A field study of indoor air quality and overheating in newly built primary classrooms in low-carbon UK schools

Sara MOHAMED[1], Lucelia RODRIGUES[2], John CALAUTIT[2] and Siddig OMER[2]

[1]Building, Energy & Environment Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

[2]Department of Architecture & Built Environment, Faculty of Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, UK

ABSTRACT

School buildings confront complex design and layout problems due to needing to respond to a wide range of environmental factors while accommodating intermittent high-density occupancy. Despite current policy-driven emphases on improving building energy efficiency, focusing exclusively on energy issues fails to capture the full effect buildings have on their occupants and the environment. This paper investigates recently constructed low-carbon schools in the UK, examining indoor environmental quality and assessing overheating assessment against established standards. The findings reveal that carbon dioxide concentrations exceeded the maximum threshold (1,000 ppm) for more than 60% of school hours during both heating and non-heating seasons and that particulate matter levels exceeded 20 g/m3 during the heating season and 10 g/m3 during the non-heating season, indicating annual individual exposure above recommended health guidelines. Furthermore, the classrooms monitored experienced overheating for more than 40% of the school day.

INTRODUCTION

Classrooms are the second most important indoor environment for children after their homes (Hou, Liu, & Li, 2015) because they spend about 25–30% of their time in schools (De Giuli, Da Pos, & De Carli, 2012; Luther, Horan, & Tokede, 2018).

Classrooms represent a crucial environment for air quality assessment because children represent a vulnerable population in terms of health concerns (Pacitto et al., 2018).

Concerns about the adverse effects of poor indoor air quality (IAQ) on children's health, efficiency and welfare have grown more pronounced, particularly given indoor air can be ten times as polluted as outdoor air in real conditions.

The notion of IAQ and indoor environmental quality (IEQ) potentially affecting students' and teachers' health and productivity is not new.

Notably, the negative health effect of poor environmental conditions can negatively impact education outcomes. Building-related problems, such as 'building-related illness' (Assoulin-Daya, Leong, Shoenfeld, & Gershwin, 2002; R. McMullan, 2002), are known to the World Health Organisation (WHO) to produce 'sick building syndrome' (SBS), which can cause serious distress and illness to occupants. (Roaf S, 1992), some of these disease symptoms cannot be clinically diagnosed nor treated medically.

This paper reports findings from a field study evaluating the performance of classrooms at a newly built school in Nottingham, evaluating the case study school building's performance in terms of IAQ through comparison between its IAQ parameters, Standers intent and industry standards.

BACKGROUND

Poor IAQ has certain psychological or physiological costs that impact students' health and performance, particularly younger age groups. Building regulatory mechanisms for the supply of appropriate IAQ is framed around carbon dioxide (CO_2) standards rather than considering other contaminants, with CO_2, the most critical human bio-effluent, produced by human respiration in proportion to their metabolic rate.

Regarding the effect of CO_2 concentration on classrooms, an analysis by (Heudorf, Neitzert, & Spark, 2009) demonstrated that CO_2 concentrations above 1,000 ppm increase absenteeism by about 10–20%. (Shendell et al., 2004) have suggested that decreasing CO2 concentrations to below 800 ppm is likely to decrease SBS symptoms such as headache, fatigue and eye/throat discomfort (Seppänen, Fisk, & Mendell, 1999). Elsewhere, Myhrvold et al. (1996) revealed that CO_2 concentrations above 1,500 ppm could contribute to headaches, dizziness, tiredness, difficulties in concentrating and unpleasant classroom odours.

However, IAQ can also be considered in terms of particle matter concentration, with fine particle matter (PM2.5) identified as a key driver of IAQ's adverse health effects (Brook Robert et al., 2010; W. H. O. WHO, 2013), including being a primary cause of air-adverse pollution's health consequences (Anderson, Thundiyil, & Stolbach, 2012; WHO, 2012)

Given $PM_{2.5}$ comprises fine particles – defined as inhalable particles that are 2.5 µm or less in diameter – $PM_{2.5}$ contamination creates serious problems for the human body's cardiopulmonary system (Anderson et al., 2012; Mullen et al., 2020).

Children are more vulnerable to the effects of PM2.5 concentration due to their small bodies and growing lungs (Brockmeyer & D'Angiulli, 2016; Landrigan, Rauh, & Galvez, 2010). Additionally, children are often more deeply embedded in specific local environments than adults; for example, they spend considerable time at school (Kweon, Mohai, Lee, & Sametshaw, 2018)

Not only does IAQ negatively affect the classroom, but overheating and consequent heat stress have major consequences for student learning. For example, during the 2006 heatwave, dozens of schools had to close when temperatures hit above 36°C (McLeod RS, Hopfe CJ, & A, 2013; Pathan, Mavrogianni, Summerfield, Oreszczyn, & Davies, 2017). Overheating is an issue of increasing significance to school building design.

Beyond buildings overheating for lengthy periods potentially having major consequences for occupant wellbeing, in extreme situations, grave dangers may result. With surface temperatures expected to continue increasing around the world and more intense hot spells predicted, classrooms overheating could become more widespread in the future (ZEROCarbonHub, 2012).

Notably, classrooms are densely occupied spaces with high occupancy levels and increasingly contain large amounts of IT equipment Lykartsis, Bahadori-Jahromi, and Mylona (2018). In addition to substantial heat gains due to operating at full or almost full capacity most of the time and attendant large internal heat gains from equipment, intermittent occupancy presents an additional challenge, with pupils regularly moving between spaces. Recent research has posed a further challenge by indicating that comfortable temperature levels are lower for children than for adults Teli, Jentsch, and James (2012), with thermal comfort field surveys conducted during spring and summer in naturally ventilated classrooms in the UK finding this comfort temperature difference to be around 2°C (Lykartsis Athanasios, B-Jahromi Ali, Mylona Anastasia, & 2017)

Furthermore, given higher levels of insulation and triple-glazed windows – part of passive house design – eliminate heat transfer through the thermal envelope and tend to maintain warmth in the winter, high thermal inertia and dependence on useful solar gains during the winter mean that buildings may be vulnerable to overheating in the summer, especially when designed with wide south- or west-facing windows and built with super insulation.

There are several causes of overheating. First, sunlight entering through windows can heat surfaces inside. Modern houses (and some renovated houses) with double-glazed windows and good insulation tend to harness this heat indoors, enabling it to build up. Meanwhile, occupants emit 'metabolic' heat, which varies depending on their level of activity, with heat also produced by normal activity, such as children playing.

Elsewhere, poor ventilation can lead heat to build up, and even low-energy lighting and appliances can contribute to heat gains. In the classroom context, both computers and whiteboards produce heat, even in standby mode. Figure 1 provides a schematic illustration of the sources of internal heat in classrooms.

