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Internal thermal environment and futureproofing of a newly built, naturally ventilated UK school

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Abstract. Research indicates that school children have lower comfort levels than adults and this exacerbates the challenge of tackling the risks of summer overheating in schools without resorting to air conditioning. UN SDG 13 calls for climate action to strengthen the resilience of our cities and reduce the impact of climate change. In this work, a modern, naturally ventilated school in Southampton, UK was used to evaluate single, “hard”, passive retrofit measures and “soft”, building management solutions that could increase the wellbeing of students and reduce current and future demand for cooling. The school was selected as it represents the current standardised design guidance for schools released in 2012 by the Department of Education (DfE). The research presents air temperature observations collected during the summer of 2015. Dynamic thermal modelling was undertaken to evaluate passive retrofit and “soft” solutions to reduce the overheating risk. The model was validated with temperature data collected from the school classrooms. The results indicate that (a) such school buildings have high likelihood of overheating, based on children’s comfort temperatures and (b) passive retrofits focused on shading and ventilation could help to reduce the classroom temperature when required. It is recommended that “soft” adaptive solutions will prove effective to reduce future air conditioning demand, but this will require a radical change in established practices. Achieving the UN Sustainable Development Goals by 2030 will require to rethink and redesign urban living and city infrastructures.

1. Introduction

Overheating in buildings has become a growing concern even in places with temperate climate [1]. The observed increase in the global average temperature, the likelihood of more frequent and longer heat wave events [2] and the multiple impacts of the urban heat island effect [3] have further raised concerns about health in cities, especially in buildings without mechanical cooling. Considering the devastating impact of the 2003 pan-European heatwave which caused in excess of 15,000 deaths [4], it is important



to investigate the ability of buildings to maintain safe thermal conditions and protect the occupants from increasing temperatures. This work focuses on overheating and its energy implications in naturally ventilated school classrooms. In this respect, three Sustainable Development Goals (SDG) are addressed, i.e. SDG13 (Climate Action), SDG11 (Sustainable Cities and Communities) and SDG3 (Good Health and Wellbeing) [5].

In the UK, school buildings have traditionally been cooled through natural ventilation, which is typically controlled on the basis of the thermal comfort conditions experienced in the classrooms. High internal heat gains, the urban heat island effect, noise and air quality affect the temperature development and the ventilation potential in the classrooms. To control these in a naturally ventilated building, classroom windows and doors are the only available options. In many cases however, the ability to control ventilation and hence temperature is further hampered by restrictors fitted to reduce window opening and external noise (from roads and adjoining classrooms) as well as for safety reasons. From the occupants' perspective, it has been reported over the last years that school children have lower comfort levels than adults [6–10], which poses further challenges in addressing summer overheating in schools without resorting to high energy demand air conditioning systems.

A previous study by the authors conducted on four UK school buildings constructed in different periods demonstrated that the most recently built schools may have a high likelihood of overheating, based on children's lower comfort limits [11]. This means that recent building design standards are not addressing the important issue of summer overheating with respect to the occupants' specific comfort requirements. Therefore, this work focuses on current UK school designs with the following objectives: a) to investigate in more detail the school's thermal environment during summer, b) to evaluate the building's likelihood of overheating according to children's comfort thresholds and c) explore passive retrofit measures and "soft" building management solutions that could futureproof schools for pupils' health and wellbeing.

1.1. Case study building

A primary school, constructed in 2013 at Southampton, UK was used as case study. The school typically accommodates 420 students aged 4 to 11 years old. According to guidance published by the UK Department of Education (DfE) and Education and Skills Funding Agency (ESFA) on school baseline design, the case study school is a Primary Type 2 420 [12].

