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A methodology for post-occupancy evaluation of ventilation rates in schools

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The importance of maintaining adequate indoor air quality in schools is recognised as a contributing factor to pupils' learning performance. This paper describes a series of field measurements that investigating the ventilation rates in four recently built secondary schools in England. All schools were assessed for compliance with the recently adopted Building Bulletin 101, which defines the set of criteria in relation to the ventilation rates and indoor air quality in new school buildings. Using the obtained results a methodology has been suggested for post-occupancy evaluation of ventilation rates in schools. The suggested methodology draws particular attention to the dynamic nature of the interaction between the building and their occupants.

Practical application: The new Building Bulletin 101 is quoted in Approved Document F as a means of compliance with Building Regulations for school buildings in the UK. This paper, based on four case studies, highlights some of the problems facing architects, mechanical engineers and building control officers associated with post-occupancy evaluation of ventilation rates in new school buildings. The methodology suggested in this paper, which differs radically from the current practice, takes into account the changing nature of the indoor environment in schools including occupancy level and occupant behaviour.

1 Introduction

The UK Government has committed to a massive programme of rebuilding and refurbishing schools in England and Wales in the next 10 to 15 years. The aim of this programme entitled 'Building Schools for the Future'[1] is '*to build facilities for the 21st century at the scale not being seen since Victorian times*'. To underpin this programme The Department for Education and Skills has published design guidance Building Bulletin 101 'Ventilation in School Buildings'.[2] This performance standard document is cited as a means of compliance with the new Building Regulations Part F (Ventilation) in England and Wales.[3] In this document CO_2 concentration has been chosen as the key performance indicator for the assessment of indoor air quality and ventilation performance in schools. The recommended ventilation performance standard states:

> '*Ventilation should be provided to limit concentration of CO_2 in all teaching and learning spaces. When measured at seated head height, during the continuous period between the start and finish of teaching on any day, the average concentration of CO_2 should not exceed 1500 ppm.*'

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The performance standard stated above is followed by advisory standards recommended by the Health and Safety Executive:

1. the maximum concentration of CO_2 should not exceed 5000 ppm during the teaching day
2. at any occupied time the occupants should be able to lower the concentration of CO_2 to 1000 ppm.

In addition Building Bulletin 101 states that purpose provided ventilation in naturally ventilated buildings should provide external air supply to all teaching and learning spaces with:

- a minimum of 3 l/s per person
- a minimum daily average of 5 l/s per person
- a capability of achieving a minimum of 8 l/s per person at any time.

Taking these requirements into account, the aim of this paper is to establish ventilation rates in recently built schools, to comment on the suitability of the Building Bulletin 101 as a means of compliance with the Building Regulations, and to suggest a new methodology for post-occupancy evaluation of ventilation rates in schools. To support the suggested methodology, a detailed analysis of factors influencing the build up of CO_2 in schools is carried out and two different methods of estimating ventilation rates are compared.

2 Methodology

Measurements were carried out in four schools in England during a heating season 2005–2006. Three out of four schools were built in compliance with Building Bulletin 93,[4] which defines noise and acoustic criteria in relation to school design. The monitoring was carried out in two selected classrooms in each school over a period of five working days. The classrooms were carefully selected to satisfy at least one of the following requirements: (a) use of different ventilation strategies, (b) reasonable occupancy levels, (c) typical teaching activities, (d) microclimatic conditions, which may reduce potential for natural ventilation. Levels of CO_2 were monitored at 5-min intervals throughout the occupied day close to the occupied zone at seated head height to indicate the overall indoor air quality and provide a means of inferring the ventilation rate based on the number of occupants. Two Gascard II infra-red gas monitors (MYCO_2) (accuracy: 2% of the range – 0–5000 ppm) coupled with HOBO dataloggers were used for the indoor measurements. In addition, outdoor CO_2 was measured using a Telaire 7001 infra-red gas monitor (accuracy: 50 ppm or 5% of the reading, whichever is greater). The estimation of the ventilation rates from the CO_2 levels was done in two ways:

(a) via direct inference[5]
(b) using the 'continuity equation'[6,7]

The estimation of ventilation rates via direct inference was carried out in a manner suggested by a previous study.[5] That study suggested that a ventilation rate of 8 L/s per person relates to a steady state CO_2 level within a room of up to 1000 ppm. It also noted that a level of 2100 ppm of CO_2 relates to a ventilation rate of 3 l/s/p. It is important to emphasise that such levels refer to the 'equilibrium' levels achieved, i.e. if the rate of emission is constant then a steady state concentration is achieved independently of classroom volume.

