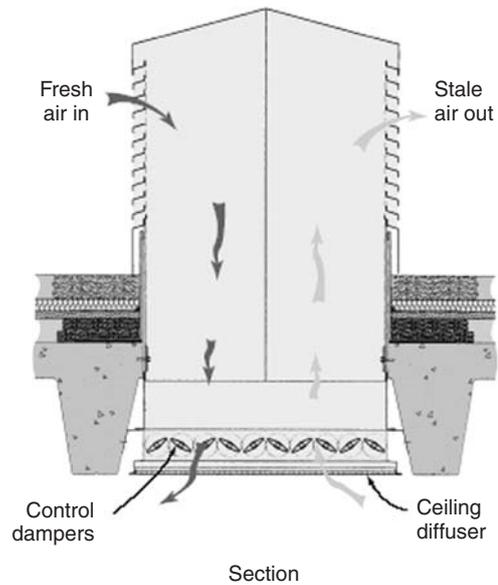
(b) Plan

**Fig. 1.** Physical configuration of room F1 (typical classroom).

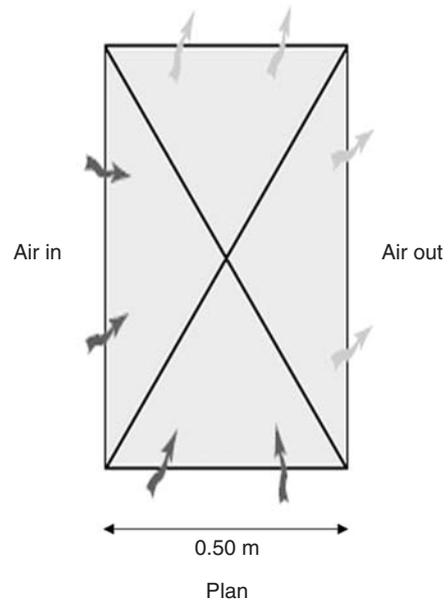
during *summer* in order to assess the levels of summertime overheating.

#### Winter Study

In order to indicate the overall IAQ and provide a means of inferring the ventilation rate based on the number of occupants, levels of CO<sub>2</sub> were monitored at 1-min intervals



Section



**Fig. 2.** Windcatcher section.

throughout the occupied day, in locations close to the occupied zone at seated head height. The monitoring took place during the heating season in the period of 12th–16th February 2007. Two Quest Technologies infra-red gas monitors (AQ5001Pro) (accuracy: 3% of the range – 0–20,000 ppm) were used for the indoor measurements. The Quest Technologies monitors included thermistor sensors measuring ambient temperature (accuracy:  $\pm 0.5^{\circ}\text{C}$ ) and capacitive sensors measuring relative humidity (accuracy: 3%). Due to interference from the occupants it is very difficult to obtain the reliable and complete set of results. These specific monitors have been chosen as they come with a dual power supply (AC power/batteries), built-in

datalogging capabilities, and a specially designed lockable enclosure, which prevents the interference from the occupants, while allowing for nonobstructed air flow around the sensors. In addition, outdoor CO<sub>2</sub> was measured using a much cheaper Telaire 7001 infra-red gas monitor (accuracy: 50 ppm or 5% of the reading, whichever is greater). Although the outside concentration of CO<sub>2</sub> does not fluctuate significantly during the day (in comparison to CO<sub>2</sub> levels found in classrooms), the outside monitoring was useful to investigate any unexpected source of CO<sub>2</sub> in vicinity of the school building. In order to minimize the cost of study associated with “loss” of the equipment during the monitoring campaign the monitoring equipment designed by various manufacturers was used. As all equipment was calibrated prior to the field monitoring, the relatively small differences in technical specifications of the monitors used were considered not being significantly important for the purpose of this study.

Ventilation rates were also estimated over suitable intervals using Equation (1), a form of “continuity equation” [11,17]:

$$C_{(t)} = C_{ex} + \frac{G}{Q} + \left( C_{in} - C_{ex} - \frac{G}{Q} \right) e^{-\frac{Q}{V}t}, \quad (1)$$

where:  $C_{(t)}$  – internal concentration of CO<sub>2</sub> at time  $t$  (ppm),  $C_{ex}$  – external concentration of carbon dioxide (ppm),  $G$  – generation rate of CO<sub>2</sub> in the space ( $\text{cm}^3 \cdot \text{s}^{-1}$ ),  $Q$  – internal–external exchange rate ( $\text{m}^3 \cdot \text{s}^{-1}$ ),  $C_{in}$  – initial concentration of CO<sub>2</sub> (ppm),  $V$  – room volume ( $\text{m}^3$ ), and  $t$  – time (s). Note that during unoccupied periods, the generation rate of CO<sub>2</sub> in the space,  $G$  was assumed to be zero.

The Equation (1) is correct only under the following assumptions:

- (a) the internal–external exchange rate,  $Q$ , and the generation rate of CO<sub>2</sub> in the space,  $G$ , are constant over the analysis period, i.e., during a given lecture,
- (b) it is sufficiently safe to assume that a steady state has been prevailing when the initial concentration of CO<sub>2</sub>,  $C_{in}$ , was taken.

After examining the CO<sub>2</sub> record, it was decided to apply the Equation (1) to 20 min blocks of data. For example, if the generation rate of CO<sub>2</sub> in the space,  $G$ , changed during this 20 min (typically because of pupils leaving or entering the room) then the time-averaged value of the CO<sub>2</sub> emission was used. The CO<sub>2</sub> emission rates per person were estimated using the method presented in Coley and Beisteiner [18] and are between 0.0041 and 0.0055 L · s<sup>-1</sup>.

The aim of the ventilation measurements was 2-fold: (a) to assess the CO<sub>2</sub> levels and to estimate time-varying ventilation rates in this newly built school without altering the normal performance of the ventilation system and (b) to carry out a number of small intervention studies in both classrooms (windows opened/closed, etc.) to test the capabilities of the design to adequately ventilate the room. Note that the number of students during the “observed” occupancy in the rooms differed from the “as designed” number of occupants. As the ventilation requirements are quoted per occupant, two ventilation rates, for the observed and designed occupancy level, were calculated and reported. Thermal comfort in classrooms in winter is a combination of the performance of the heating system and the ventilation provision. This very close relationship means that a poorly integrated approach to heating and ventilation can result in cold draughts and significant occupant discomfort. As a consequence, occupants may reduce ventilation to reduce discomfort. The following thermal comfort parameters were measured during the occupied periods in each of the selected classrooms: (a) dry bulb temperature, measured via: a platinum resistance sensor ( $\pm 0.1^\circ\text{C}$ ) screened to eliminate any thermal radiation effects, an air velocity compensation sensor, and a relative humidity compensation sensor, (b) relative humidity, measured with a VAISALA capacitive sensor ( $\pm 2\%$ ), (c) globe temperature, measured with a platinum resistance sensor ( $\pm 0.1^\circ\text{C}$ ) within a 30 mm black sphere, and (d) air velocity, measured with a DANTEC heated thermocouple sensors ( $\pm 2.5\%$  of the reading).