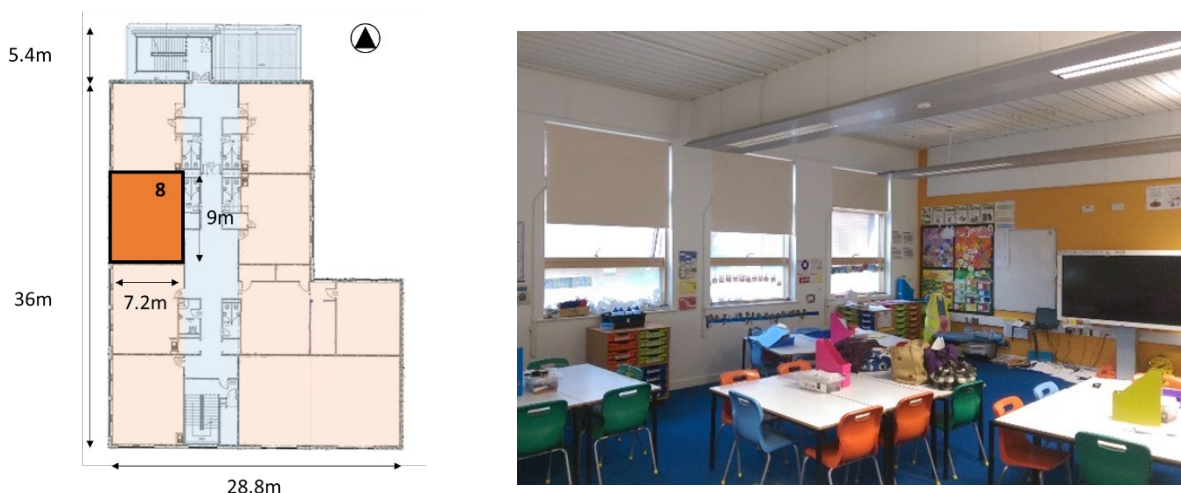


Figure 1. The floor plan of the first floor with the case study classroom shown in orange (left, Classroom 8) and a typical classroom layout and windows (right).

The main school building is bordered by the school grounds at the west, residential and domestic properties at the north and east and a dual lane road at south. The school is built in three levels and the total useful floor area is 2,331 m². Ancillary and office spaces are mainly located at the ground and second floors. The main façades orientation is East-West.

The building is naturally ventilated with manually operable windows. Heating is provided from a wet system with gas boilers (heating season from October to April). There is no air conditioning in the classrooms with the exception of a classroom where the teacher has requested and operates a movable AC unit. The total window to wall surface ratio is 0.3 for the classrooms' external walls. A typical classroom has a floor area of 65m². The window to floor surface ratio of the classrooms is around 0.14. A typical classroom is shown in Figure 1 (right).

Data were collected from eleven classrooms distributed across all levels and orientations of the school. One classroom in the first floor has been selected for modelling the thermal environment of the room. Classroom 8 is a typical classroom in the middle of the building surrounded by similar classrooms. It has a west orientation with the main openings overlooking on the school grounds.

1.1.1. Local climate

Southampton (50.91 °N, 1.404 °W) is a port city in the south of England. According to the updated Köppen-Geiger classification the climate is warm temperate, fully humid with warm summers “Cfb” [13]. In the period 2017-2019 there were on average 2,618 Heating Degree Days (T_{base}=18°C) and 192 Cooling Degree Days (T_{base}=18°C) per year. In particular 2015 was the 16th warmest year in UK history of records and there was a 1-day hot spell in July [14] when the max temperature in Southampton reached 31°C (at 15:00, [15]).

The surrounding vegetation and neighbouring buildings do not cast shadows onto the school building facades. The adjacent road is a dual lane road that has heavy traffic usually at peak hours. The traffic peak hours typically coincide with the drop-off and pick-up of the children from school.

2. Methods

In this work a mixed method data collection approach was followed. Direct observations, interviews with the building managers and teachers, and monitoring of the environmental conditions were used to evaluate the building's thermal environment. Ethical approval for data collection was gained through the University of Southampton Ethics committee. The school also provided approval to the data collection.

Indoor air temperature (°C) and relative humidity (%RH) observations were collected from a sample of 11 classrooms. Data were collected from most of the classrooms, distributed across different floors and both east and west room (window) orientations. Temperature and relative humidity miniature data loggers [16] (Figure 2) were placed in the classrooms with the permission of the head teacher and the teachers during spring 2015. Data were collected during the summer school term from April through July 2015.



Figure 2. Temperature and relative humidity miniature data loggers used in this study.

