Intelligent Buildings International

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tibi20

School building-stock climate resilience: evaluating London’s school stock overheating performance

Yair Schwartz, Ivan Korolija, Daniel Godoy-Shimizu, Sung-Min Hong, Anna Mavrogianni & Dejan Mumovic

To cite this article: Yair Schwartz, Ivan Korolija, Daniel Godoy-Shimizu, Sung-Min Hong, Anna Mavrogianni & Dejan Mumovic (08 Nov 2024): School building-stock climate resilience: evaluating London’s school stock overheating performance, Intelligent Buildings International, DOI: 10.1080/17508975.2024.2410804

To link to this article: https://doi.org/10.1080/17508975.2024.2410804

Published online: 08 Nov 2024.

INTELLIGENT BUILDINGS INTERNATIONAL
https://doi.org/10.1080/17508975.2024.2410804

School building-stock climate resilience: evaluating London's school stock overheating performance

Yair Schwartz, Ivan Korolija, Daniel Godoy-Shimizu, Sung-Min Hong, Anna Mavrogianni and Dejan Mumovic

The Bartlett School of Environment, Energy and Resources, University College London, London, UK

ABSTRACT

Indoor environmental quality (IEQ) in classrooms is crucial for students' health, wellbeing, and academic success. Rising outdoor temperatures due to climate change pose a significant risk – overheating in schools can negatively affect cognitive performance and health for both students and staff.This study examines the risk of overheating in primary and secondary schools in London, focusing on the impact of current and future climate scenarios. Using the UK Department for Education's Building Bulletin 101 (BB101) as a framework, the study integrates data from various sources, including GIS form data and a national school survey, to develop a 'one-by-one' school stock thermal model called the Modelling Platform for Schools (MPS). This model, built using EnergyPlus, allows for the analysis of school thermal performance at national, regional, and individual levels.The results show that by the 2050s, under a medium emissions scenario, average summer temperatures in schools could reach nearly 30°C – 7% higher than current levels. The study also developed an overheating-risk regression model for London schools and explored potential mitigation strategies, such as extending summer holidays or adjusting school activities to times when overheating risk is lower.

Abbreviations: BB101: Building Bulletin 101; CDC: Condition Data Collection; CIBSE: Chartered Institution of Building Service Engineers; DEC: Display Energy Certificates; DfE: Department for Education; DSY: Design Summer Year; GIS: Geographic Information System; HVAC: Heating, Ventilation, and Air Conditioning; IEQ: Indoor Environmental Quality; IPCC: Intergovernmental Panel on Climate Change; MPS: Modelling Platform for Schools; NCM: National Calculation Methodology; OS: Ordnance Survey; PDSP: Property Data Survey Programme; WWR: Window to Wall Ratio

ARTICLE HISTORY
Received 18 August 2023
Accepted 13 September 2024

KEYWORDS
Overheating; school building; climate resilience; buildings stock modelling; future climate scenarios

1. Introduction

Children spend a considerable amount of their daytime in classrooms – more than any place other than their homes (Csobod et al. 2014). Providing a good indoor environment in classrooms is therefore instrumental to pupils' health and wellbeing, and for their educational success. While school buildings are complex spaces to design and operate, especially due to their unique, intermittent and dynamic usage patterns (Becker, Goldberger, and Paciuk 2007), it is crucial that classrooms maintain good Indoor Environmental Quality (IEQ) conditions.

In the UK, many older schools were originally designed to maximise solar heat gain penetration and retain heat, in order to minimise winter space heating demand (Jenkins, Peacock, and Banfill 2009). As

CONTACT Yair Schwartz yair.schwartz@ucl.ac.uk The Bartlett School of Environment, Energy and Resources, University College London, London WC1H 0QB, UK

these school buildings were designed for a cooler climate, and since they were initially assumed to be unoccupied during summer months (whereas in practice now many are occupied for summer clubs), overheating was not considered a major risk. Minimum thermal criteria for buildings, in the form of the UK Building Regulations, were introduced in the 1970s to reduce heat loss from heated spaces through the building's external fabric. As a result, a large proportion of the current UK school stock may not be prepared to cope with potential classroom overheating (Jenkins, Peacock, and Banfill 2009).

As the world is facing global climate change, the Intergovernmental Panel on Climate Change (IPCC) predicts that the global mean surface temperature will increase by between 2.6 and 4.8°C by the end of the twenty-first century, compared to the 1986–2005 benchmark (Intergovernmental Panel on Climate Change (IPCC) 2019). Consequently, it is predicted that average summer temperatures in the UK will increase by nearly 5°C by 2070, and the number of hot days per year exceeding 28°C will rise significantly (UKCP 2018). These conditions will pose challenges to providing adequate indoor summer thermal conditions in classrooms. Evaluating the performance of school buildings, specifically on the issue of overheating risk, is, therefore, becoming increasingly important (Montazami, Gaterell, and Nicol 2015). Overheating analyses should be undertaken in multiple hierarchies: at a national/stock-level, there is a need to better understand the impact of overheating on the health and performance of pupils and staff. This is especially important, as it will help not only in tackling overheating at present, but also preparing for a future rise in temperature by informing policy and funding decisions for risk mitigation. At the building-level, analysis focussed on individual schools and their particular characteristics (climate, orientation, construction materials, use etc.) could lead to meaningful insights for head teachers, governors, and facility managers, and result in tailored overheating risk mitigation measures or refurbishment packages, especially as studies suggest that considering improvements of thermal efficiency in building envelopes can help mitigating overheating risk (Ozarisoy and Altan 2022).

Building stock thermal modelling is a modelling method widely applied for examining the thermal behaviour and energy performance of large numbers of buildings. Stock-level modelling is mainly useful for policy, as it can assist in identifying challenges and opportunities at a large scale, in exploring the impact of interventions, and in forming strategies for improving the stock's resilience to climate change or fuel crises. A 'one-by-one' building stock model (a stock model in which each and every building in the stock is modelled and simulated) responds to the need of policy makers by synthesising data at national level and data at a building level, by analysing phenomenon that is relevant to each school individually.

1.1. Aims and scope

The overarching aim of this study is to use a building stock-modelling approach to evaluate the overheating risk of school buildings in London, England. More specifically, the goals of this study are to:

- Estimate the scale of overheating in the school building stock in London, UK, under current and future climate scenarios, based on the United Kingdom Department for Education's Building Bulletin 101 (BB101) overheating evaluation protocol.
- Explore the impact of a set of adaptation measures on the risk of overheating in the London school stock.

The study presents processed data from several sources of detailed, disaggregated information on the school stock in England, that is input into the Modelling Platform for Schools (MPS (Schwartz et al. 2022)) – a building stock modelling platform that generates thermal models for each school in turn (also referred to as a 'one-by-one' school stock model). MPS automatically gathers data on every school in the stock (where data are available), models, simulates and analyses the performance of the stock in its entirety.

The analyses in this study are carried out on the primary and secondary school stock of London, modelling 899 establishments (accounting for around 60% of the schools that data were available for, following an evaluation and filtering based on data quality, and 39% of the total primary and secondary schools in the Greater London Area). By using this methodology, this study presents a detailed examination of the overheating risk of the London school stock, and explores the impact of several adaptation scenarios.

2. Background

2.1. Building stock modelling

Building stock modelling aims to gain insights into the performance of the building stock as a singular entity. Building stock models are used for exploring stock-level energy consumption and carbon emissions (Wang and

Chen 2014; Xu et al. 2012), refurbishments (Ballarini et al. 2017), Life Cycle Performance (Famuyibo, Duffy, and Strachan 2013; Mastrucci et al. 2017) and IEQ as well as occupant health (Schwartz et al. 2021b; Taylor et al. 2014) and the impact of the Urban Heat Island (Mavrogianni et al. 2012). Using a stock model can help in exploring the performance of the stock in an efficient and low-cost manner and in a relatively short time.