Measurements made in every second were averaged over 2-min intervals. The thermal comfort parameters were measured at two locations simultaneously, one being fixed at the normal work position of a pupil close to an openable window, while the second thermal comfort analyzer was moved to different locations across the rooms. Measurements were carried out with the sensors at a height of 1.1 m, which corresponds to the height recommended in ISO 7726-1985 (Thermal environments – instruments and methods for measuring thermal comfort) for head level for a sedentary occupant.

The procedure laid out in ISO Standard 7730-1995 was used to determine the Percentage of People Dissatisfied (PPD) and the Draught Dissatisfied Rating (DDR) indices and specifications of the conditions for thermal comfort. The PPD provides information on the thermal discomfort by predicting the percentage of people likely to feel too hot or too cold in a given environment. The clothing levels of “light working clothing ensemble” was selected as being the most appropriate for occupants of school classrooms

with a value of 0.7 clo. Although the clothing levels did vary pupils in the school were required to wear similar school uniforms during winter. The metabolic rate for a sedentary activity level or posture may be approximated as  $70 \text{ W} \cdot \text{m}^{-2}$  (Annex B of ISO 7730-1995). Dissatisfaction due to air movement is not a straightforward relationship to air speed; the DR takes into account fluctuations in local air speeds and local temperatures. The DR index should not exceed 15% for a comfortable environment.

### Summer Study

An attempt was made to assess the current levels of overheating inside the same two classrooms during summer. TinyTag Ultra 2 Dual Channel dataloggers (TG-4500) took measurements of dry bulb temperature (accuracy  $\pm 0.9^\circ\text{C}$ ) and relative humidity (accuracy  $\pm 3.0\%$  at  $25^\circ\text{C}$ ) at 30-min intervals during the cooling season in the period of 2nd–16th July 2008.

As the assessment of thermal comfort conditions cannot fully rely on the results derived by means of the CIBSE and ISO standards, a student and staff questionnaire survey was conducted in the period of 2nd–6th July 2007 and drew on a sample of 10 classrooms. A total of 200 questionnaires were distributed to students during the course of the class and 132 of them were completed. School occupants were invited to answer to a structured set of questions on their level of satisfaction with the environmental conditions in the specific classroom in terms of thermal, visual, and acoustic comfort, as well as air quality. A seven-point scale was used for thermal preference (from  $-3$  to  $+3$ ) and a five-point scale for the rest of the environmental factors (from  $-2$  to  $+2$ ), (Table 1).

### Thermal Modeling

The EDSL Thermal Analysis Software package [19] was used to perform a series of dynamic thermal simulations. The design objective underlying the

**Table 1.** Questionnaire survey comfort scales

VOTE	Thermal comfort	Indoor air quality	Acoustic comfort*	Visual comfort
-3	Cold	-	-	-
-2	Cool	Very stale	Very difficult	Too dark
-1	Slightly cool	Stale	Difficult	Dark
0	OK	OK	OK	OK
+1	Slightly warm	Fresh	Easy	Bright
+2	Warm	Very fresh	Very easy	Too bright
+3	Hot	-	-	-

\*Ability to hear the teacher.

simulation work was to estimate the frequency of occurrence of peak temperatures for different naturally ventilated schemes. It is well understood that the assessment of overheating in buildings is a complex procedure. The aim of the present study was not to evaluate the overheating criteria currently in use, but to simply examine whether these are met in the case study building under different scenarios. Therefore, the output of dry bulb temperature values ( $^\circ\text{C}$ ) in the classrooms was used to assess compliance with the BB101 performance standard for the avoidance of summertime overheating (Table 2).

The modeling procedure consisted of different steps of data input to the program. A simplified 3D model of the whole school was created in order to simulate the physical configuration of the existing building geometry (Figure 3). This article mainly focuses on the results in the two monitored rooms (F1 and F2).

The winter ventilation strategies were subjected to the CIBSE Test Reference Year (TRY) for London, a synthesized typical weather data set commonly used for analyzing the overall environmental performance of buildings. In order to assess overheating, the summer ventilation strategies were assessed against the CIBSE London Design Summer Year (DSY). This weather file enables the simulation of the building's summer thermal performance during a year with semi-extreme representative summers [20].

**Table 2.** The DfES Building Bulletin 101 performance standards in relation to ventilation rates, IAQ, and the avoidance of summertime overheating

Performance standard for the external air supply
Purpose-provided ventilation should provide external air supply to all teaching and learning spaces with:
(a) a minimum of $3 \text{ L} \cdot \text{s}^{-1}$ per person.
(b) a minimum daily average of $5 \text{ L} \cdot \text{s}^{-1}$ per person.
(c) a capability of achieving a minimum of $8 \text{ L} \cdot \text{s}^{-1}$ per person at any time.
Performance standard for indoor air quality
(a) The maximum concentration of $\text{CO}_2$ should not exceed 5000 ppm during the teaching day.
(b) At any occupied time the occupants should be able to lower the concentration of $\text{CO}_2$ to 1000 ppm.
Performance standard for the avoidance of overheating*
(a) There should be no more than 120 h when the air temperature in the classroom rises above $28^\circ\text{C}$ .
(b) The average internal to external temperature difference should not exceed $5^\circ\text{C}$ (i.e., the internal air temperature should be no more than $5^\circ\text{C}$ above the external air temperature on average).
(c) The internal air temperature when the space is occupied should not exceed $32^\circ\text{C}$ .

\*In order for a school not to suffer overheating two of these criteria must be met.

The TRY and DSY weather files used define the “present climate” baseline for London, e.g., the 1990s. The same ventilation strategies were tested against the UK Climate Impacts Program 2002 (UKCIP02) climate change scenarios [6], which are based on the 2000 global emissions scenarios published by the Intergovernmental Panel on Climate Change (IPCC), [21]. In these scenarios the future climatic conditions in the UK for  $50 \times 50$  km grid squares and for three 30-year time-slices (2020s, 2050s, and 2080s) are modeled. No probabilities can be attached to these four climate futures and other future possibilities are not excluded. Due to limited scope of the present study it was preferred to focus on the comparative performance of multiple ventilation strategies for different time-slices under a single “middle” scenario (medium-high).