The miniature data loggers recorded air temperature (T) at a 0.01°C resolution and relative humidity (RH) at a 0.1% resolution every 5 minutes (snapshots, not average). The manufacturer stated accuracy is +/- 0.5 °C and +/- 3% RH [16].

In situ installations had to achieve a balance between being representative of the average ambient room conditions whilst ensuring safe and secure placement of the sensors as well as minimizing

disruption to the pupils. The chosen locations for the sensors were usually in the middle and around 2m height at the rear wall of the classroom where there are large notification/thematic boards hanging on the wall. The locations of the data loggers were chosen such that (i) be away from direct internal heat sources (e.g. PC heat sinks and fans); (ii) have sufficient airflow and (iii) be shaded from direct sunlight at all times.

Small accelerometers were installed on classroom windows to monitor their state (open/close). Classrooms typically have four external windows. Each window is separated in three parts. A fixed bottom window that does not open. A middle large top pivot window opening outwards and a small top window which is controlled by a remote winding gear opener located at the side of each window. The middle and top windows are fitted with 200mm restrictor for safety reasons. Internal manual blinds are installed at each window. There are no external shades.

2.1. Building simulation assumptions

The building complies with the UK Building Regulations 2010 (PART L2A) and the U values for the building elements were assumed to be equal to the regulation limits (Table 1). According to the current Display Energy Certificate, in 2018 the building used 67 kWh/m² (total 156,674 kWh gas) heating and 38 kWh/m² (total 87910 kWh) electricity.

Table 1. U value limits for the school building elements according to the UK Building Regulations 2010 (PART L2A).

Element	U-value [W/(m ² .K)]
External walls	0.35
Roof	0.25
Party walls	0.20
Windows/doors	2.2
Floors/ceilings	0.25
High usage entrance doors	3.5

A TRNSYS [17] dynamic thermal simulation was used for the assessment of current and future overheating risk. The simulation was validated against internal temperature observations from Classroom 8 during the monitored period of 31st May to 28th July 2015. Validation utilised a bespoke EPW weather file created from data from Southampton in 2015. In addition, current overheating risk was assessed with CIBSE DSY3 (Design Summer Year, prolonged warm spell) weather file [18].

2.2. Occupancy and ventilation profiles

A typical school day in the UK starts at 08:40 and finishes at 15:20. There is a lunch break between 12:10 and 13:00. Teachers and staff typically start an hour earlier and stay an hour later in the afternoon to finish work and perform daily cleaning and maintenance tasks. In 2015, the summer term began on 19th April with summer holidays beginning on 24th July returning on September 2015. Additionally the school was also closed for summer half-term from 23rd-31st of May. Although typical overheating assessment criteria focusses on the summer period of 1st May to 30th September, assessment in this study focusses on the term time between the 31st May and 19th July 2015.

Ventilation profiles used in simulations were informed by interviews with the building managers and the data from window mounted accelerometers, summarised in (Table 2). Window usage was represented in TRNSYS through scaling opening area based on internal classroom temperatures. As simulated internal temperatures begin to exceed 22°C, window opening area scales linearly up to a maximum of 30°C, at which point all available windows are assumed to be in the open state.

Although crossflow ventilation would significantly increase the air change rate in classrooms, concerns over noise from hallways and adjacent spaces often resulted in doors to hallways remaining shut during the teaching periods. In addition, crossflow ventilation would require cooperation and synchronisation of window opening behaviour between classrooms on opposite façades. This proved

outside the scope of this study, however the viability of engineered solutions to provide crossflow whilst mitigating noise nuisance remains a further area of research.

Table 2. Summary of temperature thresholds for window opening used in TRNSYS simulations.

Number of Open Windows	Open Window Area (m ²)	Opening Threshold (°C)	Closing Threshold (°C)
1	0.78	22	18
2	1.56	25	18
3	2.34	27	18
4	3.12	30	18

3. Results and discussion

The school was found to have a high likelihood of overheating, based on adaptive school children's comfort model discussed in the previous work by Teli et al. [11]. Results in this previous study showed that 64% of the classrooms had high risk of overheating. When summer performance was compared to older medium and heavy weight school buildings it was found that the oldest medium weight design performed the best in summer [11].