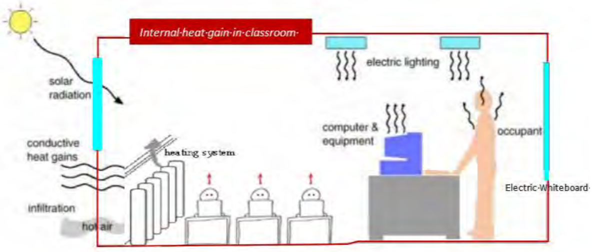

Figure 1. The internal gain and causes of overheating in the classrooms

Concerns about overheating in buildings without mechanical ventilation have increasingly considered as global average temperatures have risen over the past century. Significantly, heat waves have also become more frequent and intense (Jenkins et al., 2010b; L. Rodrigues, M. Gillot, & Tetlow, 2013; Lykartsis et al., 2018; McLeod RS et al., 2013). Accordingly, overheating issues are likely to become more serious in the future, especially given rises in temperature and increases in the frequency and intensity of extreme weather events demonstrated by the UK Climate Projections (Geoff Jenkins et al., 2010; Projections, 2009b)

However, there remains scarce data on air quality and globe temperatures for new school buildings during the summer months due to that period's open schedule. That is, it is difficult to define occupant behaviour in clustered learning environments, with the school building of particular concern given the potential to interrupt the education process.

Many factors contribute to thermal comfort, from low ventilation rates, movement, uncomfortable high temperatures, unsuitable daylight levels, low humidity and high electromagnetic radiation from appliances (McMullan, 2002). Numerous studies have attempted to examine different features affecting the internal environmental quality in primary school classrooms (see, for example, Corgnati , Filippi M, and Viazzo S (2007); HSE (2013); Mohamed (2009), concluding that poor IAQ leads to poor health and wellbeing and impacts children's performance and the quality of their education.

As discussed, children's environmental adaptive behaviours are more limited than those of adults (Haddad, Osmond, & King, 2017; Wang, 2015), a factor compounding the obvious differences produced by the teachers controlling classrooms (Korsavi & Montazami, 2020; Sepideh Sadat Korsavi & Azadeh

Montazami, 2018). The impact of poor IAQ on children is exacerbated by the fact that they rarely complain (Wargocki & Wyon, 2013; Zhang & Bluyssen, 2019), that classrooms are more crowded than other workplaces (Bakó-Biró, Clements-Croome, Kochhar, Awbi, & Williams, 2012; Wargocki & Wyon, 2007) – with classroom occupancy density four times that of office buildings (Katafygiotou & Serghides, 2014) Consequently, CO_2 exhalation rates in schools could be higher. Meanwhile, external influences, such as their type of schoolwork (Wargocki & Wyon, 2007, 2013) and their stress levels (Dascalaki & Sermpetzoglou, 2011), may also negatively impact children's perceptions of IAQ. Children's schoolwork is almost always new to them, so although adults perform routine tasks on a regular basis (Katafygiotou & Serghides, 2014). Thus, environmental factors more greatly impact children's schoolwork than adults' office work Lan, Wargocki, Wyon, and Lian (2011).

This clearly demonstrates the need to improve the overall energy efficiency of new school buildings in the context of broader environmental and educational requirements. However, it is less clear how these buildings are going to perform in future climates, where hotter-than-average summers and an increased frequency of extreme heatwave events are anticipated (Kevin Anderson & Bows, 2008) and are obvious risk factors for increased overheating within the built environment.

A case studies approach can enable a more thorough and in-depth investigation of new school buildings, with findings from such investigations able to guide potential construction projects in the education sector.

Generally speaking, the environmental requirements for schools and other learning spaces are more demanding and complex than those of other types of buildings. Although meeting these standards often produces conflict, such design requirements are fundamental for the occupants, most of whom are pupils spending most of their time indoors away from their home, meaning school buildings are essential to both their overall wellbeing and educational attainment. The approaches of the current wave of sustainable and low energy school building designs to achieving high IEQ and building user satisfaction can produce conflict with initiatives designed to improve energy efficiency. For example, overheating and poor IAQ can be produced by highly insulated and airtight modern buildings built to demanding energy standards. Therefore, this study's field measurements aim to investigate the individual environmental parameters of classrooms in newly constructed schools, examining IAQ and assessing for overheating to enable comparison with the BB101 and CIBCE School Building Standards and identification of the conflicts and problems inherent to providing a holistic system combining technological and design solutions.

METHODS

This methodology's four main steps are (1) field monitoring; (2) sampling the building and its occupants; (3) a second-level analysis acquiring data on the indoor and outdoor environments; (4) evaluation of classroom IAQ and assessment of overheating in comparison with standards.

1. Field monitoring

An in-situ method was adopted for the field study, which was generally conducted according to the monitoring strategies described in ENISO 16000_1 (2006). The centre of the classroom was generally considered the most suitable location for the field study, and monitoring equipment was set to obtain readings of concentration or level for every minute of each field study period. Continuous monitoring and regular readings enabled variation to be captured, allowing deeper insights into the dynamic indoor environment, which was constantly modified by fluctuations in pupil activities, ventilation, the windows and doors schedule, and miscellaneous externalities. The equipment was selected after consideration of accuracy, volume, robustness and low noise activity (to eliminate pupil noise). The equipment was calibrated and checked against the manufacturer's appendix. The data were downloaded, and equipment was tested after each field analysis day. The measurement devices were positioned away from both sun patches (e.g., windows) and heat sources (e.g., computers) and 1.1 m above the floor, as recommended by ISO 7726. The equipment was positioned as such to both minimise disturbances and maintain proximity to the desks of pupils. Devices were set before children arrived each morning, allowing the instruments to adapt before the main measurement collection.

2. Building and occupants sampling

The case study school's main building is separated into two parts – KS1 and KS2 – as documented in Figure 2, with KS1 including reception to Year 2 classrooms. This school was constructed in 2013 as a low-energy building.

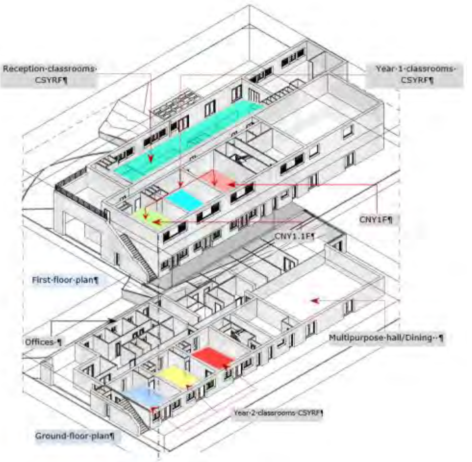

Figure 2. Case study of a new build school

To study the effect of occupant-related factors, especially adaptive behaviours, on IAQ, the school chosen for this study was naturally ventilated, following the UK norm of using windows as the main source of ventilation. Accordingly, the school uses windows for ventilation during the summer. This impacts how occupants practice adaptive performance, with it having been demonstrated that manual window operation significantly improves IAQ (Hou et al., 2015; Stabile, Dell'Isola, Frattolillo, Massimo, & Russi, 2016) and occupants' sense of relaxation.