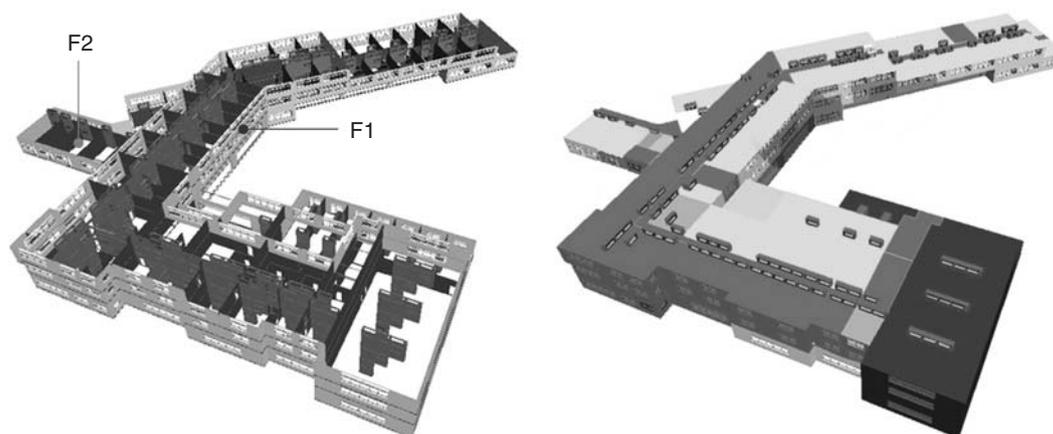
The TRY/DSY files were “morphed” according to the existing guidelines for constructing design weather data for future climates [22]. The morphing method “downscales” these data to the spatial and temporal resolutions required for the building modeling procedure, whilst preserving all physical relationships between the individual weather variables. It should be kept in mind, however, that the weather files used overestimate the impact of climate change as the baseline climate of the TRY/DSY used (1984–2004) is hotter than the baseline climate the UKCIP02 mean changes of the different environmental variables refer to (1961–1990).

The thermal properties of the building elements were specified beyond the requirements of the revised 2006 Part L2 [15]. An infiltration rate of 0.5 ac/h was assumed. The external walls consist of brickwork cavity walls filled in with polyurethane insulation ( $U$ -value =  $0.30 \text{ W} \cdot \text{m}^{-2} \cdot \text{C}$ ). The roof and ground floor are of concrete with insulation ( $U$ -value =  $0.23 \text{ W} \cdot \text{m}^{-2} \cdot \text{C}$ ). Despite the fact that the construction is “medium weight”, the thermal mass of

the horizontal elements (ceilings, floors) is not exposed as the intermediate floors are of concrete with false ceilings and carpet finishes. Double glazing windows were specified ( $U$ -value =  $1.80 \text{ W} \cdot \text{m}^{-2} \cdot \text{C}$ ). Shading is provided at all glazed elements by fixed external horizontal louvres. The external walls have a solar absorptance of 40% and the roof 65%. The surrounding land was assumed to have a 20% ground reflectance to solar radiation.

The operational characteristics of a classroom, such as the occupancy schedules and the use of electrical equipment, form a dominant factor of its thermal performance. However, they tend to be stochastic and difficult to approximate. Thus, figures for peak occupancy rather than typical occupancy were used for the base case internal conditions according to the recommendations for overheating risk assessment studies [23]. It was assumed that lights were always on as was the case in many of the classrooms surveyed. The intermittent use of the overhead projectors in the classrooms was considered negligible. The resulting occupant, lighting, and equipment heat loads were calculated by the DfES ClassCool Version 1(1).02 Software, as quoted in BB101 [14]. It was estimated that the occupancy density in each classroom was  $1.8 \text{ m}^2$  per person. Internal gains due to lighting were included at  $10 \text{ W} \cdot \text{m}^{-2}$  and an equipment load of  $4.5 \text{ W} \cdot \text{m}^{-2}$  was assumed.

The values quoted above are calculated by assuming the “worst-case scenario” of the classroom being fully occupied throughout the day. Nonetheless, this is seldom the case in a typical classroom with students leaving the class in groups for a variety of reasons (lunch, gym, special classes). It is highly likely, therefore, that the use of the above values might lead to an overestimation of the overheating risk. Hence, an additional sensitivity analysis was carried out in order to assess the impact of different



**Fig. 3.** 3D model of case study school building.

occupancy levels, lighting schedules, and equipment use on the thermal performance of the classroom. This allows for the difference between the base “worst-case” scenario and the “realistic” occupancy level scenario to be quantified. The simulations were run for continuous year-round usage, taking into account winter and summer holidays. Two scenarios of possible occupancy patterns were tested (“current timetable” and “extended hours”) and are summarized in Table 3.

A heating plant was specified for the winter and midseason simulations. The lower limit of the thermostat was set to 19°C and the upper to 21°C.

The paper focuses on the optimization of the daytime ventilation control settings. This design question was translated into the modeling task of simulating the three summer ventilation strategies summarized in Table 4. Additionally, simulations were run to assess the possible risk of overheating during winter and midseason (Table 5).

## Post Occupancy Evaluation Results

### *IAQ and Ventilation Performance during Winter*

During the monitoring of “usual” conditions in both rooms only the Monodraught system was operational as all manually operated windows were locked to reduce heating costs. In both rooms the daily average of 1500 ppm was not exceeded leading to the conclusion that the implemented ventilation strategy was providing adequate ventilation for observed occupancy levels. In the classroom F1 the average CO<sub>2</sub> level during the occupied period were 1185 ppm, while in the classroom F2 the average was 1391 ppm. The maximum recorded levels in the rooms F1 and F2 were 2570 and 2585 ppm, respectively, well below the upper limit of 5000 ppm, which may indicate that on average more than 5 L · s<sup>-1</sup> per person of outdoor air was being supplied. However, this is misleading unless one takes into account three important factors: (a) the occupancy schedule for

**Table 3.** Occupancy level scenarios tested

Name	Description	Days	Hours
Current timetable	The school follows the traditional timetable in accordance with BB101.	Monday to Friday	9 am to 3:30 p.m. with an 1-h lunch break
Extended hours	All spaces are open to the whole community or for extra-curriculum activities.	All week long	8 am to 10 p.m.

**Table 4.** Control settings of the summer ventilation strategies tested

	Type of opening	Settings	Schedule
A	Lower windows	Start to open when Tint > 21°C	Occupied hours
	Upper windows	Remain fully open when Tint > 23°C	
	Windcatcher dampers	Start to open when Tint > 19°C	
B	Lower windows	Start to open when Tint > 23°C	Occupied hours
	Upper windows	Remain fully open when Tint > 25°C	
	Windcatcher dampers	Start to open when Tint > 21°C	
C	Lower windows	Fully open	1 am – 4 p.m.
	Upper windows	Start to open when Tint > 23°C	
	Windcatcher dampers	Remain fully open when Tint > 25°C	

**Table 5.** Control settings of the winter ventilation strategies tested

	Type of opening	Settings	Schedule
A	Lower windows	Start to open when Tint > 23°C	Occupied hours
	Upper windows	Remain fully open when Tint > 25°C	
	Windcatcher dampers	Start to open when Tint > 21°C	
B	Lower windows	Start to open when Tint > 22°C	Occupied hours
	Upper windows	Remain fully open when Tint > 23°C	
	Windcatcher dampers	Locked	
C	Lower windows	Start to open when Tint > 22°C	Occupied hours
	Upper windows	Remain 50% open when Tint > 23°C	
	Windcatcher dampers	Locked	

classrooms (i.e., the classrooms were not fully utilized during the “normal” occupied hours, preventing CO<sub>2</sub> building up during the day), (b) the occupancy level during classes (i.e., number of students attending classes) and (c) occupant behavior. These factors have had a significant effect on the performance of both classrooms. Therefore, to enable comparison of the performance of the installed ventilation systems, the ventilation rates reported in Table 6 are based on both the designed and the observed occupancy levels. The averaged ventilation rates during the occupied period show that both classrooms studied could be ventilated at a higher rate than achieved in normal usage. In the classroom F1, the averaged ventilation rate during the occupied hours was 5.5 L · s<sup>-1</sup> per person – calculated for an average occupancy of 10. The averaged ventilation rate in the classroom F2 during the occupied hours was 3.4 L · s<sup>-1</sup> per person – calculated for an average occupancy of 15.