3.1. Internal thermal environment assessment

Assessment of the internal classroom temperature showed that almost all classrooms had high maximum and average temperatures during the monitored period, regardless of façade orientation and location in the building (Table 3). Classrooms with both East and West facing façades performed similarly. Most notably, classroom 8 had a maximum temperature exceeding 30°C. A common compounding factor in schools, and to an extent most public buildings, is the limitation for potential early evening and overnight purge ventilation due to security concerns of prohibited access. "Night Purge" has been shown to be an effective tool in mitigating overheating risk if utilized in the public sector [19].

Table 3. Descriptive statistics of classroom temperatures in classrooms during monitored occupied hours of the summer of 2015.

	Classrooms										
	1	2	3	4	5	6	7	8	9	10	11
Orientation	East	East	East	West	West	East	East	East	East	West	West
Average	23.0	23.4	23.8	24.4	23.6	23.9	23.5	23.6	23.0	24.0	23.8
St dev	1.1	1.0	0.8	1.0	1.4	0.9	1.4	1.5	1.6	1.3	1.5
Max	27.6	28.3	28.0	28.8	29.5	27.9	29.1	30.5	29.4	29.0	28.8
Min	19.8	20.4	21.1	20.7	19.2	20.1	18.7	17.5	17.8	20.4	20.0

Figure 3 shows the development of classroom temperature during the week, with the outdoor temperature (1 July). Classroom overnight temperature decrease is 'disconnected' from the external ambient conditions suggesting a sealed façade. Despite an external overnight temperature decrease of approximately 7°C (Figure 3), a majority of classrooms do not exceed an overnight decrease of greater than 2°C. However, temperature trends during occupied hours in classrooms more closely match ambient temperature, suggesting that classrooms operate in a free-flowing natural ventilation mode

during occupied hours. Another important observation regarding the relation of classrooms with external temperature development is the noticeable absence of lag between solar irradiance and internal temperature. As anticipated, East facing classrooms are affected primarily by solar gains in the morning, whilst West facing classrooms are mostly impacted by afternoon ambient temperature. This is primarily an indication of the low thermal mass of the building and heavy usage of blinds on the western façade. Heavy blind usage on the western façade is common amongst classrooms. TRNSYS simulations therefore reflect a high internal shading usage.

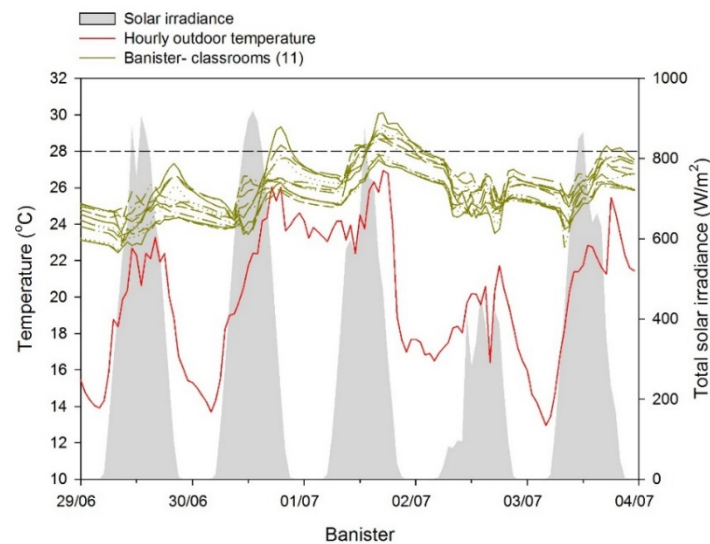


Figure 3. Hourly classroom temperature development during the week with the external temperature in the studied period.

3.2. Simulation validation and comparisons

The TRNSYS simulation was validated on an hourly time step against the 2015 weather data, producing an R^2 Error of 0.49, RMSE = 1.39 and a cross correlation of 0.70.