Literature on the theory behind building stock modelling is well established (Brøgger and Bjarne Wittchen 2018; Kavgic et al. 2010; Li et al. 2017; Swan and Ismet Ugursal 2009). Stock modelling approaches can largely be divided into the following categories: a 'Top-Down' approach – where models describing the relationships between the stock characteristics and its performance are formed based on a statistical analysis of empirical data, and a 'Bottom-Up' approach – where the empirical, statistical or simulated performance of individual buildings are extrapolated to form the basis of a large model that represents the entire stock (Dong et al. 2021; Kavgic et al. 2010; Swan and Ismet Ugursal 2009). Since they may involve simulating thousands of buildings, stock models require input data that balances the benefits of greater complexity and detail, with practical factors such as the cost of data collection and computing time. Input data needs to capture the main features that determine building performance, while keeping the stock description relatively generic so that simulation process is manageable and time efficient. Key inputs include data on physical characteristics (e.g. built form, thermal and geometrical properties), as well as systems and occupancy factors (e.g. occupant use patterns, climate, ventilation rates etc.) (Geraldi and Ghisi 2020). 'Archetype' stock modelling is one of the most common stock modelling approaches (Dong et al. 2021; Escandón et al. 2022; Grassie et al. 2022; Mavrogianni et al. 2012; Oikonomou et al. 2012). Archetype-based school models rely on the evaluation of large-scale datasets of buildings (quite often on a national level), to achieve a 'top-down' description of a variety of archetypes across a given geographic region, based on the prevalence of certain building characteristics. Such models can also integrate data from occupancy questionnaires, alongside the information on the physical & systems characteristics of the buildings (Altan and Ozarisoy 2022). A thermal stock model is developed to explore the performance of each archetype in a 'bottom-up' manner (Grassie et al. 2022; Schwartz et al. 2021a).

While archetype stock modelling can be effective, the use of a small number of models (archetypes) to represent the entire stock implies that important nuances will be lost. Detailed building geometries, and space uses are averaged out, whereas these could have an important impact on a building's performance.

Addressing these limitations, a 'one-by-one' approach involves modelling and simulating each building within a stock separately (depending on data availability). This technique offers a more detailed exploration of the stock's performance by accounting for the diversity of the buildings within it.

2.2. Overheating analysis

The risk of indoor overheating in schools has become a major concern, especially since studies have shown that it is predicted to be more prevalent in the future (Jenkins, Peacock, and Banfill 2009; Montazami, Gaterell, and Nicol 2015). Overheating can be caused by a combination of factors including building fabric characteristics and insulation, orientation and exposure, building location and climate, space ventilation and use patterns (Department of Energy and Climate Change 2015). In response to UK legislation targeting Net Zero carbon emissions by 2050 (UK Parliament 2008), schools are expected to undertake a series of mitigation measures, to reduce demand for heating and energy consumption. Importantly, however, improving the thermal properties of school building fabric and airtightness to reduce heating demand may also degrade the indoor environmental quality and increase indoor temperatures if these interventions are not carried out in a holistic way (Jenkins, Peacock, and Banfill 2009).

The UK Department for Education (DfE) issued '*Building Bulletin 101 – Guidelines on ventilation, thermal comfort and indoor air quality in schools (2018)*', (BB101) (Department for Education 2018) outlines the standards and regulations for thermal comfort and ventilation in school buildings within England. The BB101 guideline approach to overheating risk assessment is largely based on the Chartered Institution of Building Service Engineers (CIBSE) Technical Memorandum 52 (TM52). To assess the risk of overheating in schools, BB101 uses the following three criteria:

- Criterion 1 – Hours of Exceedance: The number of hours where the adaptive thermal comfort temperature threshold is exceeded (calculated over the average mean).
- Criterion 2 – Daily Weighted Exceedance: The level of exceedance of operative temperature over the adaptive thermal comfort threshold on the hottest day.
- Criterion 3 – Upper Limit Temperature: The maximum recorded temperature at a thermal zone.

A detailed description of how the relevant criteria are calculated is given in Section 3.4.

2.3. Building stock models for overheating assessment

Stock models have been used to evaluate the risk of overheating in buildings, however, these have typically been used to explore the climate resilience of residential stocks: Mavrogianni et al. (Mavrogianni et al. 2012), for example, developed a method for evaluating summertime overheating risk in dwellings in London, in search of determinant geometrical and thermal building characteristics. The impact of occupants' behaviour and use patterns on the risks of overheating in residential buildings in the UK were emphasised in a follow-up study (Mavrogianni et al. 2014). Escandon (Escandón et al. 2022) evaluated the resilience to overheating under current and 2050 climate scenarios, for the social housing stock in Southern Spain using an archetype stock model. Oikonomou et al. (Oikonomou et al. 2012) developed a residential archetype stock model for evaluating how overshadowing can assist in mitigating overheating risk in London. Taylor et al. (Taylor et al. 2014) examined the UK residential stock performance under current and future climate scenarios.

Overheating analysis using stock models to estimate non-residential buildings is scarce. Focusing specifically on classrooms within schools, Grassie et al. (Grassie et al. 2022) used 111 archetypes to represent classrooms in nearly 10,000 English schools and assessed the risk of overheating and poor air quality. The study found that classrooms oriented towards the south-east had four-to-six times the overheating time, compared with classrooms with northerly orientations. The study further found that classrooms that were built post-1976 were more prone to overheating, probably due to high levels of thermal insulation and airtightness, and limited options for passive cooling.

All-else-being-equal, compared with archetype-based models, 'one-by-one' stock modelling provides the opportunity to be more accurate, and potentially reveal greater insights into the challenges and opportunities for mitigating overheating in the school stock. This is because one-by-one models account for the specific form and envelope characteristics of each building (variables that greatly influence overheating). Naturally, however, this approach requires a greater quantity of detailed input data, in order to model the stock accurately. To the knowledge of the authors, at the time of writing, no studies have presented 'one-by-one' stock models for assessing overheating at the school building stock level.

3. Model development

The steps used for generating the school stock model and analysing the thermal simulation results are described in Figure 1 and the text below. The work in this study expands on a school model that has been developed previously (Schwartz et al. 2022). This paper will therefore briefly describe the MPS methodology, but will focus on the developments that have since been made to enable overheating analyses to be undertaken. Processes labelled 'A' in the chart were discussed in previous publications, while the processes labelled 'B' were developed for this study:

3.1. School stock data analysis

The first iteration of MPS used data from several sources of disaggregated information on the school stock (Schwartz et al. 2022), described briefly below:

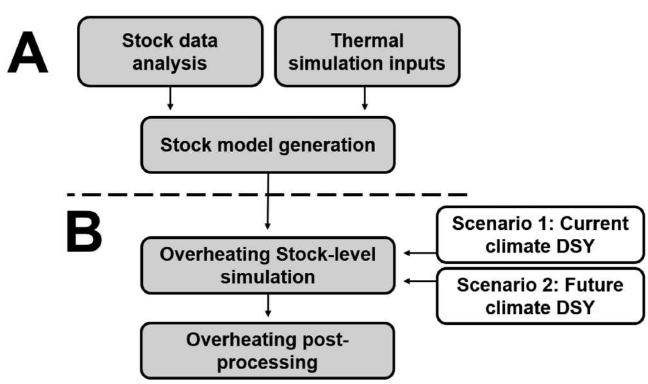


Figure 1. Study design.

- Edubase (recently renamed as Get Information About Schools) is a database of the education establishments in England (Department for Education 2022). It includes information on school status and type and, crucially, location and reference data useful for matching to other datasets.
- PDSP (Property Data Survey Programme) was a detailed survey of the school stock of England carried out between 2012 and 14 (EFA 2015). Variables available from PDSP include the envelope type, and internal systems of each school, gathered through visual inspection.
- The Display Energy Certificates (DEC) database includes information on annualised energy consumption for large public-sector buildings (split between electricity and fossil-thermal), as well as the main internal environment and main heating fuel (Department for Communities and Local Government 2015).
- Several Geographic Information System (GIS)-based datasets from Ordnance Survey (OS) provide information on building footprints, heights, and site boundaries within the UK (Ordanance Survey 2021b; Ordnance Survey 2021a).