Accordingly, it is also important to analyse the types of windows in the classrooms being studies. Figure 3 depicts a classroom with single-sided double openings, with opening level manually controlled along with the classroom's length Figure 3 also depicts a classroom with two large windows measuring 1.8 m in height.

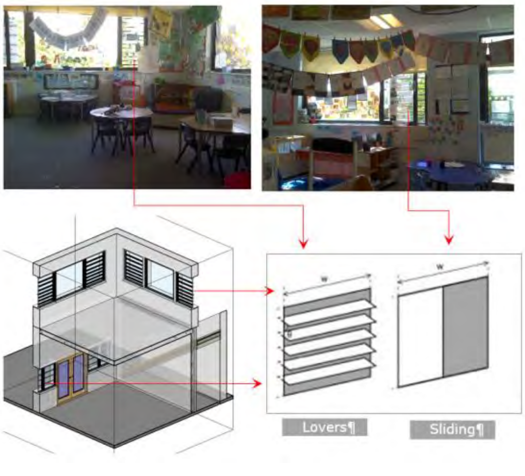

Figure 3. Window designs in case study school

3. Second-level analysis

The monitoring methodology for the case study classrooms incorporated real-time devices for various IEQ parameters, enabling dynamic changes in indoor and outdoor climates to be captured. The results compare indoor parameters (i.e. temperature, CO2, PM2.5, occupancy, window and door schedule) with outdoor parameters (i.e. ventilation, temperature, CO2 levels) to holistically describe the classroom in terms of building performance and IEQ. Monitoring was conducted during both the heating and non-heating seasons.

The second-level analysis considers classroom CO2 level, indoor air temperature, indoor air velocity, occupancy, and window and door opening schedules, as well as outdoor air temperatures, humidity and air velocity.

4. IAQ and overheating guideline criteria and standards

Although no widely accepted UK guidance on benchmarks for IAQ or overheating exists for schools, the Chartered Institution of Building Services Engineering (CIBSE) has conducted considerable consultation and analysis on the effect of climate change on both the indoor environment and weather data. Existing guidelines for the evaluation of overheating in buildings have included both (a) deterministic, defined thresholds and (b) parameters based on the adaptive thermal comfort method. Both methods have been used for the evaluation of indoor overheating levels in of this study's controlled sample.

The results were subsequently analysed to determine IAQ and indoor overheating using existing and new standards, which are discussed individually in the following paragraphs and generally follow the Environmental Design Guide by CIBSE (2006) and recent report standards by the Building Bulletin 101 (BB101; UK Government, 2018).

Fixed and deterministic thresholds for overheating

Two temperature thresholds have been defined by CIBSE for schools: a lower temperature threshold, which indicates when occupants will start to feel 'warm' (above 25°C), and a higher threshold temperature, which indicates when occupants will start to feel 'hot' (above 28°C). However, to define a fixed 'overheating' measure, an excess of more than 1% of occupied hours per year above the higher temperature benchmark is adapted to indicate a failure of the building to control overheating risk (CIBSE Guide A, 2006).

Meanwhile, BB101 establishes performance standards for summertime overheating in compliance with *Approved Document L2 for Teaching and Learning Areas:* a) The average internal to external temperature difference should not exceed 5°C (i.e., the internal air temperature should be no more than 5°C above the external air temperature on average). The Passive House School defines the threshold temperatures in winter as not exceeding 20°C, in summer as not exceeding 22°C, and, across the whole year, not exceeding 25°C for more than 5% of the year. This study collected data on actual occupancy patterns and window opening schedule during the monitoring periods.

Building Bulletin 101 BB101 (2018) recently produced by the UK government and was developed to regulate indoor thermal conditions in UK classrooms and assess overheating risks overheating at the design stage and under operational conditions. Performance in use for the Priority Schools Building Programme specifies that when the external air temperature is above 20°C, the average temperature difference across 30 minutes intervals should not exceed 5°C. During the heating season, the regulatory framework establishes minimum indoor temperatures of 16°C in workplaces.

Fixed and deterministic thresholds for CO$_2$ levels

For naturally ventilated classrooms, both sets of guidelines recommend an average concentration of CO2 during occupied periods not exceeding 1,500 ppm;

furthermore, at any occupied time, occupants should be able to reduce the CO_2 concentration to 1,000 ppm, with the maximum CO_2 concentration during a typical teaching day never exceeding 2000 ppm for more than 20 minutes.

Thresholds for particle matter

In 2006, a WHO, committee elaborated international standards for deriving indoor environmental guideline principles WHO, (2010), establishing a scientific framework for legally enforceable requirements for indoor conditions. Fine particle matter thresholds indicated a maximum of 8 μg/m^3 average annual concentration value and a maximum of 25 μg/m^3 daily concentration value.

Particles are classified by their diameter (usually referred to as particle size) because this property determines their movement and their suspension in the air and their deposition in the lungs, as well as being commonly linked to chemical structure (Morawska and Salthammer, 2003). The key indoor causes of particles in school environments are human activity, plants and building materials, particularly mineral fibres. Particles often infiltrate the classrooms through ventilation, infiltrating from the outdoor environment, especially in urban areas where exhaust from vehicles is common.

Criteria based on the adaptive thermal comfort approach

The recent publications regarding school buildings by the BB101 and the CIBCE have included guidelines on preventing overheating, which consequently impacts thermal comfort, IAQ, lighting and ventilation, according to the 'Environmental Circle' framework developed by Montazami, Gaterell, and Nicol (2015), which emphasises the importance of a holistic approach. This circle considers sub-parameters representing environmental conditions such as humidity, air temperature, air velocity, parts-per-million, background noise, reverberation time, uniformity, lighting level, and radiant temperature. The BS EN15251 Standard and guides by the BB101 and the CIBCE have been used to assess overheating in the (mostly) naturally ventilated buildings monitored. All three deliver formulas for calculating the comfortable indoor temperature, with the adaptive thermal comfort method describing comfort temperature bands as variables of outdoor ambient temperature ref, which is commonly recognised as a more rigorous alternative to evaluating indoor overheating. The comfort temperature is related to the running mean of the outside dry-bulb temperature, as demonstrated by Equation (1):

$$T_C = 0.31 \times T_{rm} + 17.8 \qquad (1)$$

Where:

T_{rm} is the running mean temperture (◦C), T_C is comfort temperature.