Ventilation rates were also estimated over suitable intervals using Equation (1), a form of 'continuity equation:'[6,7]

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

where:

$C_{(t)}$ – internal concentration of carbon dioxide at time t (ppm),

C_{ex} – external concentration of carbon dioxide (ppm),
G – generation rate of carbon dioxide in the space (cm^3/s),
Q – internal-external exchange rate (m^3/s),
C_{in} – initial concentration of carbon dioxide (ppm),
V – room volume (m^3), and
t – time (s).

Note that air may enter a measured zone not only directly from outdoors, but also from neighbouring zones, whose CO_2 concentration may differ from that of outdoor air. These inter-zone air flows influence the CO_2 concentration in the measured zone, but can be measured only with more complex techniques.[7] Nevertheless, the ventilation rate deduced from Equation (1) is useful for two reasons: (a) CO_2 is defined as the 'pollutant of interest' in Building Bulletin 101, and (b) it corresponds to the effective outdoor air flow rate that would result in the same CO_2 concentration in the measured room without inter-zone air flows. Note that the authors attempted to estimate averaged ventilation rates using PFT (per fluorocarbon tracer gas) method. However, this approach has been abandoned as significant number of receptors and sources were either misplaced or stolen.

3 Case study A

The study for this school relate to a block that was built in 2003. The school is located in a suburban residential area of town and is used for a variety of standard teaching activities including IT and business studies. Table 1 contains the following technical details for both monitored classrooms: (1) classroom identification, (2) location of the school building, i.e. urban, suburban and rural, (3) mode of ventilation, i.e. natural ventilation (NV), mixed mode (MM) and mechanical ventilation (MV), (4) classroom volume [m^3], (5) type of ventilation, (6) windows type, (7) maximum openable area [m^2], (8) heating type and (9) various comments related to its operation and design.

A typical diagram of CO_2 levels based on the recorded 5-min values is shown in Figure 1 for Classroom A2. Generally, on each day, the levels of CO_2 increased from the start of the day reaching a peak at 12:15 (end of the morning session) and decreasing during the lunch time when the classrooms are generally unoccupied. The CO_2 levels start increasing again after the lunch break reaching the afternoon peak at 15:30. Note that due to the number of pupils (and their behaviour) it was not always easy to establish the precise occupancy pattern in the school. Table 2 shows the average CO_2 levels measured in each classroom for a typical day. The average CO_2 levels exceeded the upper limit of 1500 ppm in both classrooms on Monday. In both classrooms, the automatic windows and passive stack ventilation were not in use. It is noted that the day was relatively cold (min. temperature: $-6°C$; max. temperature: $9°C$).

Figure 2 shows the cumulative percentage of CO_2 in each room of interest. An attempt was made to estimate ventilation rates via direct inference. For the A1 and A2 rooms, ~60% of measurements were below 1500 ppm implying ventilation rates of at least 5 l/s per person. Note that ~15% of measurements exceeded 2100 ppm implying ventilation rates below 3 l/s per person. It is clear that this method of estimating ventilation rates and reporting on performance of the ventilation strategy suffers from the following deficiencies:

1. the 'equilibrium' levels of CO_2 are hardly ever achieved (Figure 1)
2. reporting on ventilation rates achieved using the cumulative percentage of CO_2 is misleading as the 'favourable' ventilation rates maybe a consequence of the occupancy level rather than performance of the ventilation system.