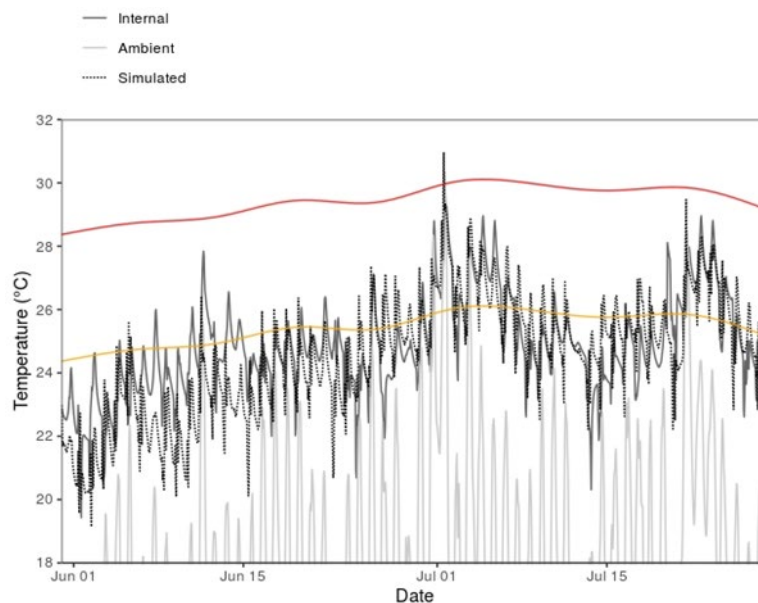


Figure 4. Hourly internal, ambient and TRNSYS simulated temperature from 31st May - 19th July 2015. $T_{\text{comfchild}}$ limits T_{Max} and T_{Upp} represented in orange and red respectively.

This suggests that the TRNSYS simulation and assumptions are relatively representative of the thermal performance of classroom 8 over the selected period (Figure 4). Both the monitored and simulated data were compared against the child-based thermal comfort equation developed by Teli et al. [11] based on children's thermal sensation votes and measured indoor thermal conditions.

This adaptation of the EN 15251 relationship, between comfort temperature (T_{comf}) and exponentially weighted running mean, was used as a baseline for adapting the existing CIBSE TM52 Overheating Criteria II [20]. Performance of monitored and simulated temperature data against the modified CIBSE TM52 Criteria 1 through 3 is available in (Table 4). A building is classed as overheating if any two of the criteria are exceeded. In general, the criteria are [11]:

CIBSE TM52 Overheating Criteria [20]

- Criterion 1 Hours of exceedance (H_e): the number of hours (H_e) during which the indoor operative temperature (T_{op}) exceeds the upper limit of the comfort temperature range ($T_{\text{comf}} \pm 3^\circ\text{C}$) by 1°C or more should not be more than 3% of the occupied hours. $H_e \leq 3\%$ of occupied hours, when $\Delta T \geq 1^\circ\text{C}$ where $\Delta T = T_{\text{op}} - T_{\text{max}}$.
- Criterion 2 Daily Weighted exceedance (W_e): for each day the sum of the weighted exceedance for each 1°C above the upper limit of the comfort temperature range, the allowable maximum T_{max} , should be less or equal to 6. $W_e \leq 6$, where $W_e = (\sum h_e) \times WF$ and h_e is the time (h).
- Criterion 3 Threshold/absolute upper limit temperature (T_{upp}): the indoor operative temperature should not exceed the T_{max} by 4°C or more at any time ($T_{\text{upp}} = T_{\text{max}} + 4^\circ\text{C}$) and $\Delta T \leq 4^\circ\text{C}$.

3.3. Retrofit opportunities and soft interventions

The 2015 weather file was utilised in order to benchmark potential 'hard' retrofit (installation of external louvre shading and reflective window coating) and 'soft' (an informed ventilation profile and night purge ventilation) interventions. These were then compared against the adapted CIBSE Criteria, TM52_{ad}.

A common retrofit method considered is the installation of an external louvre that protrudes approximately 1.1m from the west façade. This option has the primary benefit of reducing direct beam radiation, reducing the dependence on heavy blind usage during the summer months whilst improving natural light. This however has a high initial capital cost.

The second 'hard' retrofit option involves reducing the emissivity of the external glazing. Current glazing is assumed to have a total solar heat gain coefficient g-value=0.5. This option reduces the g-value approximately to 0.3, by utilising a low-e coating or film on the outside of classroom windows.