Standard EN15251 (2009) gives T_{rm} = the mean radiant temperature which is calculated from Tg (globe temperature), Ta (Air Temperature and air Velocity V, as the diameter d of the globe temperatures is (0.075):

$$T_{rm} = \left[\left(T_g + 273\right)^4 + \left(1.2 \times 10^8 d^{-0.4}\right) v^{0.6}\left(T_g - T_a\right)\right]^{0.25} - 273 \qquad (2)$$

Where all temperatures are in °C, Tg is global temperature, D and ε are the diameter and emissivity of the globe respectively, and airspeed (v) is in m/s. The globe thermometer used in this study (diameter: 0.075 m) found in figure (4)below was manufactured and calibrated when used in the field study

The diameter of the Globe temperatures is 0.075m

Figure (4) Indoor and outdoor Global the globe and air temperature device used in field study (PCE-WB-20SD)

Operative temperature (OT or T_{op}) combines the mean radiant temperature (MRT or Trm) and AT (Ta) and has been widely used in previous studies combining behavioural and adaptative temperature factors. When indoor airspeed is below 0.1 m/s, Equation (2) is used:

$$T_O = {}^{1}\!/_{2}\, T_a + {}^{1}\!/_{2}\, T_{rm} \qquad (3)$$

This alternative criterion proposed by British Standard and developed by Nicol regarding the percentage of overheating is only valid for spaces engaged in mainly inactive activities such as offices, classrooms etc,Nicol et al, (2009).

RESULTS AND DISCUSSION

Overheating assessment

Classrooms CSYRF and CSY1F, shown in Figures 5 and 6, face south and north, respectively. As is typical of a school employing single-sided ventilation, doors and windows are not opened at the same time. Additionally, the internal roller blind was raised most of the time. However, windows were covered with pupils' drawings and other schoolwork, helping to prevent solar radiation. As Figures 5 and 6 indicate, during summer, the recorded temperature was 23.8°C at the start of the day, which could be explained as a result of the window and the door having both been open when there was no occupancy (or before the start of the day). Temperatures began to gradually increase at 8:54, reaching above 26°C, before falling slightly when the students went to play outdoors. The global and air temperatures peaked at 13:30 (the end of the day), with temperatures recorded between 26.5°C and above 27°C when the windows were open, and the door was closed.

The field study results demonstrate that temperatures were above 27.5°C from 13:00 to 14:45. There are many possible causes of this overheating: the single-sided ventilation, the presence of a wall built through the classroom to separate different classroom groups, and the occupancy, along with the school building having been built using super insulation in the walls to attain low-carbon status under Passive House regulations standards.

According to the fixed benchmarks provided by BB101 and CIBCE, for classroom, the average indoor air temperatures were highest between 9:00 and 10:00, at around 25°C; for classroom CSYRF, the mean temperatures were more consistent, reaching a maximum of 25.7°C throughout the day, particularly after the lunch break. On 27/02/2020, classroom CNYRF, the highest mean indoor air temperatures, above 25°C, were recorded at 13:30. To assess classroom overheating during school hours, it is worth considering that external air temperature was sustained at levels above 20° C. However, according to the BB101 benchmark, the average temperature difference between indoor and outdoor temperatures over 30-minute intervals should not exceed 5°C. However, when outdoor air temperatures reached 21°C (at 14:00), the indoor classroom temperature reached above 27°C.

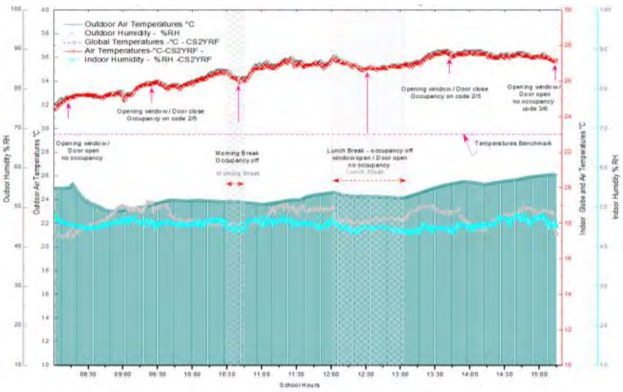

Figure 5. The continuous measurement of classroom CNY1F's indoor air temperature, globe temperature and humidity compared to outdoor air temperature during the non-heating season

Furthermore, the results show that the significant variations in recorded temperatures between the classrooms and the outside environment reached up to 5–6°C, falling below the BB101 standards. Figures 4 and 5 also compare the inside air temperatures to the corresponding outdoor air temperatures at 30-second intervals, revealing that indoor air temperatures steadily responded to outdoor temperatures, as well as to the window and door operation schedule. Specifically, there was a steep increase in air temperatures inside the classroom, which reached between 27.3°C and 27.5°C between 9:30 and 10:11, followed by a slight temperature drop to the range 26.4–26.2°C. This slight decline might have been caused by occupants when opening the window. These findings suggest that the air temperature profile of the classrooms monitored during the field study

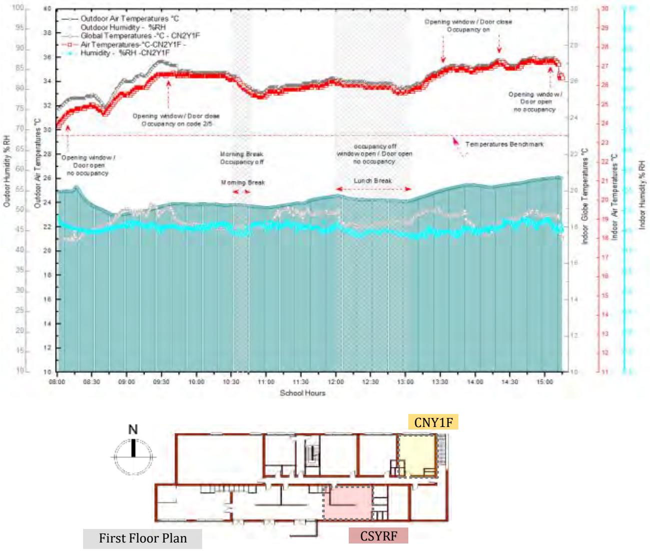

Figure 6. The continuous measurement of classroom CRYRF's indoor air temperature, globe temperature and humidity compared to outdoor air temperature during the non-heating season

experienced overheating, with the temperature variations between 25°C and 27°C exceeding the CIBCE fixed thresholds, which are rendered as dashed lines in the figures. As such, Figure 5 offers important insight into how outdoor conditions influence the natural ventilation inside classrooms.

Figure 7 shows the proportion of different ranges of monitored temperatures during summer in the classrooms. The figures demonstrate the air temperatures, showing that the values for temperatures above 25°C were 41.08% for CNY1F and 64.12% for CSYRF.