Table 1 Monitored classrooms

Room	Location	V	Vol.	Type	Windows	Openable area (m^2)	Heating	Comments
A1	suburban	NV	280	Cross-ventilated stack effect	Electrically actuated top hung × 3 and manually operated top hung × 2	0.80	Underfloor	Control is by a BMS which opens the dampers in the vertical stacks on an occupancy time schedule. Once fully open, occupant over-ride is enabled to allow the actuated windows to be opened or closed by the occupants, using local push-button controls. Rain detectors close the windows automatically when precipitation is detected. Night pre-cooling is also enabled in summer, under BMS control, when the outside air temperature is suitable. There are also a number of manually openable windows, which have no actuators. These are generally left closed in winter and manually opened under occupant control
A2	suburban	NV	140	Cross-ventilated stack effect		0.80	Underfloor	to maximise cooling in summer. Both monitored classrooms were fitted with trickle ventilators.
B1	suburban	MM	181	Variable speed fan and automatic windows	High-level electrically-actuated top hung × 2	0.40	Underfloor	100% fresh air is fed into the packaged air handling unit where it is conditioned (tempered) – the system being controlled by a BMS. The tempered air from the AHU is conveyed to each classroom through externally buried concrete pipes (any mould growth in the pipes was not an issue that was investigated). Suspended ceilings were not generally fitted so that
B2	suburban	MV	302	Variable speed fan	Top hung × 4	0.60	Underfloor and trench heating	the exposed thermal mass could provide some passive cooling.
C1	rural	NV	151	Single sided	Top hung × 3	0.65	LTHW	In both rooms some thought had been given to providing cross ventilation by providing a small grill into the suspended ceiling and a duct that led to the atrium space from which the classrooms were entered. No fan was found. A smoke test carried out suggested that the ducted extract contributed
C2	rural	NV	151	Single sided	Top hung × 3	0.65	LTHW	insignificantly to the ventilation strategy in the room.
D1	suburban	MV	177	Two ceiling based supplies and one extract	Low-level top hung × 2	0.36	Underfloor	The fresh air is tempered and conveyed to the room via a simple duct system mounted in a void above the suspended ceiling. The extract, which leads to the large void space above the suspended ceiling, is not separately ducted but a small transfer hole connects
D2	suburban	MV	138		Low-level top hung × 2	0.36	Underfloor	this plenum void to the corridor. The corridors have additional extract fans located on the roof.

A summary of the key ventilation rates obtained using Equation (1) is presented in Table 2. Note the difference in ventilation rates obtained for 'observed' and designed occupancy (2.8 and 1.3 l/s per person, respectively, for automatic windows and passive stack ventilation closed).

4 Case study B

This school is located in an urban residential area and was opened in September 2003. There are ~1100 pupils. The school has a combination of mixed mode ventilation and full mechanical ventilation systems. Table 1 contains the technical details for both monitored classrooms.

As in the previous case study, on each day, the levels of CO_2 increased from the start of the day reaching a peak at the end of each teaching session and decreasing significantly during the lunch time and other periods when the classrooms are generally unoccupied for longer time (Figure 3). The CO_2 levels start increasing again after the lunch break reaching the afternoon peak at the end of last session. On Tuesday 28th March 2006 no students attended the scheduled classes (Figure 3).

The observed CO_2 patterns indicated the existence of discrepancies between the operational and designed performance of the tested ventilation strategies. This was further investigated via conversations with resident