To test the capability of the system to deliver 8 L · s<sup>-1</sup> per person for the maximum designed occupancy levels an intervention study was carried out as follows: All manually operable windows were fully opened on one side, and dampers were partially opened (20% of the total openable area) on the other side. Note that F2 was a deep plan room and that the openable area of windows in both rooms was only 0.32 m<sup>2</sup>. The ventilation design failed to comply with this specific requirement delivering 6.8 and 4.4 L · s<sup>-1</sup> per person in rooms F1 and F2, respectively, the minimum ventilation rates were 2.6 and 1.1 L · s<sup>-1</sup> per person. Although unsatisfactory, this shows that if better designed this advanced naturally ventilated system could have potential to provide a minimum ventilation rate of 3 L · s<sup>-1</sup> per person at any time as required by BB101.

#### *Thermal Performance during Winter*

With regard to the internal temperatures, CIBSE Guide A1 [24] suggests design criteria for educational buildings. For teaching spaces the specified winter

temperature is 19–21°C. The average temperatures found in the school were fairly constant varying between 24°C and 25°C. During the monitoring period the occupancy levels were varying between 10 and 18 and the ICT equipment was used intermittently. Obviously, these rooms did not meet CIBSE recommended levels for winter conditions and sometimes barely falling within the summer upper limit, indicating that there could be some discomfort among students due to the thermal environment. The average external temperatures were ~10°C with maximum temperatures exceeding 15°C for a few hours only. Note that these relatively high internal temperatures were supplemented with a low averaged ventilation rate of 3.4 L · s<sup>-1</sup> per person during the occupied hours and the occupants were not able to open windows at any time. Although due to restricted window opening the system was capable to deliver only 6.8 L · s<sup>-1</sup> per person and 4.4 L · s<sup>-1</sup> per person in the “purge” mode in the rooms F1 and F2, respectively, the intervention studies investigating cross-ventilation mode showed that this was sufficient to lower the temperature in both rooms. Therefore, the phenomenon of “winter overheating” can be associated with the under-ventilation of naturally ventilated classrooms.

Dissatisfaction due to air movement does not have a simple relationship with air speed; the draught index takes into account fluctuations in local air speeds and local temperatures in order to determine the PPD due to draughts. Note that the draught risk barely exceeded the generally accepted level of 15% a number of times in the Room F2 only (Table 7).

#### *Thermal Performance during Summer*

Unfortunately, the summer monitoring did not allow for the analysis of the actual thermal performance of the classrooms mainly due to: (a) exceptionally low external air temperatures, not typical of UK summer conditions

**Table 6.** CO<sub>2</sub> levels and ventilation rates in the two classrooms during winter

Occupancy levels	Observed			Observed	Designed	
Ventilation strategy	“Usual” mode: All windows closed, operational windcatcher system			“Usual” mode: All windows closed, operational windcatcher system	“Purge” mode: All windows open, windcatcher damper 20% open	
	Monitored CO <sub>2</sub> concentration (ppm)			Inferred ventilation rates [L · s <sup>-1</sup> per person (given average occupancy)]		
Room	Min	Max	Std	Avg	Min	Max
F1	1185	2570	458	5.5 (10)	2.6 (30)	6.8 (30)
F2	1391	2585	487	3.4 (15)	1.1 (30)	4.4 (30)

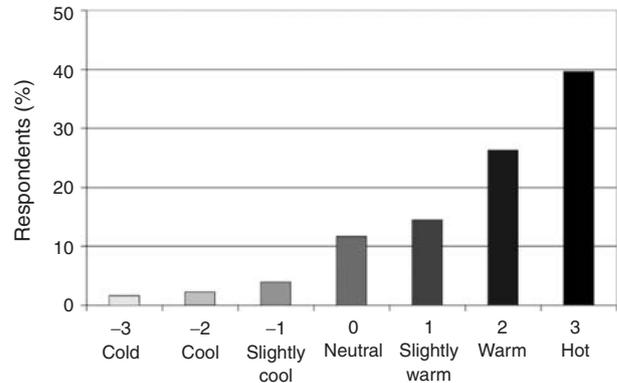
(July 2007) and, (b) low occupancy levels. Nevertheless, as outdoor ambient temperatures remained between 13°C and 24°C for most of the monitoring period, the obtained results could be regarded as indicative of the thermal performance of the building fabric during midseason. Monitoring data suggests that indoor temperatures approached the upper limit of the comfort zone (28°C) when only 40% of internal (occupant and equipment) heat loads were produced ( Figure 4). Thus, it is highly possible that overheating might occur at higher external air temperatures.

#### Occupant Comfort during Summer

In accordance with the monitoring data, the questionnaire survey results clearly illustrated the problem of summer overheating in the school. Based on their experience from past summers, 40% of the occupants stated that they usually feel “hot” and 26% that they feel “warm” (mean = 1.73, 95% c.i. between 1.51 and 1.94), (Figure 5). However, a discussion with the facilities manager revealed that the building had suffered from inappropriate user control as the windcatcher system control settings were accidentally set to “winter mode”

during previous summers. Due to this malfunction, it is not known whether better occupant comfort levels could have been achieved if the “summer mode” control settings were applied. Furthermore, it was observed that due to security issues, in most classrooms only a small fraction (~10 cm) of the single top hung windows could be opened. Thus, no additional cooling could be provided.

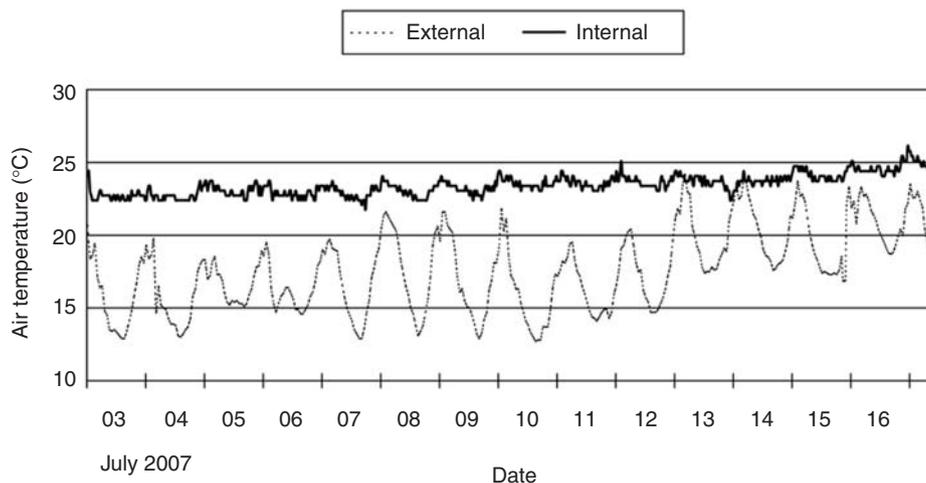
Overall air quality inside the classrooms was generally assessed as “good” by 40% of the respondents.