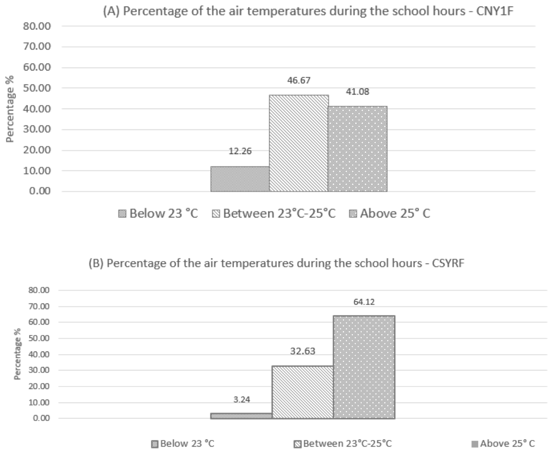

Figure 7. Proportions of air temperatures within certain ranges during occupied hours during field monitoring for (a) classroom CNY1F (b) classroom CSYRF

To go probe the environmental performances of the classrooms, Figure 8 provides minimum, maximum and average temperatures during school time for every hour, demonstrating how the temperatures in classrooms CN2Y2.1G and CN2Y2G exceeded the temperature benchmarks, with even the minimum temperatures exceeding the BB101 and CIBCE recommended inside temperatures during the summer monitoring period. This is represented in Figure 7 by the red-lined benchmark that all of the temperature recordings exceed (minimum, maximum, and, consequently, mean temperatures).

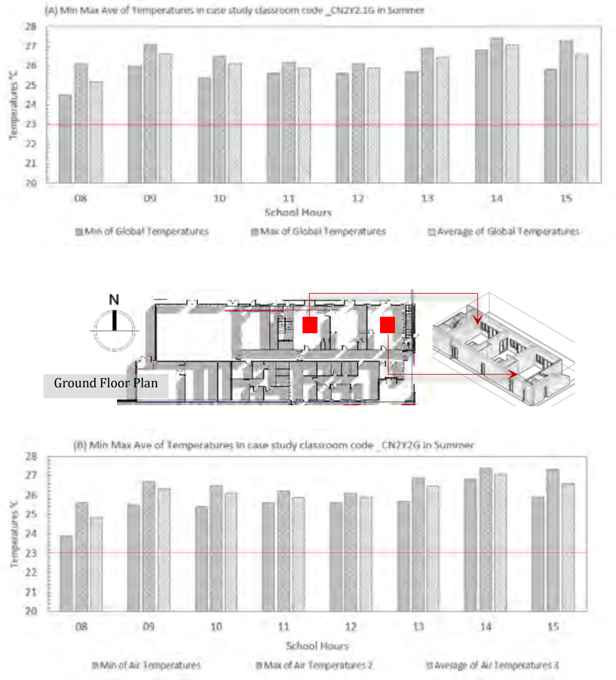

Figure 8. The minimum, maximum and average temperatures during school hours during summer for (a) classroom CN2Y2.1G (a) and (b) CN2Y2.1G

Concerning criteria for adaptive thermal comfort, Figure 9 shows the plotted operative temperatures after applying Equations (1), (2) and (3)using values from the air and globe temperature measures collected during the winter monitoring period. These measurements demonstrate that the plotted temperatures exceed the BS EN15251 (2007) guidelines, which dictate that outside temperatures between 1°C and 5°C exceed the thermal comfort zone. In the graphs presented, these results presented as differently coded lines: the unbroken red line shows the 80% acceptability limit, and the blue dotted line shows the 90% acceptability limit. Both of which increase gradually as the mean outdoor air temperature and mean indoor operative temperature increase.

Regarding the winter monitoring period, both the BS EN15251 Standard and the BB1010 and CIBCE guidelines were used to assess overheating in the (mostly) naturally ventilated buildings. Based on their formulas for calculating comfortable indoor temperatures, Figure 10 shows the plotted operative temperatures following calculations using Equations (1) to (3) using the air and globe temperature measures, proving that the plotted temperatures exceed what is recommended by the BS EN15251 (2007) guidelines, which dictate that outside temperatures between 1°C and 5°C exceed the thermal comfort zone.

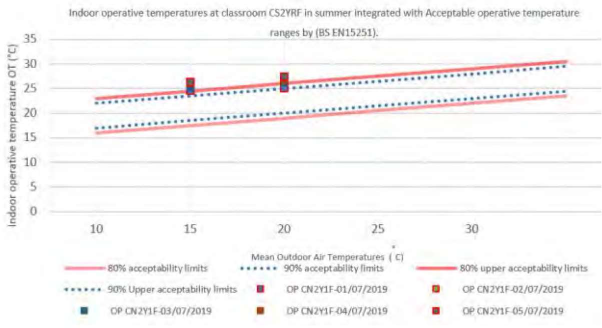

Figure 9. Indoor operative temperatures for classrooms CN2Y1F and CS2YRF during summer compared with the acceptable operative temperature ranges prescribed by BS EN15251 (2007)

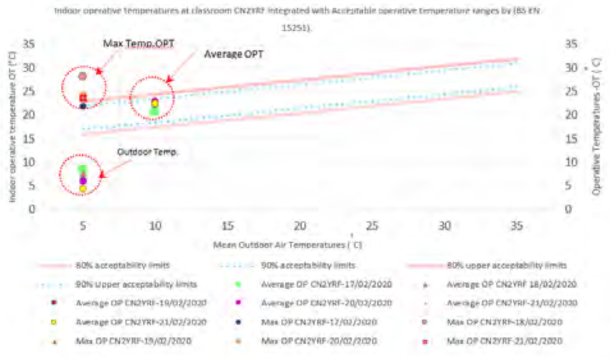

Figure 10. Indoor operative temperatures for classroom CS2YRF during winter compared with the acceptable operative temperature ranges prescribed by BS EN15251 (2007)

Indoor air quality results

Typical profiles of the CO2 levels during teaching days in the heating season for classrooms CN1Y2.1F and CN1Y1.1F are presented.

These profiles indicate that indoor CO2 levels increased rapidly from the start of the day, reaching the first peak before the morning break. This is likely due to the brevity of the morning break, during which children are sometimes asked not to leave their classroom, resulting in indoor levels not reaching equilibrium with outdoor levels.

Figures 11 and 12 present the gradual increases after the lunch-time break, which exceed the average daily guidelines for the heating season by more than 2,000 ppm and for more than 20 minutes. Using an operable approach alone did not sufficiently provide adequate ventilation, resulting in maximum concentrations averaging 1,500 ppm during the monitoring period.

As expected, higher indoor CO_2 levels were associated with higher indoor temperatures, with both seeming to increase in the presence of occupants and increasing, respectively, the sensible and latent heat gains. However, the association between CO_2 levels and indoor temperatures remained significant after controlling for density and number of occupants, indicating that reduced ventilation rates promote overheating. Furthermore, opening and closing windows manually did not provide adequate ventilation. Consequently, the maximum CO_2 concentration averaged as high as 4,000ppm and generally 3,500 ppm between 14:00 and 15:00 on school days. Figures 11 and 12 show the minimum, maximum and average concentrations for every school hour during the five working days monitored.