For the present study, data from PDSP were replaced with its successor, the Condition Data Collection (CDC) survey (Education and Skills Funding Agency 2017). Carried out between 2017 and 2019, CDC was another visual inspection of the school stock of England, collecting detailed information on the building form, envelope types (including glazing ratios for the walls and roof as well as the proportion of single – and multi-glazed windows), Heating, Ventilation, and Air Conditioning (HVAC) systems, and the breakdown of internal uses (floor area for classrooms, IT space, etc.). Data were collected at the level of each school block (within the context of the CDC and PDSP surveys 'blocks' are defined by distinct construction ages, as well as physical separation). The condition of each variable was also collected, defined as a grade from A to D based on visual inspection. For the present study, the CDC data were processed and integrated into the model using the same approach as that undertaken for PDSP, described in the previous paper (Schwartz et al. 2022): The CDC data were cleaned, with unlikely or internally inconsistent entries removed; the data were then aggregated to a school block level; and finally, the CDC blocks were matched to specific building footprints within each school site boundary by comparing the floor areas. The data that support the findings of this study are available from the PDSP (EFA 2015) and the CDC programmes (Education and Skills Funding Agency 2017). Restrictions may apply to the availability of these data, which were used under permission for this study.

Table 1 summarises the data used in the present study, gathered from the above sources.

3.2. Thermal simulation inputs

The relevant data, once processed, were then used as inputs for the EnergyPlus thermal simulation tool – one of the most widely used dynamic building performance simulation tools worldwide (DoE 2020).

While information on the building forms, Window toWall Ratios (WWR) and locations were obtained from the school databases, as described in chapter 3.1, the dynamic simulation carried out within MPS requires considerably more input data. Other thermal modelling input parameters (occupancy, schedules, internal loads, etc.) were applied from relevant modelling guidelines and protocols as listed below (please see Tables 2 and 3).

Activity and internal gains are described in Table 2. Schools' use and activity categories were taken from the CDC database, to reflect the actual building use patterns for each school. The study attempted to follow

Table 1. Summary of input data collected for each school.

Category	Variable	Detail	Source
Form	Building form and height data	Total floor area, footprints, and average heights [per block]	CDC and OS
Construction	Building envelope	Window-to-wall ratios (WWR), and % single-glazing [per block]	CDC
Construction	Building age	Construction age [per block]	CDC
Occupancy	Internal use	Breakdown of internal uses [per block]	CDC
Systems	HVAC type	Proportion of floor area with Mechanical Ventilation (MV) and Air Conditioning (AC) per block	CDC
Miscellanea	School characteristics	School type and status [per school]	Edubase
Miscellanea	Climate	School location (northing and easting) [per school]	Edubase and OS

Table 2. Activities and internal gains.

Activity (as termed in CDC)	Equipment (W/m^2)	Lighting (W/m^2)	Occupancy ($persons/m^2$)	Metabolic rate (W/person)	Ventilation (l/s/person)**
Teaching*	10	7.2	0.615	115 (Primary) 125 (secondary)	8
IT*	30	7.2	0.2183	120	8
Kitchen	40	7	0.0943	180	25
Sport/ Dining/ Assembly	10.97	3.2	0.1071	205	10
WC/ Shower/ Changing/ Circulation / Other	2	1.7	0.11	140	10

*Inputs for Teaching and IT are based on BB101 (Department for Education 2018). Inputs for other spaces are taken from NCM (NCM 2016).
**Ventilation was set to be fixed, assuming a certain air change rate is achieved.

the BB101 (Department for Education 2018) guidelines for overheating assessment, and therefore used the BB101 internal load figures wherever possible. Since BB101 only provides activity and internal gains data for 'Teaching' and 'IT' spaces, internal loads for other uses (e.g. kitchen, sports hall, circulation) were taken from the National Calculation Methodology (NCM) (NCM 2016). The study used the BB101 occupancy profile. Occupancy schedules were set to be fully occupied during weekdays from 9 am to 4 pm (during May-Sep period).

The occupancy density was normalised to reflect the distribution of spaces within each thermal zone.

Construction age data were collected from the CDC database. Envelope thermal performance inputs were assigned based on construction age bands, as described in Table 3. Build-ups for each construction era category and element type were developed and converted into thermal properties and U-Values for modelling, using assumptions based on previous studies (Hong et al. 2014; Schwartz et al. 2022). A constant infiltration rate of 0.5 ac/h was applied to the model. Window U-Values were determined based on data from CDC on the buildings' construction age and the assumed glazing type (single or double) at each era. CDC was also used to determine the WWR for each glazing type.

In order to evaluate the present and potential future climate resilience of the London school stock, the study compared the overheating performance of the stock in two scenarios: a current climate scenario, using the London Heathrow Design Summer Year (DSY) weather file, and a future climate scenario – using the DSY weather file for 2050s predictions with 50% probability and a medium emissions scenario. The 2050s scenario was selected as it is supposed to predict a relatively realistic future climate change scenario (CIBSE 2016).

The London climate is generally classified as Cfb by the Köppen-Geiger (Kottek et al. 2006) which is the warm temperate climate, fully humid with a warm summer. The most important characteristics of the current and future climate scenarios, from the perspective of overheating, are summarised in Figure 2. While the predicted increase in the global horizontal solar radiation in the 2050s climate, when compared to the current climate, tends to be minimal except a slightly larger deviation in August, the difference in outdoor air dry bulb temperatures is more substantial. The daily mean outdoor air dry bulb temperature through the May-September period in 2050s climate is between 2°C and 2.4°C higher than the same temperature in the current climate weather file. For further information on modelling assumptions please see Schwartz et al. (2022).

3.3. Model construction

The CDC data bring an additional layer of information on the distribution of activities across each building block within the school site. School activities are represented by five use categories: Teaching, IT, Kitchen,

Table 3. Construction age and *U*-values.

Assumed construction era	Pre-1919	Inter war	1945–1966	1967–1976	Post-1976
Construction year in CDC	Pre 1900–1920	1921–1940	1941–1970	1971–1980	1981–2020
Building Element *U*-Value($W/m^2/k$)					
External Wall	1.80	1.80	1.70	1.70	0.83
Roof (Flat)	1.87	1.87	1.87	1.13	0.57
Roof (Pitched)	2.90	2.90	1.85	1.25	0.54
Ground floor	1.50	1.50	1.40	1.40	0.94
Windows	5.70 single glazed / 1.9 double glazed				

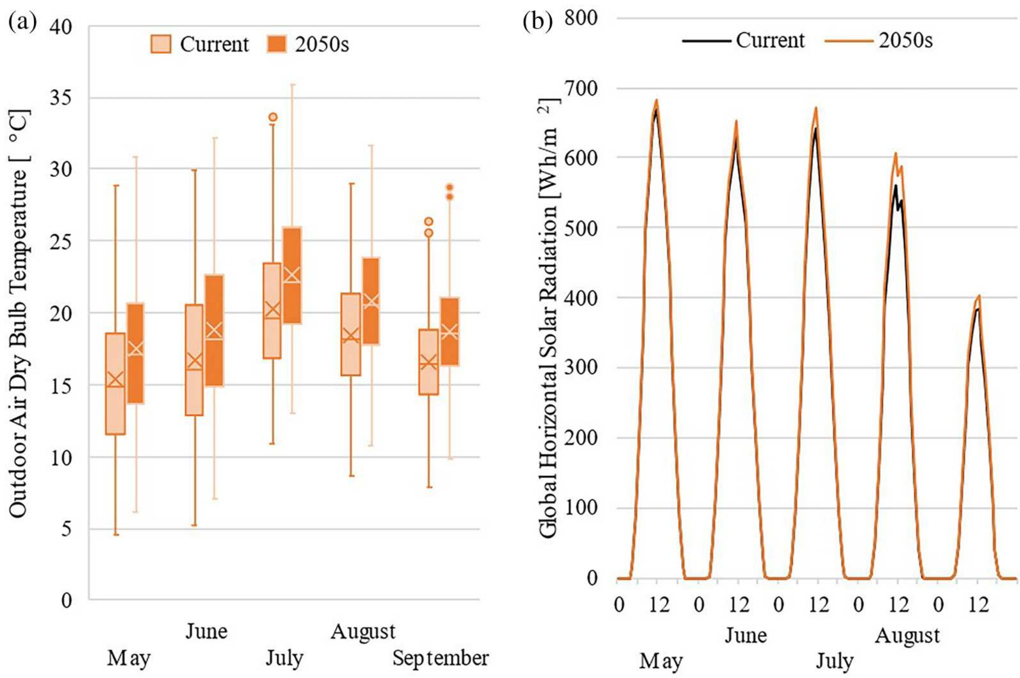


Figure 2. Outdoor air dry bulb temperature (a) and global horizontal solar radiation (b) in current and 2050s climate scenarios.