The first 'soft' intervention aims to address incorrect ventilation practices often seen in climates that have not typically experienced 'warmer extremes'. This scenario intends to provide instruction for teachers in the most vulnerable classrooms during heatwave or extreme events. Under this hypothetical scenario, on days where ambient temperatures are set to exceed 25°C , teachers are instructed via email, push notifications or morning meetings, to close windows and blinds in order to reduce unnecessary air changes and direct solar radiation into the classrooms during the hottest parts of the day. Engaging in short amounts of purge ventilation before and after the school day. Although ideally the façade should be entirely sealed, limited window opening is permitted in order to maintain the required 2.6ACH for good air quality. This is an 'inversion' of the currently exhibited ventilation strategy where the windows are left open during the day.

Although night purge ventilation currently has significant barriers due to concerns over safety, the overheating risk reduction potential has been demonstrated for comparative purposes. In instances where smaller windows could allow night purge whilst not allowing access, it could remain a low-cost option for mitigating overheating risk. Under this scenario, one small window is left open overnight whilst the remaining windows are closed. Similar to the previous scenario, the façade is left sealed during occupied hours with limited window opening permitted in order to maintain the required 2.6ACH.

Table 4. Performance of ‘hard’ retrofit and ‘soft’ intervention scenarios examined in this study, against the modified for children’s comfort $TM52_{ad}$ based criteria (Crit.1 - 3) [20].

<i>Category</i>	<i>Crit. 1^a</i>	<i>Crit. 2^b</i>	<i>Crit. 3^c</i>	<i>TM52_{ad} result</i>
Monitored Internal	13.6%	11	0	Fail
Simulated Internal	14.2%	17	1	Fail
External Shading	7.0%	8	1	Fail
Emissivity	7.9%	8	1	Fail
Informed Ventilation	10.5%	11	1	Fail
Night Purge	0.8%	1	0	Pass

^a% Occupied hours, ^b hours of exceedance, ^c 1(True):exceeds upper threshold)

As seen in (Table 4), the ‘hard’ retrofit strategies performed consistently better in Criterion 1, *Hours of exceedance* (H_e) and Criterion 2 *daily weighted exceedance* (W_e). The threshold limit for Criterion 1 is 3% of occupied hours, therefore the night purge ventilations strategy is the only strategy to pass this criterion. Typically, any exceedance of Criterion 2 and 3 would result in a failure against these criteria, as outlined in Table 4. Almost all simulations have one day (the same day) whereby they exceed the absolute upper limit (T_{upp}). Although this would typically suggest the simulations have a poor prediction rate for maximum daily temperature, monitored internal temperature only passes this threshold by approximate 0.2°C. The prediction error for maximum temperature for this period is 1°C between monitored and simulated. In order to provide a more descriptive metric, the number of days when exceedances occur for criteria 2 and 3 has been estimated instead. Under $TM52$, failure of two or more Criteria represents a failure of the standard. The only measure that results to Pass of the more stringent child based adapted $TM52_{ad}$ overheating model is the night purge ventilation strategy.

4. Conclusions

This study addressed a newly built, naturally ventilated school in Southampton, UK as a case study to investigate if there are “soft” measures which could help to achieve comfort in schools under future climate and considering children’s specific needs, without resorting to high-energy air-conditioning systems.

The results show that passive measures and adaptive behaviour could reduce the exposure of students and staff to high temperature internal environments. Passive retrofits focusing on shading and ventilation could- to a great extent- control the classroom temperature. It is likely that eventually a combination of mechanical and natural ventilation might be necessary in the future, but the measures examined in this study would still help to reduce the use of energy and resources as much as possible.

Furthermore, there are “soft” solutions that require a radical rethinking of current everyday living conditions and lifestyles. For example, this study showed that closing the windows during the hottest parts of the day and planning night purges could play an important role in overheating risk control. However, such solutions will need to change established everyday practices. This might still be a better option than costly, forced adjustment of lifestyle as a response to extreme climate change.

Future work will look at the cooling loads required to achieve students’ comfort under current and future climate projections and it will evaluate the energy savings that could be achieved with a combination of the measures discussed here and cooling systems.