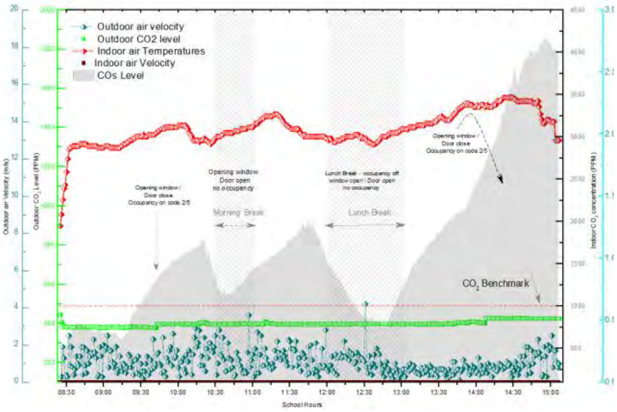

Figure 11. The continuous monitoring of all field study parameters – CO2 concentration, air velocity and air temperatures indoors vs CO2 level, air velocity and air temperatures outdoors – for classroom CN1Y1F during the heating season

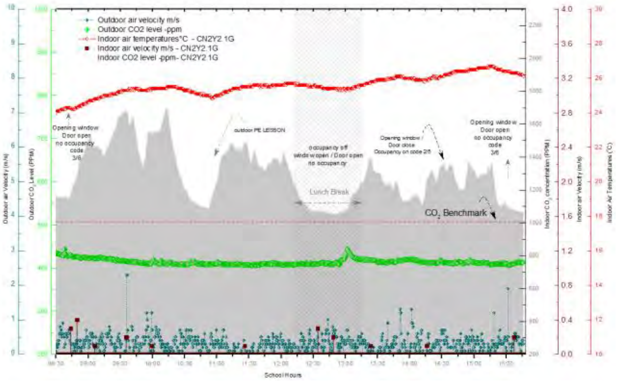

Figure 12. The continuous monitoring of all field study parameters – CO2 concentration, air velocity and air temperatures indoors vs CO2 level, air velocity and air temperature outdoors for classroom CN1Y2F during the heating season

Meanwhile, Figure 13 shows the CO2 concentration for all classrooms during school hours in the heating season, indicating CO_2 levels frequently exceeding 1500 and 2000ppm for more than 20 minutes.

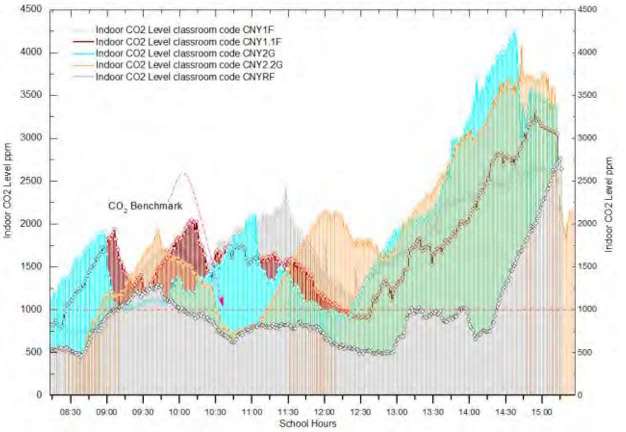

Figure 13. The continuous monitoring of CO2 levels during teaching periods in the case study classrooms

Regarding PM2.5 levels, Figures 14 and 15 present PM2.5 levels during the five days of monitoring of classrooms CNY1F and CN2YRF in winter, showing high concentrations of PM2.5, particularly during teaching activities.

This result could be attributed to the continued re-suspension of deposited indoor particles as a consequence of the absence of fresh air during the heating season when windows were not operated regularly.

The indoor levels were likely also affected by the orientation of the classroom relative to the unpaved playground, which promotes maximum concentration.

In classroom CSYR.1F, maximum concentration levels ranging between 35ug/m^3 and 67 ug/m^3 were recorded. However, there are several possible reasons for this high level of particle matter, such as the wall-to-wall carpets and the conduct of activities with ventilation low. Notably, several previous studies have indicated that PM2.5 derives from a mixture of organic carbon from skin flakes and cotton fibres from clothing, along with other organic materials and rich components extracted from chalk, which are labelled organic textile chalk (Amato et al., 2014). This also explains the high variation in $PM_{2.5}$ in the reception classroom, particularly with regard to pupil occupancy, as shown in Figure 14.

Figure 15 also demonstrates that classroom CNY2.1G features a large source of $PM_{2.5}$ compared to classroom CSYR.1F. This could be due to the classroom's position near the outside playground and its link to the nearest corridor. As noted, Figures 14 and 15 demonstrate the existence of particle matters and their various levels throughout the day, with classroom CNY2.1G featuring a greater concentration than classroom CNYRF.

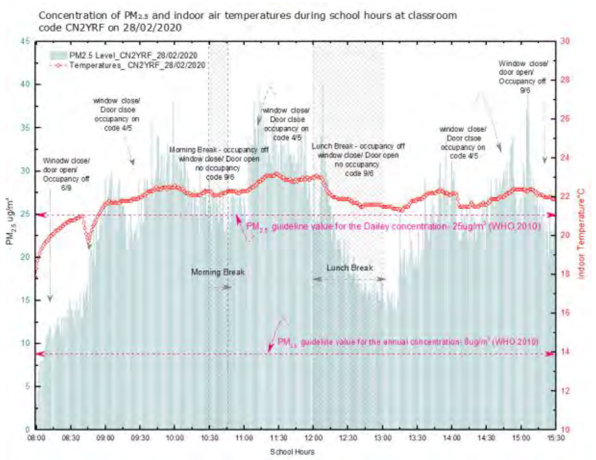

Figure 14. PM2.5 concentration and indoor temperatures during school hours for classroom code CSYR.1F

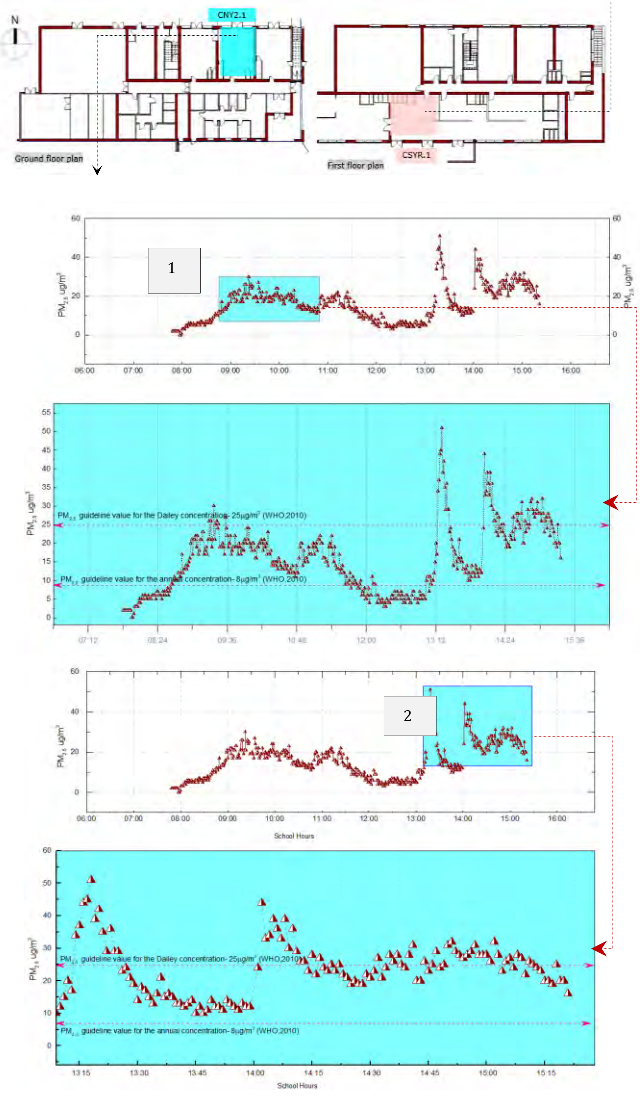

Figure 15. PM2.5 concentrations and indoor temperatures during school hours for classroom CNY2.1G compared with the WHO benchmark