Sport/Dining/Assembly, and Others which includes corridors, wet zones and changing rooms. Each of these categories has a distinctive set of parameters, as presented in Table 2, which are the integral component of a thermal simulation. Unfortunately, where multiple activities exist within a single school block, the CDC data do not provide information on where each of these activities happens within the block. For example, the data might reveal that a school block occupied area is 70%/30% split between teaching and kitchen spaces, but the specific location of the kitchen activities cannot be identified in an automated way at present: while the CDC database contains floorplan drawings, these are not consistent and cannot, at the moment, be read automatically. Where necessary, the distribution of activities has been integrated into the model on a block-by-block basis, by area-weighting the values presented in Table 2. The 70%/30% teaching/kitchen split example would result in 19 W/m^2 equipment gains, 0.46 ppl/m^2, a metabolic rate of 128.4 W/p (secondary school case) and 9.05 l/s/p of ventilation requirements. Through the analysed period, which is from 1st May until 30th September, all internal gains, occupancy, and ventilation criteria were modelled at full capacity between 9 am and 4 pm during weekdays and at 0 capacity during all other periods. It is noted that, though this is the BB101 modelling guidelines, these assumptions may not reflect true school occupancy, especially during the summer holidays period (July 15th – September 1st), where school buildings may be used for summer clubs or other community activities.

Another improvement from the previous model, achievable due to the switch to CDC data, is related to the glazing representation. In addition to the WWR provided for each building block, CDC also holds information about the percentage of windows that are still single glazed. Like the internal use data, no geospatial data are available indicating where single-glazing windows are located within any given block. This has been integrated within the model by having two glazing units per exposed wall, one double-glazed and the other single-glazed sized to match the proportions presented in the CDC data (see Figure 3). It is noted that surrounding buildings were not modelled, and therefore their impact on overshading over windows had not been explored in this study.

By combining the CDC, OS, NCM and BB101 data within MPS, the dynamic thermal simulation models of 702 London primary and 197 secondary schools are automatically created (899 in total). The high-level physical characteristics of the modelled schools are broadly similar to the characteristics of the overall London stock. The ratios of the interquartile ranges of the modelled sample of schools to the population are within 5% for primary and secondary school total floor area; within 1% for primary & secondary school

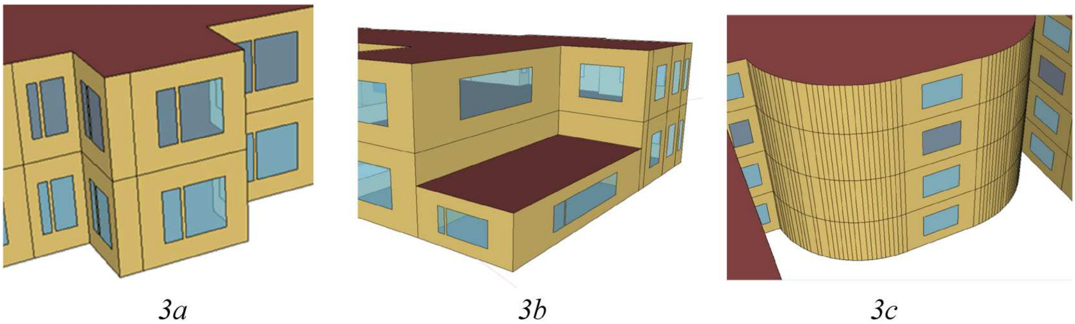


Figure 3. Vertical glazing arrangements within MPS.

window-to-wall ratio (WWR) and school construction date; and within 6% for secondary school block height. While the 50th and 75th percentile values for the primary school block height ratios are 1.00, the 25^{th} percentile value is 0.83 (the average block height is 1.0 storeys in the modelled stock, and 1.2 across the population). The distribution of these schools across 33 Greater London Area boroughs is visualised in Figure 4. Schools are represented by 6779 thermal zones (4257 in primary schools and 2522 in secondary schools) occupying nearly 4.5 km^2 of floor area of which 52% are covered by primary schools and the rest by secondary schools.

To minimise the deviation from the CDC input data, and to focus on the dominant spaces within school sites, two filters were applied to the simulation results. This results in a massive reduction in the number of thermal zones used for the analysis. The remaining 4264 thermal zones (an over 37% reduction in the number of thermal zones), are spread across 890 schools. Note that this large reduction of thermal zones only results in small reductions in modelled floor area and volume; only 2.8% and 3% respectively.

The first filter excluded all thermal zones with a footprint area less than or equal to 50 m^2. The second filter is related to the modelled WWR compared to the CDC input data. All thermal zones with modelled WWR more than 20% smaller than the CDC WWR were excluded. The discrepancy between the modelled and CDC WWR is caused by two factors. Theoretically, the WWR can be applied to all exposed horizontal surfaces, however, in certain cases the height of an exposed surface might not be sufficient to accommodate windows within the model. This could occur where two adjacent structures have different heights: The taller structure might have a thermal zone where some walls are partially a party wall and partially exposed to the outdoors. The MPS allows windows to be included in such walls only if the exposed portion of the wall is 80% or more of the total wall height (see Figure 3b). The second factor that determines the inclusion of the window is the width of the exposed wall. If the exposed wall width is less than 1 m, windows are not

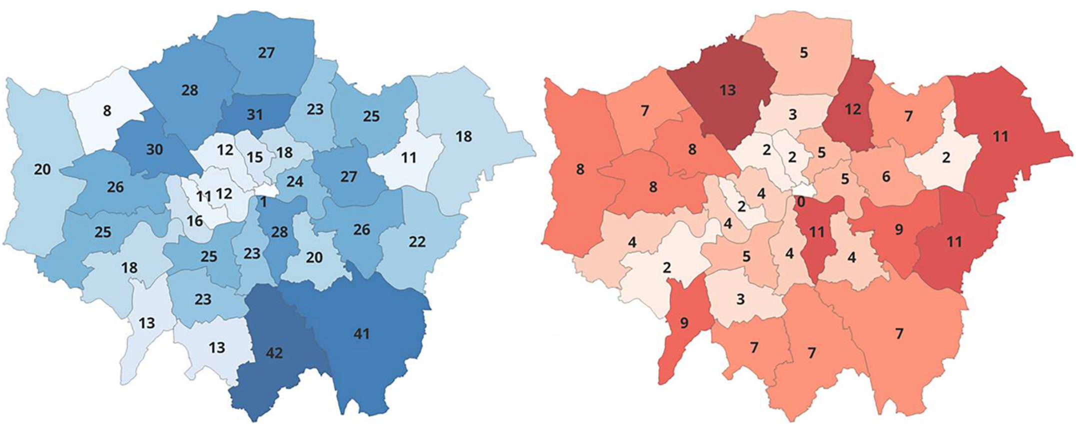


Figure 4. The distribution of the school stock across the Greater London Area boroughs: Primary Schools (left); Secondary Schools (right).

modelled. Reflecting the underlying building footprint data, such narrow wall surfaces are often elements within larger curved wall elements (see Figure 3c).

The split between the number of primary and secondary schools, the number of thermal zones and the total floor area in each school type are presented in Figures 4–6. As expected, slightly over one-fifth of all schools are secondary schools, which account for nearly 40% of all modelled thermal zones and nearly half of the school stock floor area. The complexity of secondary schools is also reflected in the number of thermal zones. While the vast majority of primary schools have been modelled with up to five thermal zones (80%) and nearly all of them have less than ten thermal zones (over 97%), the secondary school stock is significantly more complex. Only 38% of them have five or fewer thermal zones, and 31% between 6 and 10 thermal zones. More complex secondary school buildings have 11–15 thermal zones (17% of the stock) or 16–20 thermal zones (10% of the stock), while around 4% of secondary schools have more than 20 thermal zones.

3.4. Overheating assessment (the BB101 criteria – post processing)

The overheating criteria were calculated per thermal zone. To assess the risk of overheating in schools, this study uses the BB101 Criterion 1, 2 and 3 as the proxy for overheating. It is noted that MPS can compute any other type of overheating assessment method, but the BB101 criteria have been selected as they are commonly used for defining the minimum requirement of schools overheating assessment across England (DfE 2018).

Criterion 1 defines a minimum requirement for the BB101 overheating assessment, while criteria 2 and 3 act as measures for short-term overheating discomfort and should only be reported.