Achieving the UN Sustainable Development Goals by 2030 will require to rethink and redesign urban living and city infrastructures. This work is looking in particular to address the key targets of SDG 13 (Climate Action) relevant to strengthening resilience, mitigating and reducing the impact of climate change on school buildings, and to inform policy for climate change related planning. At the same time, it focuses on the health and wellbeing of young children (SDG 3), who spend a considerable part of their lives at school and on passive measures to address building overheating (SDG 11).

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References

- [1] Lomas KJ, Giridharan R. Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case-study of hospital wards. *Build Environ* [Internet]. 2012 Sep 1 [cited 2019 May 10];55:57–72. Available from: <https://www.sciencedirect.com/science/article/pii/S0360132311004227>
- [2] Pachauri RK, Mayer L, Intergovernmental Panel on Climate Change. *Climate change 2014 : synthesis report*. 151 p.
- [3] Santamouris M. Recent progress on urban overheating and heat island research. integrated assessment of the energy, environmental, vulnerability and health impact synergies with the global climate change. *Energy and Buildings*. 2019.
- [4] Department of Health. *Heatwave plan for England: Protecting health and reducing harm from severe heat and heatwaves*. Public Health England. 2015.
- [5] The Sustainable Development Goals Report 2018 [Internet]. UN; 2018 [cited 2020 Jan 15]. (The Sustainable Development Goals Report). Available from: https://www.un-ilibrary.org/economic-and-social-development/the-sustainable-development-goals-report-2018_7d014b41-en
- [6] Montazami A, Gaterell M, Nicol F, Lumley M, Thoua C. Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms. *Build Environ*. 2017;
- [7] Haddad S, Osmond P, King S. Revisiting thermal comfort models in Iranian classrooms during the warm season. *Build Res Inf*. 2017;
- [8] Trebilcock M, Soto J, Figueroa R. Thermal comfort in primary schools : a field study in Chile. *Proc 8th Wind Conf Count Cost Comf a Chang world Cumberl Lodg Wind UK*, 10-13 April 2014. 2014;
- [9] Teli D, Jentsch MF, James PAB. Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. *Energy Build*. 2012;
- [10] ter Mors S, Hensen JLM, Loomans MGLC, Boerstra AC. Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. *Build Environ*. 2011;
- [11] Teli D, Bourikas L, James PAB, Bahaj AS. Thermal Performance Evaluation of School Buildings using a Children-based Adaptive Comfort Model. *Procedia Environ Sci*. 2017;38:844–51.
- [12] Education and Skills Funding Agency, UK Department for Education. *Baseline design: 420 place primary school with 26 place nursery* [Internet]. online; 2014. Available from: <https://www.gov.uk/government/publications/baseline-design-420-place-primary-school-with-26-place-nursery>
- [13] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Köppen-Geiger climate classification updated. *Meteorol Zeitschrift*. 2006 Jun;15(3):259–63.
- [14] Kendon M, Mccarthy M, Jevrejeva S, Legg T. *State of the UK Climate 2015* [Internet]. Available from: <http://www.sat.dundee.ac.uk/>

- [15] The Southampton Weather Team. Southampton Weather [Internet]. [cited 2020 Jan 15]. Available from: <http://www.southamptonweather.co.uk/>
- [16] MadgeTech. RHTemp101A Data logger, relative humidity and air temperature data logger. [Internet]. Available from: <https://www.madgetech.com/products/rhtemp101a/>
- [17] Klein SA, et al. TRNSYS 18: A Transient System Simulation Program, Solar Energy Laboratory, University of Wisconsin [Internet]. Madison, USA; 2017. Available from: <http://sel.me.wisc.edu/trnsys>
- [18] CIBSE. CIBSE Weather Data Sets. Chartered Institution of Building Services Engineers. 2016.
- [19] Cosar-Jorda P, Buswell RA. Estimating the Air Change Rates in Dwellings Using a Heat Balance Approach. *Energy Procedia*. 2015 Nov;78:573–8.
- [20] CIBSE. The limits of thermal comfort : avoiding overheating in European buildings. CIBSE TM52 2013 p. 1–25.