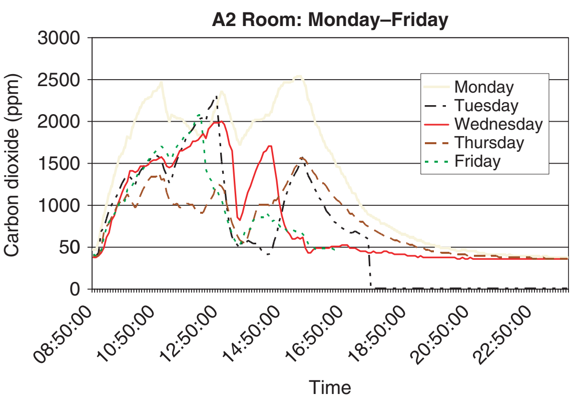

Figure 1 Room A2 – carbon dioxide levels during a five day period

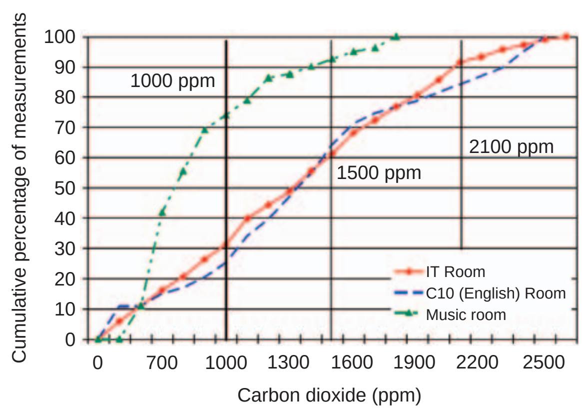

Figure 2 Cumulative percentage of CO_2 concentration measured in each classroom

Table 2 Summary of IAQ and ventilation results

Room	CO_2 max (ppm)	CO_2 av (ppm)	CO_2 STD (–)	'PURGE' (l/s/p)	'MIN' (l/s/p)	'USUAL' (l/s/p)
A1	3127	1778	712	6.1 (30)	n/a	n/a
A2	2530	1972	601	5.4 (50)	1.3 (50)***	2.8 (30)
B1	1472	853	268	5.3 (25)	0.6 (25)	6.3 (12)
B2	1615	1100	320	10.5 (25)	1.7 (25)**	4.5 (25)
C1	1857	960	331	3.9 (30)	0.9 (30)*	3.6 (10)
C2	1725	1054	397	3.9 (30)	n/a	n/a
D1	1047	789	171	8.4 (30)	0.5 (30)	8.4 (30)
D2	880	733	142	8.0 (30)	0.5 (30)	9.4 (30)

*Trickle ventilators, **Trench heating, ***stack/damper.