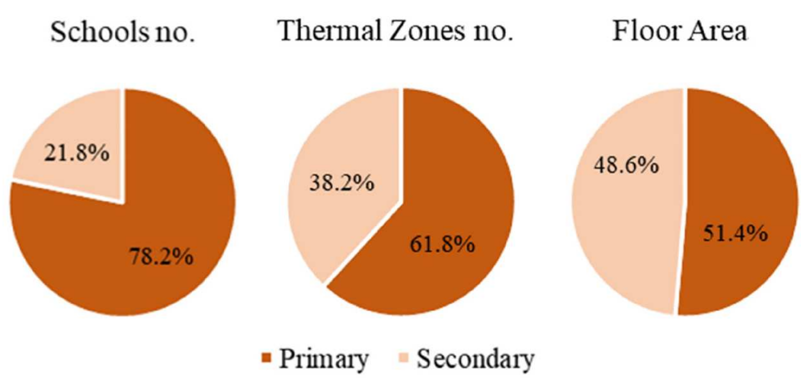


Figure 5. Percentage of primary and secondary schools by numbers, thermal zones and total floor area.

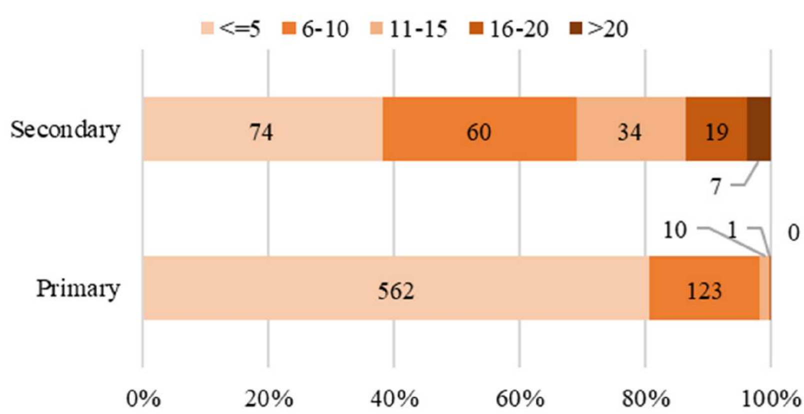


Figure 6. Number of thermal zones by school type.

Criterion 1 (Hours of Exceedance) is the total number of occupied hours during which the internal operative temperature exceeds a maximum acceptable temperature by 1 degree or more. A thermal zone fails criterion 1 if there are more than 40 such hours during the assessed period. In this case, the maximum acceptable temperature is expressed as $T_{max} = 0.33$ x $T_{rm} + 22.8$, where T_{rm} is the running mean external temperature.

Criterion 2 (Daily Weighted Exceedance) measures the severity of the overheating. It looks at the time during which the indoor temperature goes outside a desired range. This is measured in hours, and a factor is considered depending on how many degrees the range has been exceeded. It states that the overheating weighted exceedance should be equal to or less than 6 in any day:

$$W_e = \Sigma h_e xwf = (h_{e0}x0) + (h_{e1}x1) + (h_{e2}x2) + (h_{e3}x3)$$

where W_e = Weighted Exceedance, and where the weighting factor $wf = 0$ if $\Delta T \leq 0$, otherwise $wf = \Delta T$, and h_{ey} = time in hours when $wf = y$

Criterion 3 (Upper Limit Temperature) sets an absolute maximum value for the indoor operative temperature where ΔT between indoor temperature and T_{max} (as defined above) shall not exceed 4K.

4. Results and discussion

This results section is divided into three parts. The first section presents an analysis of the thermal performance of the London school building stock by describing the indoor temperature distributions across the stock during the examined months and times of the day. The second section quantifies the overheating risk, as defined by BB101. The last section explores how school operation time might affect the BB101 overheating risk.

4.1. School building stock thermal performance

The first set of analyses is focused on the school stock's thermal performance, both under the current climate (DSY1 weather file – a moderately warm assumed summer) and the 2050s climate scenario (predictions with 50% probability and a medium emissions scenario).

Figure 7 compares the distribution of temperatures (minimum, maximum, mean) in the simulated zones during the occupied hours under both climate scenarios. The simulation results show that under the current climate, the average minimum temperature is relatively low: 17.7°C under current climate scenario and 19.4°C for the 2050s one, while average maximum temperatures are predicted to rise from 36.8 (under current climate scenario) to 38.8°C (2050s climate scenario). A similar 2°C increase is also noted in average mean temperatures, which increase from 27.9°C under the current climate to 29.8°C under the 2050 weather file.

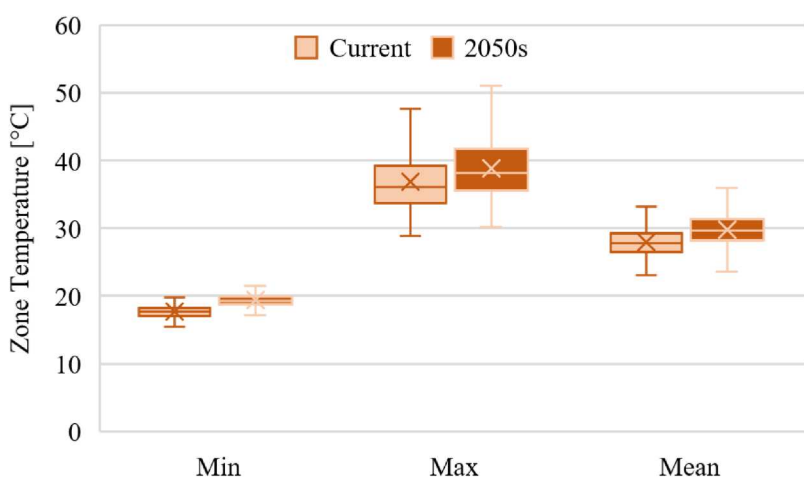


Figure 7. The distribution of zone temperatures during the occupied hours in current and future climate scenarios.

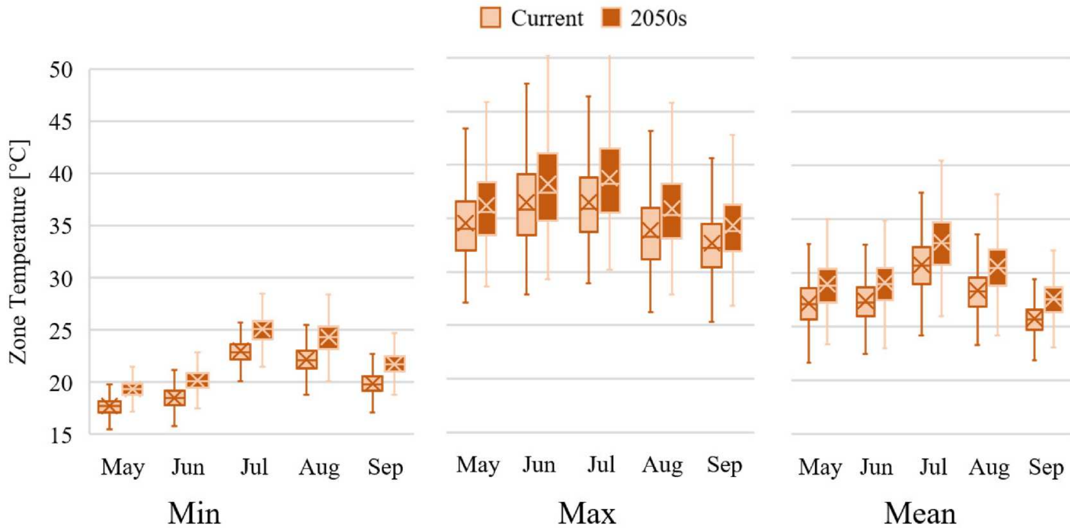


Figure 8. Minimum, Maximum and Mean average zone temperatures distribution by month.

A closer look into the temperature distribution by simulated month (Figure 8) indicates that while the average minimum temperatures are pretty moderate in May and June under both scenarios, the average minimum temperatures in July and August are 23°C (current climate) and 25°C (2050 climate). Looking at average maximum temperatures, temperatures in June and July reach around 36.5°C under the current climate scenario, and are estimated to exceed 38°C for 2050s. Furthermore, the average maximum temperature did not fall below 32°C throughout the examined months. Interestingly, by all measures, zone temperatures in July were higher than in August while, in terms of average maximum temperatures, zones were also hotter in June than in August.