**Fig. 5.** Occupant questionnaire survey results – thermal comfort vote.

**Table 7.** Thermal comfort parameters in the two classrooms during winter

Occupancy levels	Observed						
Ventilation strategy	All windows closed, operational windcatcher system						
	Monitored dry bulb temperature (°C)		Monitored relative humidity (%)		Calculated thermal comfort parameters		
Room	Min	Max	Min	Max	PPD	DR	
F1	24.2	25.0	39	55	< 10	< 10	
F2	24.2	25.1	40	52	< 16	< 16	



**Fig. 4.** Summer monitoring results – dry bulb temperature (°C) in room F1.

Nonetheless, 33% of them found indoor air “stale” (mean = -0.31, 95% c.i. between -0.44 and -0.18). This result agrees with the observations related to limited ventilation from the windows and the windcatcher system.

High levels of acoustic comfort were recorded in all classrooms. Approximately 3 out of 4 students had no problem in hearing the teacher (mean = 0.65, 95% c.i. between 0.51 and 0.78). This proves the advantage of natural ventilation systems compared to mechanically driven ventilation and HVAC systems, which compromise the indoor acoustic comfort levels due to increased background noise.

The overall lighting conditions were generally judged as good or slightly bright by nearly all respondents (67% “OK”, 29% “bright”, mean = 0.29, 95% c.i. between 0.21 and 0.37). Nevertheless, it was observed that internal curtains were drawn in many classrooms and lighting was principally provided by artificial lighting rather than daylight, hence increasing energy consumption.

Anecdotal evidence collected from the teachers suggested that the occupant control over temperature, ventilation rates, and lighting levels was limited.

## Thermal Modeling Results

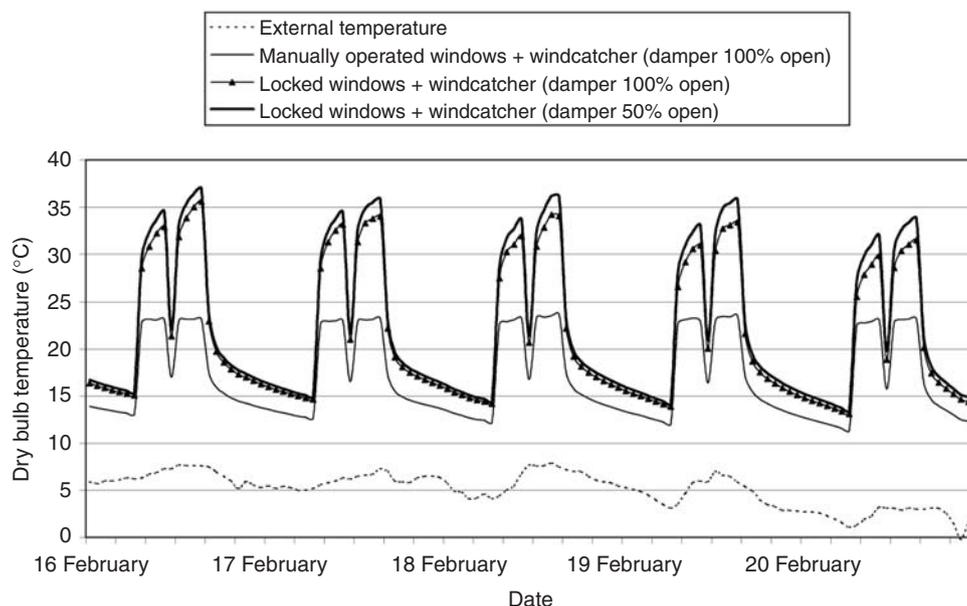
### Winter Overheating Assessment

The field survey indicated that some rooms are prone to winter overheating when the manually operated windows remain closed in order to minimize heat losses and the

ventilation system relies solely on the winter windcatcher damper control settings. According to simulation results room F2 is the most likely to suffer from winter overheating. As is clearly shown in Figure 6, indoor temperatures in the range 28–38°C might occur for full occupancy. This leads up to 328 h with internal temperatures above 28°C during winter and midseason in the 1990s, compared to only 17 h if the windows are allowed to open (cross-ventilation). This underpins the observation made during the intervention studies that increased ventilation rates are necessary in order to purge the rapidly accumulated heat in rooms with exceptionally high internal heat gains.

### Summer Overheating Assessment

The comparative thermal performance of the three summer ventilation strategies during a period of five continuous hot weekdays in the 1990s is illustrated in Figures 7 and 8. When daytime ventilation is applied (Strategy A), the windows and the windcatcher damper remain open during most of the occupied hours. As a result, the internal temperatures closely follow the fluctuations and the peaks of the external temperature. Internal values are limited by daytime ventilation to ~2°C above the external. The classroom performs slightly better, when the windcatcher dampers remain open during the night (Strategy B). However, the cooling effect of this strategy is limited compared to providing additional night purge cross ventilation by opening both the upper windows and the windcatcher dampers (Strategy C).