CONCLUSION

This paper has considered IAQ and overheating in newly built primary schools that are naturally ventilated based on data collected during the heating and non-heating seasons.

Responding to conflicts between energy and IEQ targets, this research confirms that building design focusing primarily on energy can produce unintended consequences for IEQ.

The analysis of the data collected has been examined using a fixed and adaptive approach, indicating that the issue of classrooms overheating is extensive and not limited to newly constructed buildings, as is typically predicted by studies relying on dynamic thermal simulation.

This research and the recordings collected have indicated that the internal air and globe temperatures fell well below the acceptable standard regulations for comfortable temperatures, with spaces overheated for more than 60% of their occupied time. Such results might be explained by newly constructed schools featuring more insulation and greater airtightness, causing more heat to be retained in the classrooms.

Indoor CO_2 and $PM_{2.5}$ concentrations remained significant predictors of IAQ after controlling for occupancy effects. Therefore, the relationship between temperatures and both CO_2 and $PM_{2.5}$, beyond the re-suspension of the particles, could be connected to low ventilation rates.

Indoor $PM_{2.5}$ levels recorded during a representative two-week period of the academic year suggest that each person's annual exposure to $PM_{2.5}$ in the classroom was higher than that recommended by the WHO 2010 guidelines. Given monitoring was performed over representative weeks of the non-heating and heating seasons, this field study's results suggest that the levels and concentrations could exceed the annual recommendation. Meanwhile, the results showed that the $PM_{2.5}$ levels recorded in all classrooms were higher than 20 μg/m3 in the heating season and 10 μg/m3 in the non-heating season, indicating that each individual's daily exposure to $PM_{2.5}$ was also higher than the WHO 2010 guidelines.

Elsewhere, the results indicate that achieving appropriate ventilation was problematic for most of the classrooms monitored, with cross ventilation not possible due to the school's original design. This low ventilation rate, along with the building envelope's increased airtightness and the singular learning-cluster plan, seems to promote CO_2 concentrations above the recommended guidelines. In reaching this conclusion, measuring overall CO_2 concentration was found to be a useful proxy in the context of IAQ investigations in schools.

Notably, an increased ventilation rate was not able to effectively remove sources of indoor pollutants, with building orientation in the prevailing wind direction and outdoor air pollution being more important for predicting the indoor concentration of pollutants generated outdoors.

Ultimately, school IAQ is diverse across space and time, and it is necessary to embrace a holistic and balanced approach to the built environment, maintaining energy efficiency to meet low-carbon targets as well as emphasising the protection of school buildings and occupants from poor IAQ.

REFERENCES

Amato, F., Rivas, I., Viana, M., Moreno, T., Bouso, L., Reche, C., . . . Querol, X. (2014). Sources of indoor and outdoor PM2.5 concentrations in primary schools. *Science of The Total Environment, 490*, 757-765. doi:https://doi.org/10.1016/j.scitotenv.2014.05.051

Anderson, J. O., Thundiyil, J. G., & Stolbach, A. (2012). Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health. *Journal of Medical Toxicology, 8*(2), 166-175. doi:10.1007/s13181-011-0203-1

Assoulin-Daya, Y., Leong, A., Shoenfeld, Y., & Gershwin, M. E. (2002). Studies of sick building syndrome. IV. Mycotoxicosis. *J Asthma, 39*(3), 191-201. doi:10.1081/jas-120002468

Bakó-Biró, Z., Clements-Croome, D. J., Kochhar, N., Awbi, H. B., & Williams, M. J. (2012). Ventilation rates in schools and pupils' performance. *Building and Environment, 48*, 215-223. doi:https://doi.org/10.1016/j.buildenv.2011.08.018

BB101. (2018). *Ventilation, thermal comfort and indoor air quality 2018*. Retrieved from https://www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings

Brockmeyer, S., & D'Angiulli, A. (2016). How air pollution alters brain development: The role of neuroinflammation. *Translational Neuroscience, 7*(1), 24-30. doi:10.1515/tnsci-2016-0005

Brook Robert, D., Rajagopalan, S., Pope, C. A., Brook Jeffrey, R., Bhatnagar, A., Diez-Roux Ana, V., . . . Kaufman Joel, D. (2010). Particulate Matter Air Pollution and Cardiovascular Disease. *Circulation, 121*(21), 2331-2378. doi:10.1161/CIR.0b013e3181dbece1

Corgnati , Filippi M, & Viazzo S. (2007). Perception of the thermal environment in high school and university classrooms. *Building and Environment*.

Dascalaki, E. G., & Sermpetzoglou, V. G. (2011). Energy performance and indoor environmental quality in Hellenic schools. *Energy and Buildings, 43*(2), 718-727. doi:https://doi.org/10.1016/j.enbuild.2010.11.017

De Giuli, V., Da Pos, O., & De Carli, M. (2012). Indoor environmental quality and pupil perception in Italian primary schools. *Building and Environment, 56*, 335-345. doi:https://doi.org/10.1016/j.buildenv.2012.03.024

Geoff Jenkins, James Murphy, David Sexton, Jason Lowe, Phil Jones, & Kilsby, C. (2010). *UK Climate Projections: Briefing report*. Retrieved from http://cedadocs.ceda.ac.uk/1321/1/breifing_report_full.pdf

Haddad, S., Osmond, P., & King, S. (2017). Revisiting thermal comfort models in Iranian classrooms during the warm season. *Building Research & Information, 45*(4), 457-473. doi:10.1080/09613218.2016.1140950

Heudorf, U., Neitzert, V., & Spark, J. (2009). Particulate matter and carbon dioxide in classrooms – The impact of cleaning and ventilation. *International Journal of Hygiene and Environmental Health, 212*(1), 45-55. doi:https://doi.org/10.1016/j.ijheh.2007.09.011

Hou, Y., Liu, J., & Li, J. (2015). Investigation of Indoor Air Quality in Primary School Classrooms. *Procedia Engineering, 121*, 830-837. doi:https://doi.org/10.1016/j.proeng.2015.09.037

HSE. (2013). Thermal comfort: workplace temprature and thermal comfort .WWW<http://www.hse.gov.uk/temprature/thermal/index.htm>.