A more granulated analysis was undertaken, using MPS, looking into temperature ranges across the different simulated months. Figure 9 shows the distribution of the percentage of time internal zone temperature exceed 25, 30, 35 and 40°C under current (top) and future (bottom) climate scenarios.

The results in Figure 9 confirm July as the hottest month, with a zone temperature exceeding 25°C 95% of the occupied time under the current climate scenario, and 100% of the time under the 2050 climate. A significant increase in % of the time over 30°C was noted, when comparing current and future climates, especially between June and August: an increase from 31 to 42% in June, 55–75% in July and from 28 to 53% in August.

Figures 8 and 9 have identified the period between June and August as the time with the highest average indoor temperatures, and July, in particular, as the single hottest month. This is expected, especially since July has the highest number of Cooling Degree Days (CDD) per month and higher irradiance than August (Betti et al. 2024). It is worth pointing out that while some of the highest temperatures in Figure 8 were reached during the summer-break period (July 15th – September 1st), the BB101 protocol sets out the simulated period to include these months at full capacity. The potential impact of this is further discussed in section 4.2.

The risk of overheating in the building stock is known to vary throughout the day. This reflects external factors like the diurnal trends of outside air temperature and solar gains, as well as building factors like any exposed thermal mass heating up through the day. Therefore, further analysis was undertaken to explore the temperature distribution throughout the day across the school stock. Figure 10 shows the distribution of the percentage of occupied time in which simulated zone temperature was above 25°C, 30°C, 35°C, and 40°C. Outputs are presented for each occupied hour (between 9:00 and 16:00) for each temperature threshold, for both current and future climate scenarios.

The results show the extent of the likelihood for higher temperatures throughout the day. For example, Figure 10 shows that the percentage of occurrences where simulated zones exceeded 25°C increased from an average of nearly 56% at 9:00 to almost 85% by 16:00 (in the current climate scenario). Figure 10 also

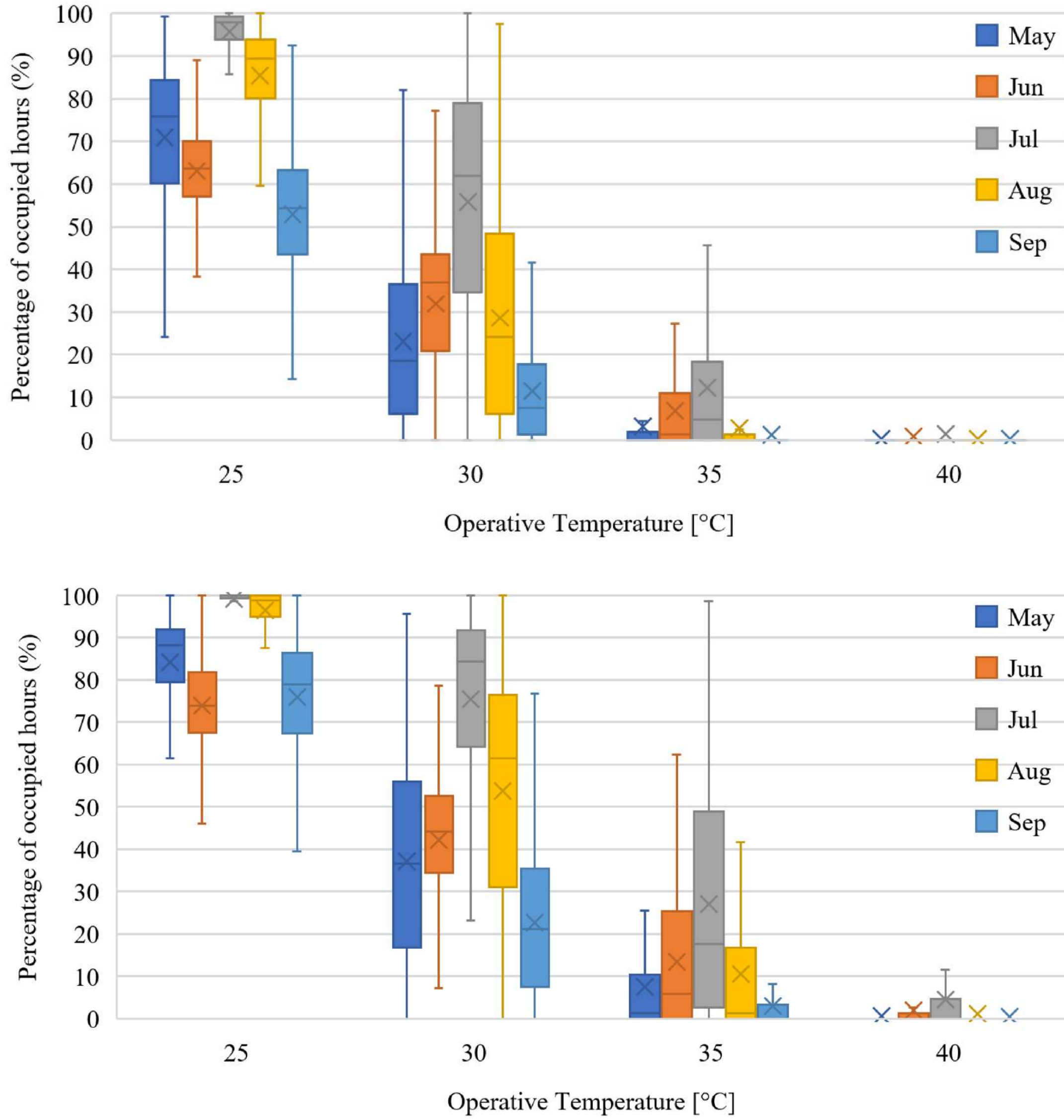


Figure 9. Distribution of the percentage of hours where simulated zone temperature was above 25°C, 30°C, 35°C, and 40°C, by month. Current climate (top) and 2050 climate (bottom).

indicates that spaces spend a significant amount of time (25% of the time) with internal temperatures exceeding 30°C after mid-day.

A comparison of these results with those of the future climate scenario reveals how changes in local climate are expected to impact on internal temperatures, even early in the day. The 2050s results in Figure 10 show that the percentage of occurrences where simulated zones exceeded 25°C at 9:00 rose to nearly 72%, and to over 92% at 16:00. Also, these zones will exceed 30°C for at least 41% of the time after mid-day in the 2050s scenario. This percentage goes up for hours later in the day. Alarmingly, nearly 3% of the simulated zones reached the unbearable temperature of 40°C towards the end of the school day.

The modelling assumptions within MPS have been taken from school design and assessment guidelines, as outlined above. Nonetheless, the assumed ventilation rates may be higher than those found in reality in some school buildings. Where this is the case, the internal conditions may be higher than predicted. On the other hand, BB101 also does not consider the impact of increased natural ventilation due to window opening. It is possible that window opening could reduce indoor temperatures, particularly in regions like