**Fig. 6.** Thermal simulation – dry bulb temperature (°C) in room F2 during five winter weekdays (1990s time-slice).

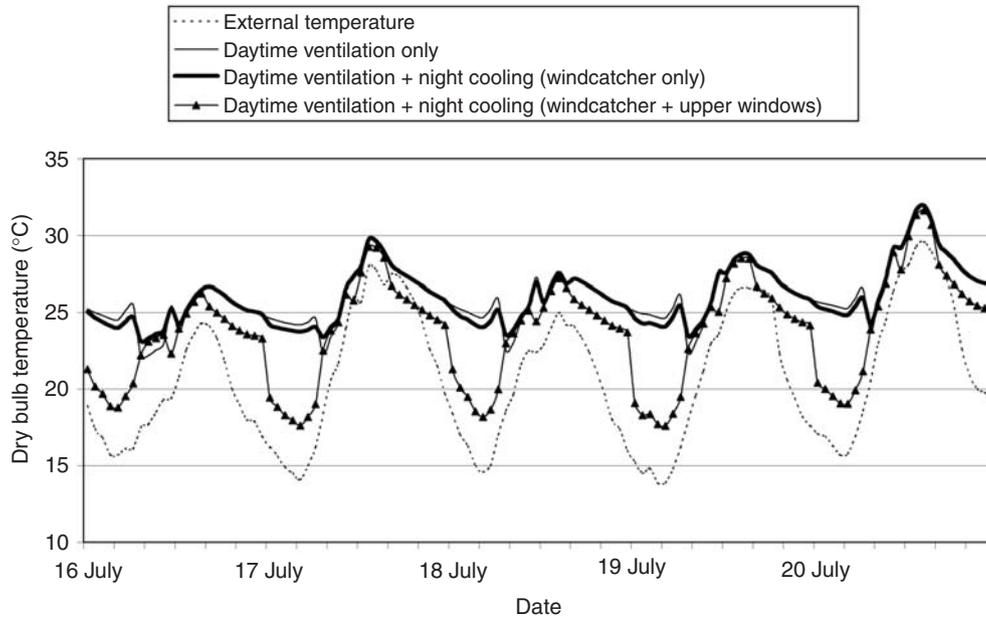
Allowing the ingress of night-time air to pre-cool the structure reduces morning temperatures by  $\sim 1^{\circ}\text{C}$ . Overall, the number of occupied hours with internal temperatures exceeding  $28^{\circ}\text{C}$  is reduced by up to 22 h if Strategy C is applied. Nevertheless, security issues might restrict the operation of the upper windows during night-time.

Additional analysis indicated that, as expected, the maximum ventilation rates are achieved indoors for wind directions, which are perpendicular to the windcatcher inlet/outlet surfaces (Figure 9). In addition, ventilation

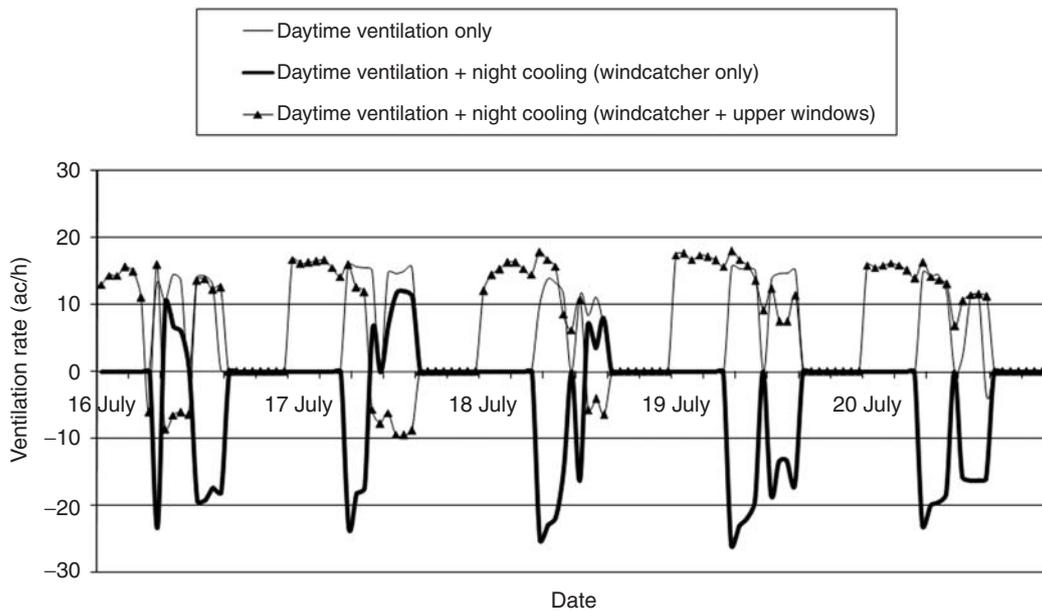
rates increase with wind speed. However, there is a wider distribution of ventilation rate values at the lower range of wind speeds. This could be possibly attributed to the fact that in some instances high ventilation rates can be achieved under low wind speeds with indoor air movement mainly driven by the stack effect rather than cross ventilation.

#### Climate Change Scenarios

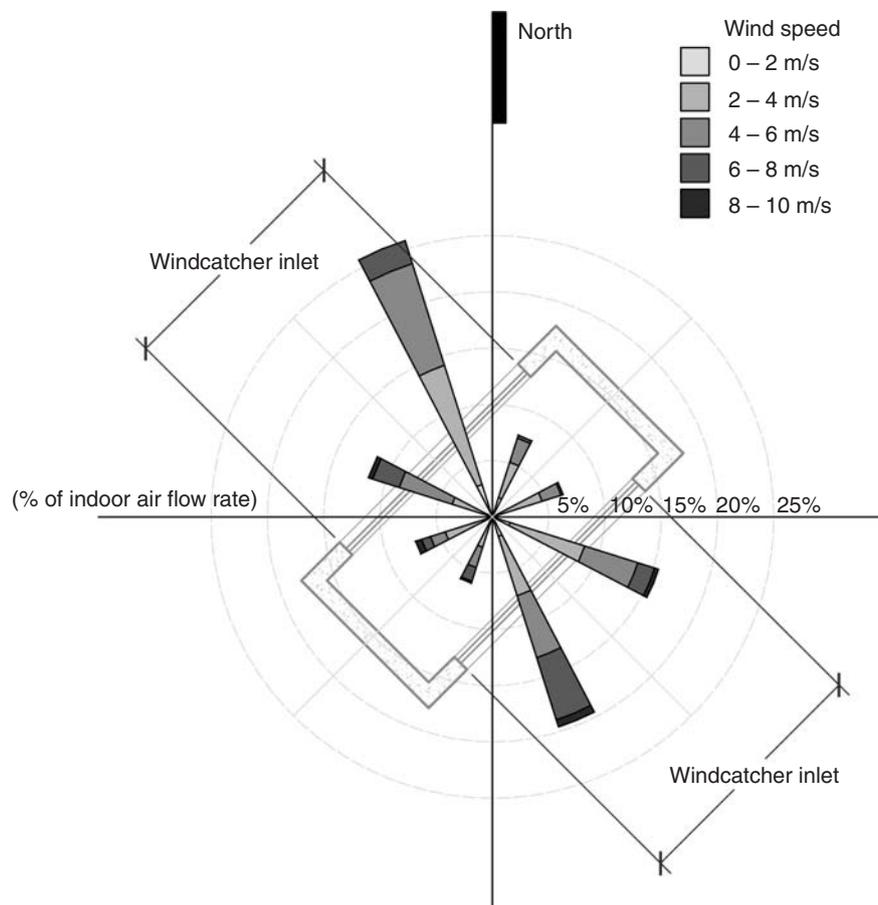
All strategies were tested against the BB101 performance standards for the avoidance of overheating (Table 2).



**Fig. 7.** Thermal simulation – dry bulb temperature ( $^{\circ}\text{C}$ ) in room F1 during five continuous hot weekdays (1990s time-slice).



**Fig. 8.** Thermal simulation – ventilation rates ( $\text{ac}\cdot\text{h}^{-1}$ ) in room F1 during five continuous hot weekdays (1990s time-slice).



**Fig. 9.** Achieved ventilation rates during the summer period as a function of wind speed and direction (windcatcher in Room F1).