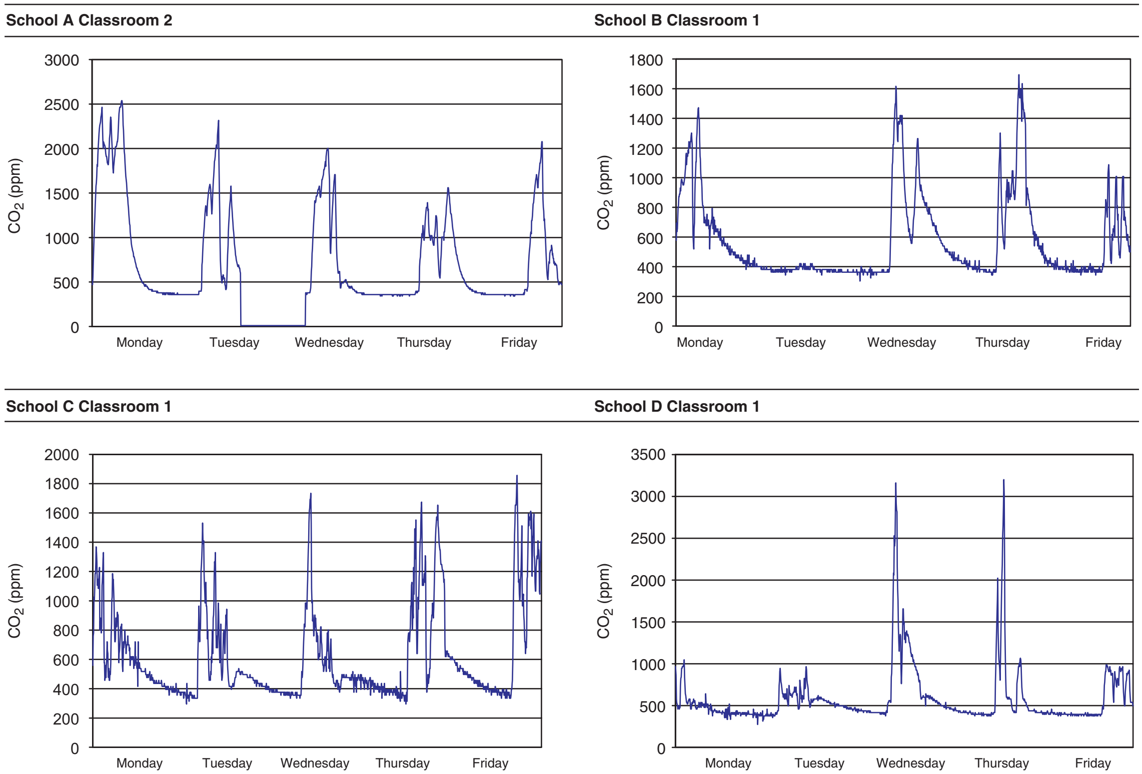

Figure 3 Carbon dioxide levels recorded over a 5 day period

teachers and the facility manager. The following issues were noted:

(a) Classroom B1: the designed ventilation strategy in this room relied on both mechanical (fan assisted fresh air inlet) and natural ventilation (automatic windows). During programmed occupancy periods the windows are set to remain open until the measured room space temperature falls below the set point by more than 2°C. However, due to security reasons (the classroom was located on the ground floor) the automatic windows were shut. As a consequence, the role of the mechanical ventilation supply has shifted from a supplementary one to being the main ventilation provider.

(b) Classroom B2: the volume of the flow entering the room through the heater battery was too high causing discomfort to the students sitting near the trench. By reducing the air flow through the battery the problem of discomfort was addressed, but as a consequence of the reduced air flow the operational performance of the mechanical ventilation system was degraded. In this case it was not possible to change the furniture layout without incurring excessive costs (fixed furniture).

Table 2 shows the average CO_2 levels measured in the classroom B1 for days with the mechanical ventilation ON ('standard' building operational performance) and the mechanical ventilation OFF (intervention study). Note that the number of students during the 'observed' occupancy of the room B1 is very low, usually 50% of the 'as designed' number of occupants. The average CO_2 levels did not exceed the upper limit of 1500 ppm in both rooms. Note that maximum values in the region of 1500 ppm were achieved despite low occupancy and low classroom usage during the 'normal' occupied hours.

Equation (1) has also been used to estimate the ventilation rates during both the occupied and unoccupied hours (Table 2). Note that a number of small intervention studies were carried out in classroom B2 (windows opened/closed, mechanical ventilation on/off) to test the capabilities of the design to adequately ventilate the room. Classroom B2 is located on the ground floor of the monitored teaching block – just opposite the school's kitchen. The kitchen exhausts face the teaching block and the associated odours can be detected in the classroom. As a consequence the teachers are reluctant to use the manually operated windows. It is noted that existing guidelines relating to the positioning of kitchen exhausts in schools seem to be very broad and general.

5 Case study C

The study for this school relate to a block that was opened in 2004. The school is located at an exposed rural site and represents a basic single sided naturally ventilated design with openable windows into deep classrooms. Table 1 contains the technical details for both monitored classrooms.

A typical diagram of CO_2 levels based on the recorded 5-min values is shown in Figure 3 for room C1. It appears that the (relatively) satisfactory results for the two classrooms are due to the occupants' behaviour rather than the 'standard' ventilation strategy. The doors were kept open very often, allowing dilution of CO_2 via the large volume of the double height atrium. Table 2 shows the average CO_2 levels measured in each classroom for each of the monitored days. The average CO_2 levels exceeded 1000 ppm in room C2 only. The lower values in room C1 are partially due to low occupancy levels in the room. Despite low occupancy, the maximum levels recorded were still high. Unfortunately, due to interference from the room occupants some of the data was lost (from room C2). A summary of the key ventilation results obtained using the Equation (1) is presented in Table 2.

6 Case study D

This study relates to a new 900 place secondary school located in a suburban setting that was completed in 2005. The school is in close proximity to a major motorway, which imposed external noise constraints that affected the detailed design of the building. The school is serviced by mechanical ventilation with under floor heating and manual windows. Table 1 contains the technical details for both monitored classrooms.