Jenkins, G., Murphy, J., Sexton, D., Lowe, J., Jones, P., & Kilsby, C. (2010b). *UK Climate Projection Briefing Report*. Retrieved from

Katafygiotou, M. C., & Serghides, D. K. (2014). Indoor comfort and energy performance of buildings in relation to occupants' satisfaction: investigation in secondary schools of Cyprus. *Advances in Building Energy Research, 8*(2), 216-240. doi:10.1080/17512549.2013.865554

Kevin Anderson, & Bows, A. (2008). Reframing the climate change challenge in light of post-2000 emission trends: The Royal Society Publishing.

Korsavi, S. S., & Montazami, A. (2020). Children's thermal comfort and adaptive behaviours; UK primary schools during non-heating and heating seasons. *Energy and Buildings, 214*, 109857. doi:https://doi.org/10.1016/j.enbuild.2020.109857

Kweon, B. S., Mohai, P., Lee, S., & Sametshaw, A. M. (2018). Proximity of public schools to major highways and industrial facilities, and students' school performance and health hazards. *Environment and Planning B: Urban Analytics and City Science, 45*(2), 312-329. doi:10.1177/0265813516673060

L. Rodrigues, M. Gillot, & Tetlow, D. (2013). The summer overheating potential in a low- energy steel frame house in future climate scenarios. *Sustain Cities Society*, 1-15.

Lan, L., Wargocki, P., Wyon, D. P., & Lian, Z. (2011). Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance. *Indoor Air, 21*(5), 376-390. doi:https://doi.org/10.1111/j.1600-0668.2011.00714.x

Landrigan, P. J., Rauh, V. A., & Galvez, M. P. (2010). Environmental justice and the health of children. *Mount Sinai Journal of Medicine, 77*(2), 178-187. doi:10.1002/msj.20173

Luther, M. B., Horan, P., & Tokede, O. (2018). Investigating CO2 concentration and occupancy in school classrooms at different stages in their life cycle. *Architectural Science Review, 61*(1-2), 83-95. doi:10.1080/00038628.2017.1416576

Lykartsis, A., Bahadori-Jahromi, A., & Mylona, A. (2018). Investigating risk of overheating for school buildings under extreme hot weather conditions. 277-287. doi:10.12989/eri.2017.5.4.277

Lykartsis Athanasios, B-Jahromi Ali, Mylona Anastasia, & (2017). Investigating risk of overheating for school buildings under extreme hot weather conditions. *Advances in Energy Research*.

McLeod RS, Hopfe CJ, & A, K. (2013). An investigation into future performance and overheating risks in passivhaus dwellings'. *Building and Environment*, 189–209.

McMullan. (2002). *Environmental science in buiding* (5th Ed.).

McMullan, R. (2002). *Environmental Science in Building*: Palgrave.

Mohamed, M. (2009). *Investigating The Environmental Perfomance Of Government Primary School in Egypt.* (Doctorate Of Philosophy), University Of Dundee.

Montazami, A., Gaterell, M., & Nicol, F. (2015). A comprehensive review of environmental design in UK schools: History, conflicts and solutions. *Renewable and Sustainable Energy Reviews, 46*, 249-264. doi:https://doi.org/10.1016/j.rser.2015.02.012

Mullen, C., Grineski, S., Collins, T., Xing, W., Whitaker, R., Sayahi, T., . . . Kelly, K. (2020). Patterns of distributive environmental inequity under different PM2.5 air pollution scenarios for Salt Lake County public schools. *Environmental Research, 186*, 109543. doi:https://doi.org/10.1016/j.envres.2020.109543

Pacitto, A., Stabile, L., Viana, M., Scungio, M., Reche, C., Querol, X., . . . Buonanno, G. (2018). Particle-related exposure, dose and lung cancer risk of primary school children in two European countries. *Science of The Total Environment, 616-617*, 720-729. doi:https://doi.org/10.1016/j.scitotenv.2017.10.256

Pathan, A., Mavrogianni, A., Summerfield, A., Oreszczyn, T., & Davies, M. (2017). Monitoring summer indoor overheating in the London housing stock. *Energy and Buildings, 141*, 361-378. doi:https://doi.org/10.1016/j.enbuild.2017.02.049

Projections, U. C. (2009b). Adapting to climate change.

Roaf S, H. M. (1992). *Energy efficient building ; a design guide*. Oxford: Blackwell scientific publications LTD.

Sepideh Sadat Korsavi, & Azadeh Montazami. (2018). Adaptive Behaviours and Occupancy Patterns in UK Primary Schools: Impacts on Comfort and Indoor Quality

Seppänen, O. A., Fisk, W. J., & Mendell, M. J. (1999). Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. *Indoor Air, 9*(4), 226-252. doi:10.1111/j.1600-0668.1999.00003.x

Shendell, D. G., Prill, R., Fisk, W. J., Apte, M. G., Blake, D., & Faulkner, D. (2004). Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air, 14*(5), 333-341. doi:10.1111/j.1600-0668.2004.00251.x

Stabile, L., Dell'Isola, M., Frattolillo, A., Massimo, A., & Russi, A. (2016). Effect of natural ventilation and manual airing on indoor air quality in naturally ventilated Italian classrooms. *Building and Environment, 98*, 180-189. doi:https://doi.org/10.1016/j.buildenv.2016.01.009

Teli, D., Jentsch, M. F., & James, P. A. B. (2012). Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. *Energy and Buildings, 53*, 166-182. doi:https://doi.org/10.1016/j.enbuild.2012.06.022

Wang, Y. (2015). Chinese university students' ELF awareness: Impacts of language education in China. *Englishes in Practice, 2*(4), 86-106. doi:https://doi.org/10.1515/eip-2015-0004

Wargocki, P., & Wyon, D. P. (2007). The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children (RP-1257). *HVAC&R Research, 13*(2), 165-191. doi:10.1080/10789669.2007.10390950

Wargocki, P., & Wyon, D. P. (2013). Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Building and Environment, 59*, 581-589. doi:https://doi.org/10.1016/j.buildenv.2012.10.007

WHO. (2012). Burden of disease from Household Air Pollution for 2012 [Press release]. Retrieved from https://www.who.int/phe/health_topics/outdoorair/databases/FINAL_HAP_AAP_BoD_24March2014.pdf

WHO, W. H. O. (2013). Review of evidence on health aspects of air pollution

ZEROCarbonHub. (2012). Overheating in homes.

Zhang, D., & Bluyssen, P. M. (2019). Actions of primary school teachers to improve the indoor environmental quality of classrooms in the Netherlands. *Intelligent Buildings International*, 1-13. doi:10.1080/17508975.2019.1617100