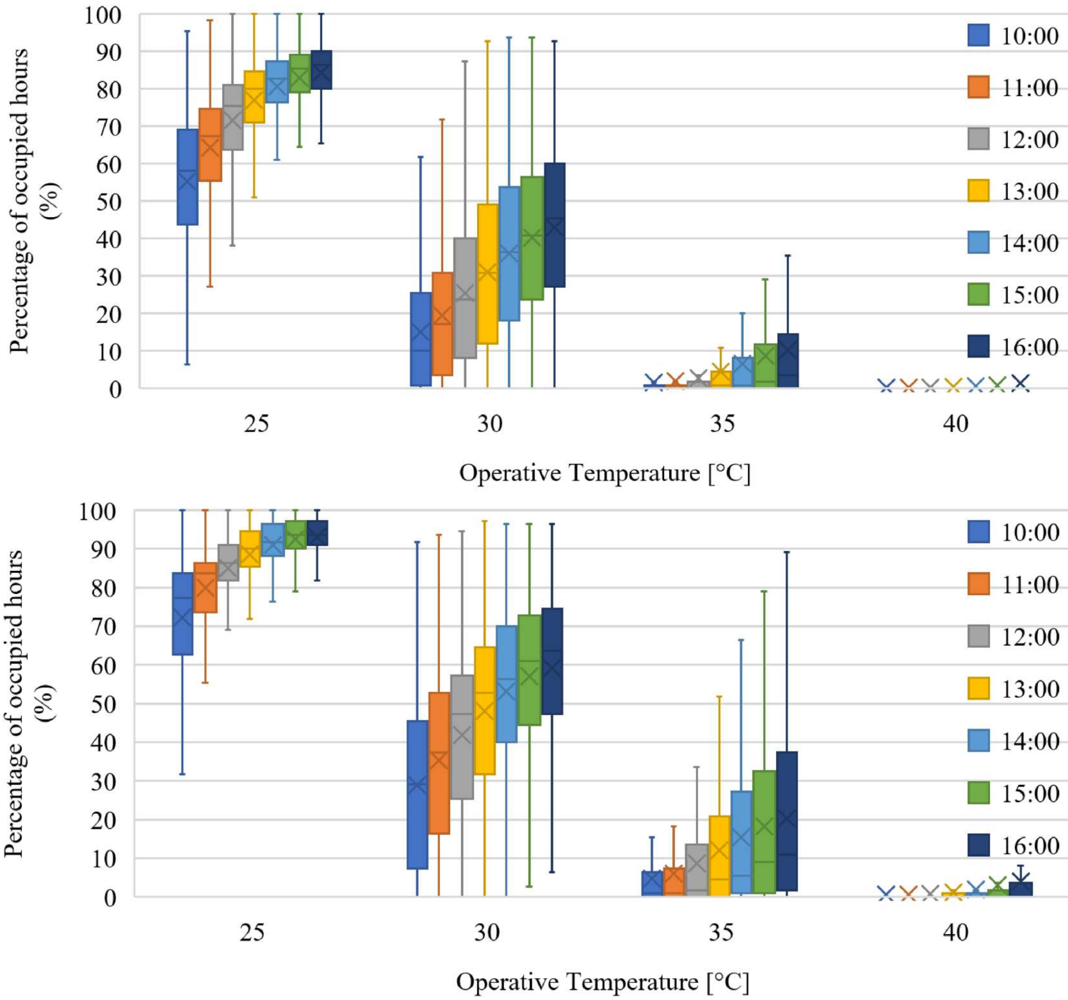


Figure 10. Percentage of hours where simulated temperature was above 25°C, 30°C, 35°C, and 40°C, by hour. Current climate (top) and 2050 climate (bottom).

London, where outdoor temperatures are relatively low most of the year. It is acknowledged that in reality, during a high temperature period, schools and school teachers would be taking actions such as maximising cross flow ventilation or adjusting curtains and other shading devices. The actual temperatures and overheating hours may therefore be less than modelled here due to actions that change the thermal response of the classrooms. While window opening could reduce indoor temperatures, in instances of heatwaves or unusually warm mornings, natural ventilation during the day might lead to an increase in indoor temperatures. This is more likely to occur in thermally heavyweight school buildings that may have been cooled down by exposure to cold outdoor conditions the night before.

4.2. BB101 criteria

Following the analysis of the general indoor temperature performance of the school stock, further analysis was carried for the BB101 overheating Criteria. As previously noted, within BB101, criterion 1 is treated as a minimum requirement for the entire overheating risk assessment (when 40 h of failure are allowed), while criteria 2 and 3 are simply for information purposes only.

Figure 11 shows that a stark 93% of the zones fail BB101's mandatory criteria 1 under the current climate scenario. The extent of overheating is also expressed in the high percentage of zones failing criteria 2 and 3. These findings show the severity and scale of the overheating problem in UK schools.

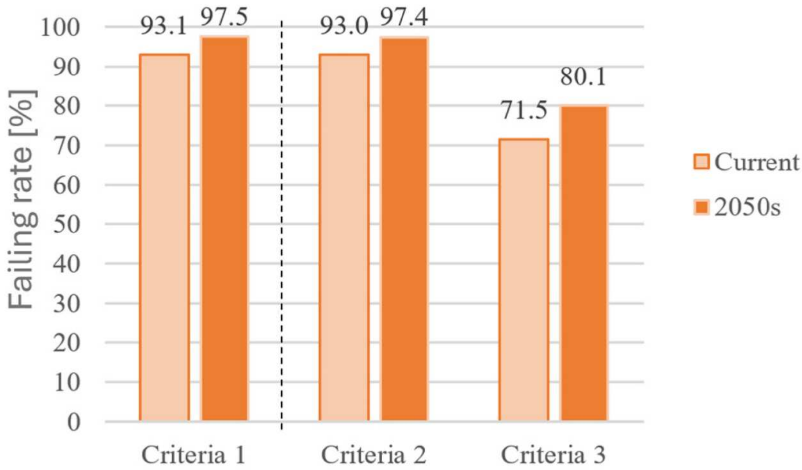


Figure 11. BB101 criteria 1 (mandatory), 2 and 3 (reporting only) for current and 2050s climate – percentage of zones failing rate (all schools).

Looking at these figures at a primary and secondary schools separately, Figure 12 shows that while there are no massive differences in failure rates, zones in primary schools tend to fail more frequently than secondaries. This might be due to the smaller size of primary schools and the fact that there might be more dense on classroom areas than auxiliary areas.

The binary aspect of a zone passing or failing each criterion hides the real scale of zone's discomfort conditions through the analysed period. For example, the criteria 1 40 hr threshold hides the fact that, on average, during nearly 40% of occupied hours (or, more than 290 h between May – September) indoor temperatures will be above the maximum acceptable temperature (as shown in Figure 13). This is more evident for the 2050s climate, where this percentage rises to nearly 50% (or, 350 failed hours). Only a single instance of failing for both criteria 2 and 3 does not reveal the thermal zones, on average, fail criteria 2 for around 35% of occupied days and fail criteria 3 for 10% of occupied hours when simulated with the current London weather file. These percentages are even more severe for the future weather file; nearly 50% and almost 20% failure for criterion 2 and 3 respectively.

4.3. Exploring adaptation measures – teaching time and BB101 criteria

The last set of analysis investigate basic adaptation measures, and explore the impact of changing occupancy schedules in schools on school performance compared with the BB101 Criteria.

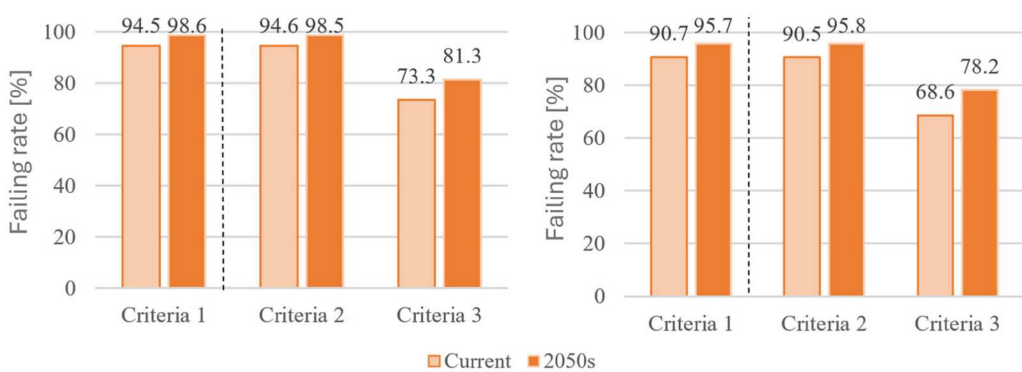


Figure 12. BB101 criteria 1 (mandatory), 2 and 3 (reporting only) for current and 2050s climate – percentage of zones failing rate: Primary school (left) and Secondary schools (right).