A typical diagram of CO_2 levels based on the recorded 5-min values is shown in Figure 3 for one of the classrooms. The operational performance of the 'standard' ventilation strategy (i.e. without intervention) was monitored on Monday, Tuesday and Friday. On Wednesday and Thursday a number of small intervention studies were carried out to test the capability of the system to provide different ventilation rates.

Table 2 shows the average CO_2 levels measured in each classroom. The value of 1000 ppm was exceeded only once for a very short period of time. Note that during that short period, the number of the occupants in the room exceeded the designed number of occupants by 2. During the intervention studies the mechanical ventilation system was turned off with the consent of the classroom teacher. The averaged values of CO_2 then exceeded the recommended value of 1500 ppm in both classrooms. Note that the given averages and maximum values of CO_2 could be higher, but it was not possible to keep the mechanical ventilation system turned off for any longer period to explore this issue.

As in the previous case studies, ventilation rates were estimated using the continuity equation. A summary of the key CO_2 results using Equation (1) is presented in Table 2. Note that the averaged estimated ventilation rate in the room D1 calculated for the occupied period is 8.4 l/s per person (the ventilation rates calculated during the occupied periods take into account occasional door and window opening). In the room D2 the averaged estimated ventilation rate calculated for the occupied period is 8.0 l/s per person for maximum occupancy. Note that manually operated windows were used occasionally during the same period. These results show considerable over ventilation, which may effect the energy consumption of the school.

7 Discussion

Ventilation rates in the schools were established using two different methods. The estimation of ventilation rates via direct inference was carried out following a previous study,[5] which suggested that a ventilation rate of 8 l/s per person relates to a steady state CO_2 levels within a room of up to 1000 ppm. It is also noted that a level of 2100 ppm of CO_2 relates to a ventilation rate of 3 l/s/p. It is important to emphasise that such levels refer to the 'equilibrium' levels achieved, i.e. if the rate of emission is constant then a steady state concentration is achieved independently of classroom volume. Inspection of the data (Figures 1, 3) suggests that such equilibrium was rarely achieved and thus direct inference in this manner is not generally appropriate.

The second method based on the continuity equation is more useful as it gives more realistic time varying ventilation rates. It corresponds to the outdoor air flow rate that would result in the same CO_2 concentration in the measured room without inter-zone air flows. Unlike the first method, which is based on the assumption of the constant CO_2 production rate (i.e. it assumes a constant number of pupils through out the day), the second method takes this into account. It was found that this factor could not be overlooked in the schools that were studied. Equally important is the fact that the initial concentration of CO_2 in classrooms do not always equilibrate to the external level at the beginning of the new class. In most cases the CO_2 levels build up during the day forming two peaks: the morning one just before the lunch break and in the afternoon just before the end of the last class (Figure 1). This is due to the following: a) the breaks between two classes are short (usually 5 min) not allowing the CO_2 concentration to equilibrate to the external level, (b) in some cases pupils are allowed to stay in classrooms during the breaks contributing to an even more rapid build up of CO_2 levels, (c) the lack of an effective ventilation strategy.

In this study all the schools except for one satisfied the recommended performance standards (Table 2) leading to the conclusion that the implemented ventilation strategy provides adequate ventilation. However, this is misleading unless one takes into account three important factors: (a) the occupancy schedule for classrooms (i.e. the classrooms were not fully utilised during the 'normal' occupied hours, preventing CO_2 building up during the day), (b) the occupancy level during classes (i.e. number of students attending classes) and (c) occupant behaviour. As shown in the case studies, these factors have had a determinant effect on the performance of some classrooms.

Therefore, a post-occupancy evaluation methodology focusing on ventilation in schools has to take into account the dynamic nature of the interaction between ventilation strategies in schools and occupant related issues. The methodology shown in Table 3 represents a balanced approach to evaluation of ventilation rates in schools and should ensure that the obtained results may be used to assess the compliance with Building Bulletin 101. Despite the fact that the suggested methodology is more complex than the current practice of taking single CO_2 measurements in all classrooms, it is straightforward and relatively simple.