The simulation results obtained for room F1 for all time-slices under the medium-high emissions scenario are summarized in Figure 10.

A common trend observed in the performance of all strategies is that, as the temperature differential between indoors and outdoors decreases, the number of hours with internal temperatures above the comfort limits increases. This illustrates the fact that indoor thermal conditions become increasingly reliant on the outdoor temperatures: occupants will tend to leave windows open for a longer time even if external air offers no cooling benefit.

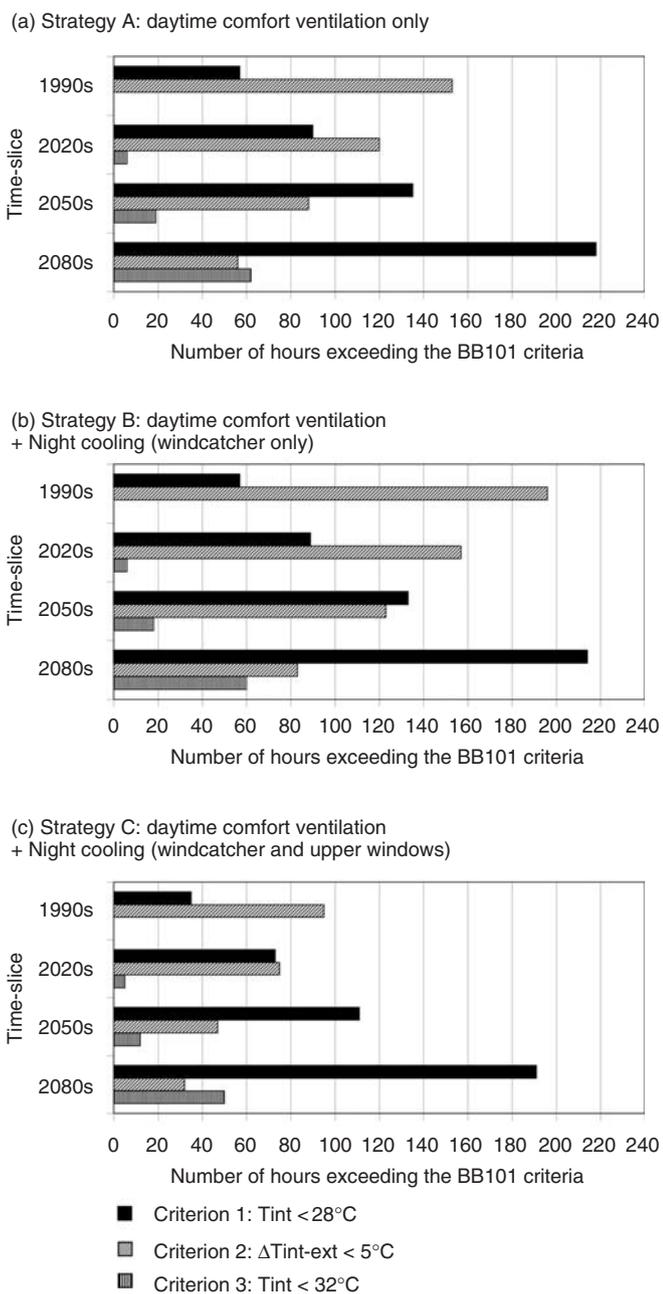
For all strategies, the occurrence of indoor temperatures above 28°C seems to be linearly correlated with time. Simulation predictions indicated that the BB101 criteria will be met in the typical classroom by daytime ventilation only (Strategy A) until the 2020s. As external air temperatures increase, the cooling benefit of night ventilation provided by the windcatcher system (Strategy B) could alleviate the problem of overheating. In the 2050s, higher airflow rates will be required e.g., by opening the upper windows during night-time in order to maintain daytime indoor temperatures below 28°C. Even this

strategy however proves to be unsuccessful in the 2080s time-slice (Figure 11).

To conclude, the cooling potential of daytime ventilation will be increasingly restricted due the increased frequency of summertime temperatures in the range 30–35°C by the middle of the century. However, limiting the airflow rates during the day might not lead to the desired effect as it would restrict the dissipation of the rapid heat build up during the day. Therefore, it is highly likely that progressing to a mixed-mode approach should be considered in order to satisfy the cooling demands of the typical classroom after the 2050s.

#### *Future Trends in School Use and Occupancy Levels*

As mentioned earlier, it should be borne in mind that the results presented above refer to the worst case scenario (full attendance, lights always on). Thus, it is probable that the risk of overheating is overestimated and comfort standards could be met if realistic occupancy levels are maintained. In addition, technological advances could lead to lower equipment power loads in the future.



**Fig. 10.** Thermal simulation – Summer overheating assessment of room F1 according to BB101 criteria.

The sensitivity of the thermal modeling process to the input of internal heat gain values is quantified in Figure 12 for Strategy B under the medium-high emissions 2050s scenario. The number of hours exceeding 28°C is reduced by 19% for 50% attendance as was the case for many of the teaching areas during the summer period. A further reduction of ~7% is achieved by eliminating the use of artificial lighting inside the classrooms. The simulations clearly indicated that the increased use of ICT equipment could significantly exacerbate the problem of overheating;

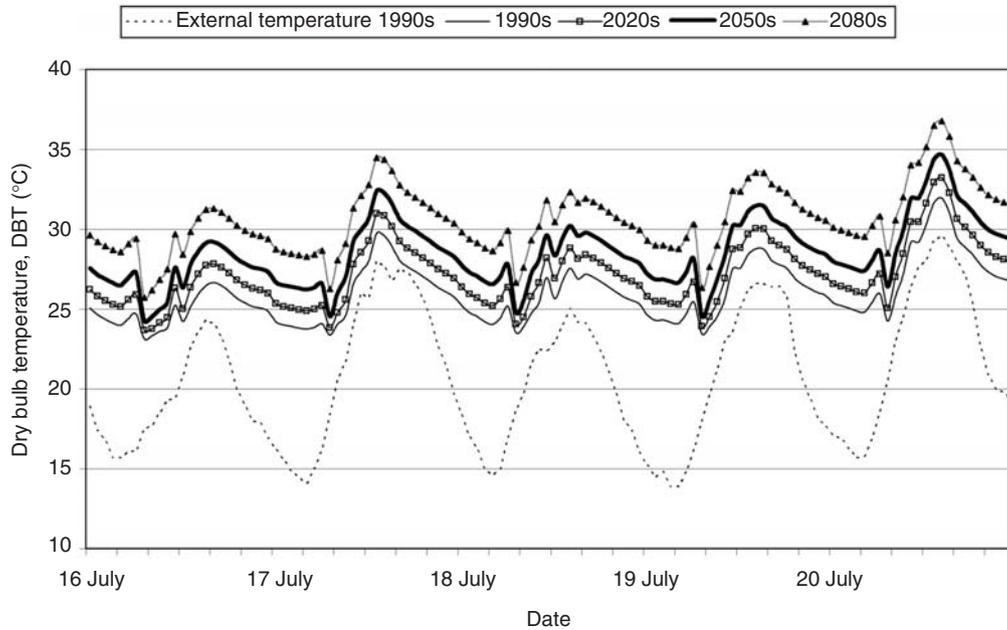
the addition of one PC per pupil and one overhead projector used continuously in each classroom results in a 94% increase of temperatures above 28°C. This might render additional cooling measures necessary in the future in order to purge the extra accumulated heat. The impact of the extension of the traditional timetable under the medium-high emissions 2050s scenario and when Strategy B is applied is also examined (Figure 13). A 29% increase in the number of occupied hours leads to an increase on the number of hours with internal summertime temperatures rising above 28°C of ~21 and 28% in the rooms F1 and F2, respectively. It has to be noted that peak temperatures tend to occur to a large extent during evening hours when the radiant temperatures of the surrounding surfaces will also be higher. This in turn can result in a further deterioration of the thermal conditions.