In addition to the quantitative analysis of ventilation rates, the researchers have attempted to provide an insight on the attitude of facility managers, teachers, and pupils on the ventilation performance in classrooms. Three out of four schools have been equipped with BMS providing them with an opportunity to balance energy consumption and ventilation requirements to some extent. However, in the opinions of the team, neither of the facility managers/caretakers was fully conversant with the BMS. This raises an important issue – training the relevant people (at least the caretaker and facility manager) how to use the ventilation system effectively. The teachers also did not receive any information as to how to use the

Table 3 Methodology for post-occupancy evaluation of ventilation rates in schools

Step		Description
1	☐	Monitoring should only be carried out during the heating season (e.g. November–March)
2	☐	Temperature and wind speed data should be collected from local Met Office sites. Monitoring should be only carried out if temperature and wind speed are likely to be below 12°C and 4 m/s consecutively.
3	☐	To prepare for fieldwork, if available, review architectural and M&E drawings. Note that 'as designed' and 'as installed' drawings may differ from the actual on site situation.
4	☐	Create a list of the classrooms which will be monitored according to the following rules: • if more than one ventilation strategy is employed to provide adequate ventilation in a school each room selected should represent a different ventilation strategy (e.g. different window types, sky lights, stack ventilation, single/cross ventilation, constant/variable air speed fans); • rooms with reported complaints related to the air quality should be added on the monitoring list; Contact the facility manager to check if the selected rooms satisfy the following criteria: a. ☐ is the selected room regularly occupied throughout the day? (the room should ideally be occupied all the time except for lunch breaks) b. ☐ is the occupancy level of the selected room similar to the maximum/designed occupancy? (this issue is especially relevant in the new schools or in the schools with low attendance; the actual occupancy level should ideally be the same as the designed occupancy during the test day)
5	☐	CO_2 monitors should be placed at head height away from the main air flow patterns in the room; the following rules should be followed: a. ☐ the outside levels of CO_2 should be determined by averaging three single measurements taken in the vicinity of the school throughout the day (morning, midday and afternoon); b. ☐ the number of students fluctuates during the day (even during the class); therefore, a note of student number should be taken at 15–20 min intervals; c. ☐ all fire doors should be closed when not in use (it has been noted that some of the teachers tend to keep doors to the classrooms open all the time, which does not comply with the fire safety regulations); d. ☐ to assess compliance with BB101 in relation to average CO_2 levels during the occupied period (e.g. 08.30–15.30 including lunch break) the IAQ consultant should take care not to affect the normal performance of the ventilation system, by for example preventing the regular occupants of the building behaving differently. e. ☐ at the end of the test day the IAQ consultant should test the capability of the purpose provided ventilation to deliver 8 l/s per person;
6	☐	The ventilation rates should be calculated using Equation (1) for both: a. ☐ occupied periods at 15–20 min intervals b. ☐ unoccupied period at the end of the day at 1 min intervals (the shorter interval of time is consequence of rapid change of CO_2 caused by testing the capability of the system to deliver 8 l/s per person.)
7	☐	Data analysis and report writing. If the performance of the purpose provided ventilation fails to comply with the Building Bulletin 101, the reasons for the failure should be investigated in details by undertaking CO_2 monitoring over a period of 5 days (Monday–Friday).

ventilation systems most appropriately. The information on the ventilation systems was usually 'buried' within dozens of thick folders and even then with no guidelines how to get the most of the system.

8 Conclusions

This paper describes a series of field measurements that investigated the ventilation rates in four recently built secondary schools in England. All schools were assessed for compliance with the recently adopted Building Bulletin 101, which defines the set of criteria in relation to the ventilation rates and indoor air quality in new schools. Importantly, the paper draws particular attention to the dynamic nature of the interaction between the building and their occupants. It was shown that in some cases the apparently satisfactory results for the ventilation rates in schools are due to the occupants' behaviour rather than the 'standard' ventilation strategy. As Building Bulletin 101 is not prescriptive, but performance based, the development of a straightforward methodology for evaluating ventilation rates in schools is essential. The methodology suggested in the paper is balanced and takes into account both: the complexity of the environment in schools and the need of regulatory bodies and industry for straightforward and effective guidance. In addition, the study highlighted importance of training and security issues on performance of ventilation systems in the schools.

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