## Conclusions

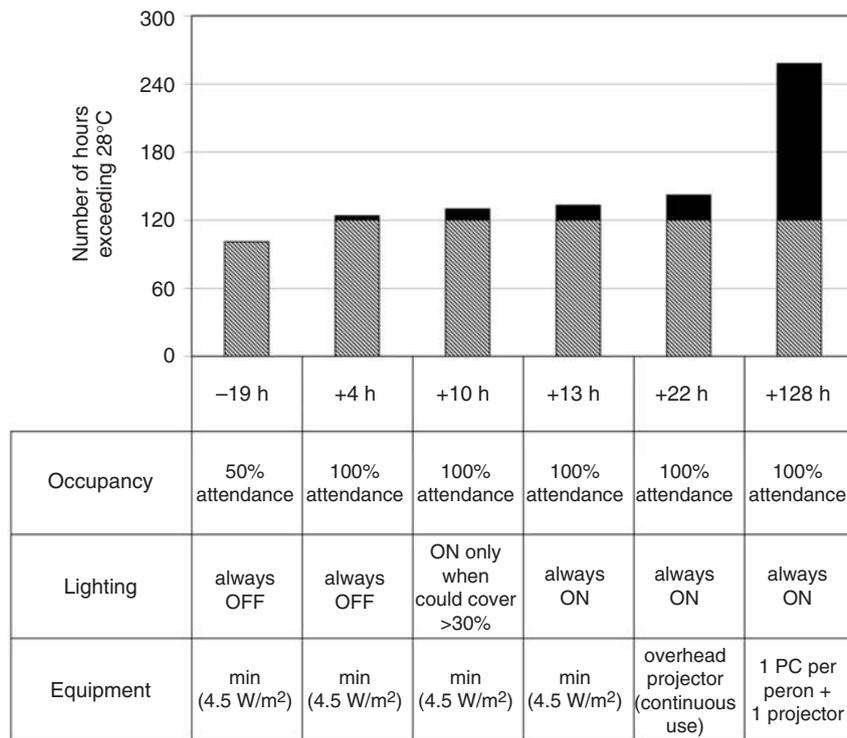
In relation to IAQ both monitored classrooms met the requirement of not exceeding 1500 ppm of CO<sub>2</sub> averaged over the day, but none met the need to readily provide 8 L · s<sup>-1</sup> per person under the easy control of the occupants. It would seem that the basic requirement of 1500 ppm of CO<sub>2</sub> is achieved as a consequence of the damper areas being just sufficient to provide that level of 3 L · s<sup>-1</sup> per person at low and intermittent occupancy. To meet the higher supply rate of 8 L · s<sup>-1</sup> per person in the natural ventilation designs as required by BB101 the openable area of window installations might need to be increased.

The thermal comfort in the classrooms monitored during winter was mostly acceptable, but temperatures tended to be much higher in practice than assumed during design. In this specific case the cause of this was dual: inadequate control of the heating system and the inadequate ventilation provision unable to remove the heat.

The study of summer thermal comfort conditions illustrated the fact that ventilative cooling in schools can be a “double-edged sword” [7]. The simulation predictions indicate that naturally ventilated school buildings coupled with advanced control system settings exhibit adequate thermal performance until the 2050s, since a significant portion of the external air temperatures during the summer term remains below 25°C. In addition, night ventilation proved to be beneficial even for a thermally lightweight structure. However, as temperatures are expected to rise from 2050s onwards, daytime ventilation will become an



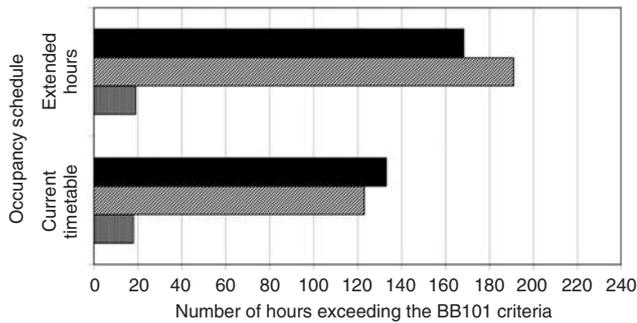
**Fig. 11.** Thermal simulation - Dry bulb temperature (°C) in room F1 for summer Strategy B for all time-slices under the UKCIP02 Medium-High emissions scenario.



**Fig. 12.** Thermal simulation – thermal performance of room F1 for summer Strategy B under the UKCIP02 Medium-High emissions scenario (2050s time-slice): sensitivity analysis for different internal gain schedules.

undesired heat source and it will be increasingly difficult to provide the required cooling loads during the 2080s. Thermal modeling also showed that the school fails to meet the overheating criteria when the current timetable is extended and, more importantly, when ICT equipment is

used extensively throughout the day. Thus, the design of naturally ventilated buildings should take into account these possible future trends. Importantly, before progressing to a mixed-mode approach, alternative strategies should be considered for the avoidance of overheating in



**Fig. 13.** Thermal simulation – thermal performance of room F1 for summer Strategy B under the UKCIP02 Medium-High emissions scenario (2050s time-slice): current timetable vs. extended hours.

schools in the longer term. These might include: (a) the increase of the thermal capacity of the building elements in conjunction with night-time cooling, as long as security issues are resolved and (b) the increase of controlled infiltration rates e.g., either by increasing the size of windcatcher dampers or by adding trickle ventilators. Further research should also investigate the impact of different size and orientation windcatcher arrangements on achieved ventilation rates in relation to the prevailing wind speed and direction of a given site.

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Last but not the least, the survey highlighted the fact that the inter-relationship between a natural ventilation system and the occupants is a key issue for its success. Automatic controls and manual override systems should be well integrated and easy to handle. In addition, the occupant awareness of the system should be promoted.

## Nomenclature

- DBT – Dry bulb temperature  
 DDR – Draught dissatisfied rating  
 DSY – Design summer year  
 PPD – Percentage of people dissatisfied  
 RH – Relative humidity  
 TRY – Test reference year

## Acknowledgments

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