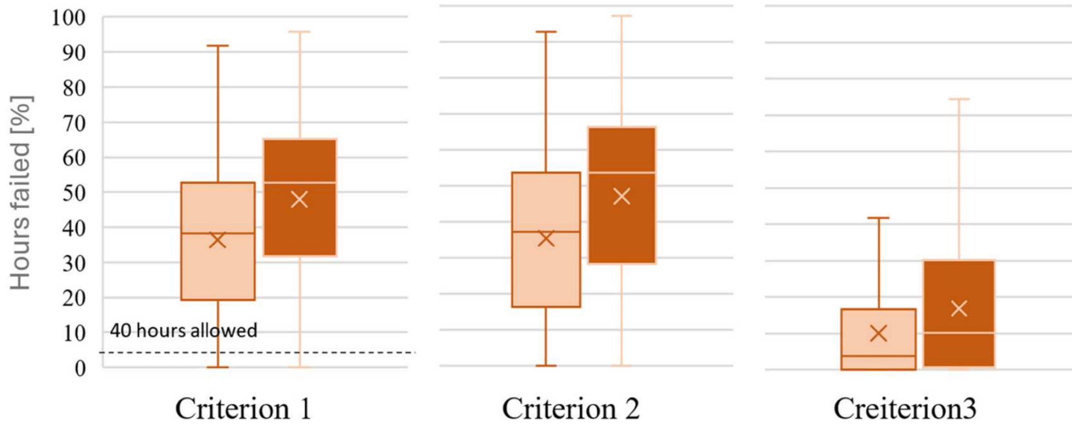


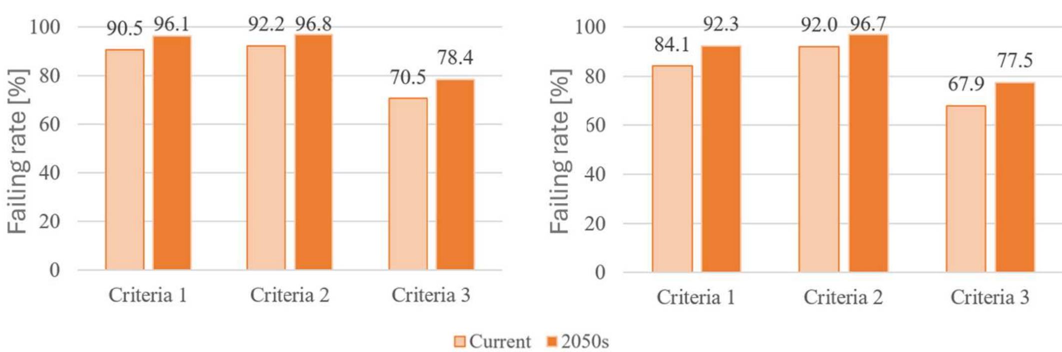
Figure 13. percentage of hours where simulated zones failed Criterion 1, 2 and 3, current climate and 2050s climate scenarios.

The BB101 modelling and simulation guideline suggests that, for the purpose of overheating risk assessment, models should assume schools are occupied to their full capacity not only during the school term, but also during the summer break (July 15th – September 1st). It is noted that in reality, it is not likely that all schools would be fully occupied for the entire summer. While some schools might host activities during the summer, these are typically minimal, in terms of occupancy levels.

Recognising this, Figure 14a explores the rate of failing Criteria 1, 2 and 3 under a more realistic assumption; that schools are unoccupied between July 15th – September 1st.

Following the findings in Figures 7 and 8, this study seeks to explore the impact of basic overheating mitigation measures. In line with the school schedule of some countries in continental Europe, the study explored the impact of the school year ending on June 15th on BB101 criteria, recognising that indoor temperatures are highest during July. These are further expressed in Figure 14b. It is noted that changing the school term dates or the daily teaching hours might have socioeconomic impacts, issues of student welfare and pedagogical implications. These would require a careful attention if such adaptation measures were considered, but are outside of the scope of the present study.

Compared to the results in Figure 11 (occupancy throughout the summer), Figure 14a only shows a 1.1% increase in the number of thermal zones that had passed all three criteria, and 2.6% increase in passing the mandatory Criterion 1, under the current climate scenario, and as little as 0.7% and 1.4% in 2050s climate. Surprisingly, even avoiding the hot month of July does not appreciably improve the rate of passing all three criteria. Figure 14b shows a modest improvement of 1.5% in passing all three criteria and 9% in passing Criterion 1 (for current climate) compared to the current BB101 modelling guidelines, and 1% (all criteria) and 5.2% (Criterion 1) using 2050s climate scenario.



a. Excluding summer break (July 15th - September 1st)

b. Extended summer break (June 15th - September 1st)

Figure 14. The impact of school term length on failing BB101.

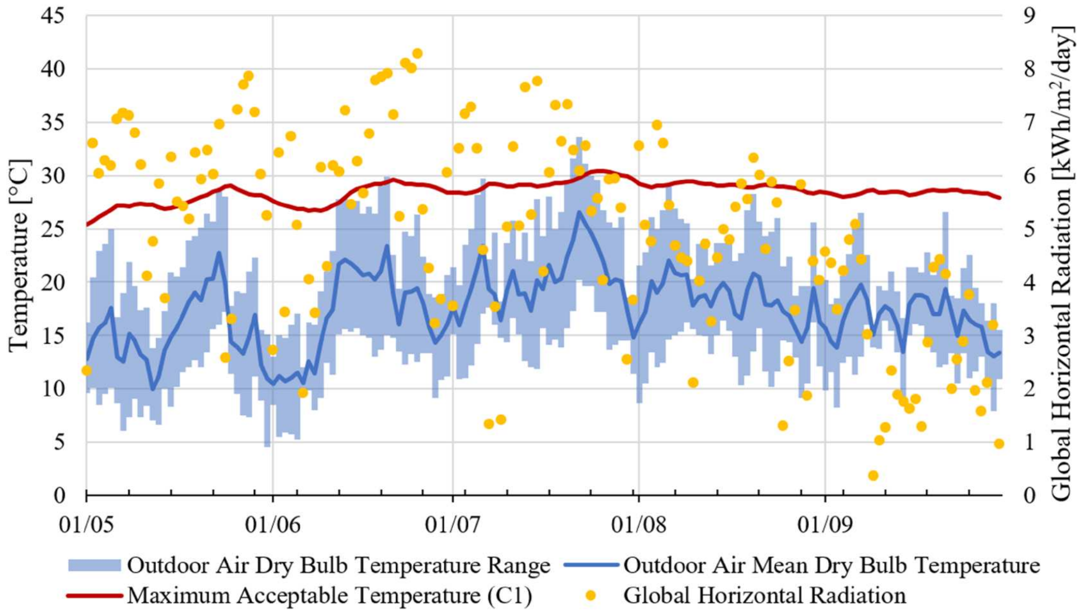


Figure 15. London Heathrow DSY1 weather file stats for the BB101 assessment period.

It appears that the reason for the marginal rates of improvements is associated with (a) the definition of the BB101 methodology for assessing overheating risk and (b) the characteristics of the local climate. Criterion 1, for example, relies on the 'adaptive comfort' model which assumes that occupants grow accustomed to external conditions over time. Since 'comfort' under this model is relative rather than absolute, occupants are assumed to feel comfortable at higher temperatures during late summer, but experience overheating discomfort at the same temperatures in the spring. The red line in Figure 15 shows the maximum acceptable indoor air operative temperature beyond which overheating discomfort hours are recorded. It can be observed that, for the London Heathrow DSY1 weather file, the maximum acceptable indoor air operative temperature is lower for most of May and the first half of June when compared to the rest of the BB101 assessed period. Coupling this with the exceptionally sunny days during these periods (Global Horizontal Radiation in Figure 15), in particular when compared to August and September, and a large number of days in May with maximum daily temperatures over 20°C, results in accumulating the BB101 Criteria failures early in the assessed period.

As Figure 10 shows that indoor temperature increases along the day, Figure 16 explores the impact of shortening school days, to avoid pupils occupying schools during the hottest part of the day. Simulations were carried out for the school day to end at 15:00, 14:00, 13:00 and 12:00, under the 'realistic' scenario, when the school term ends on July 15th.

Results indicate that finishing school early can have a significant impact on BB101 criteria failure rates. While finishing school at 15:00 only shows around 5% improvement in passing all three criteria and around 8% in the mandatory Criterion 1 (3% and 2% under the 2050s climate), these are massively improved when school days end at 12pm: The overall pass rate is increased by almost 30%, and passing Criterion 1 is improved by more than 35% (22% and 26% for the 2050s climate).

While reducing school hours might be a challenging solution to implement in practice, with potentially significant socioeconomic impacts for families and communities, this study suggests that it could be an appropriate solution for mitigating overheating in those specific days where overheating is anticipated – when outdoor temperatures are expected to be severely high.

4.4. Overheating model for London

Since Criterion 1 is defined as a minimum criterion for passing BB101, a model expressing the relationship between the predicted number of hours of Criterion 1 failure under current and future climates has

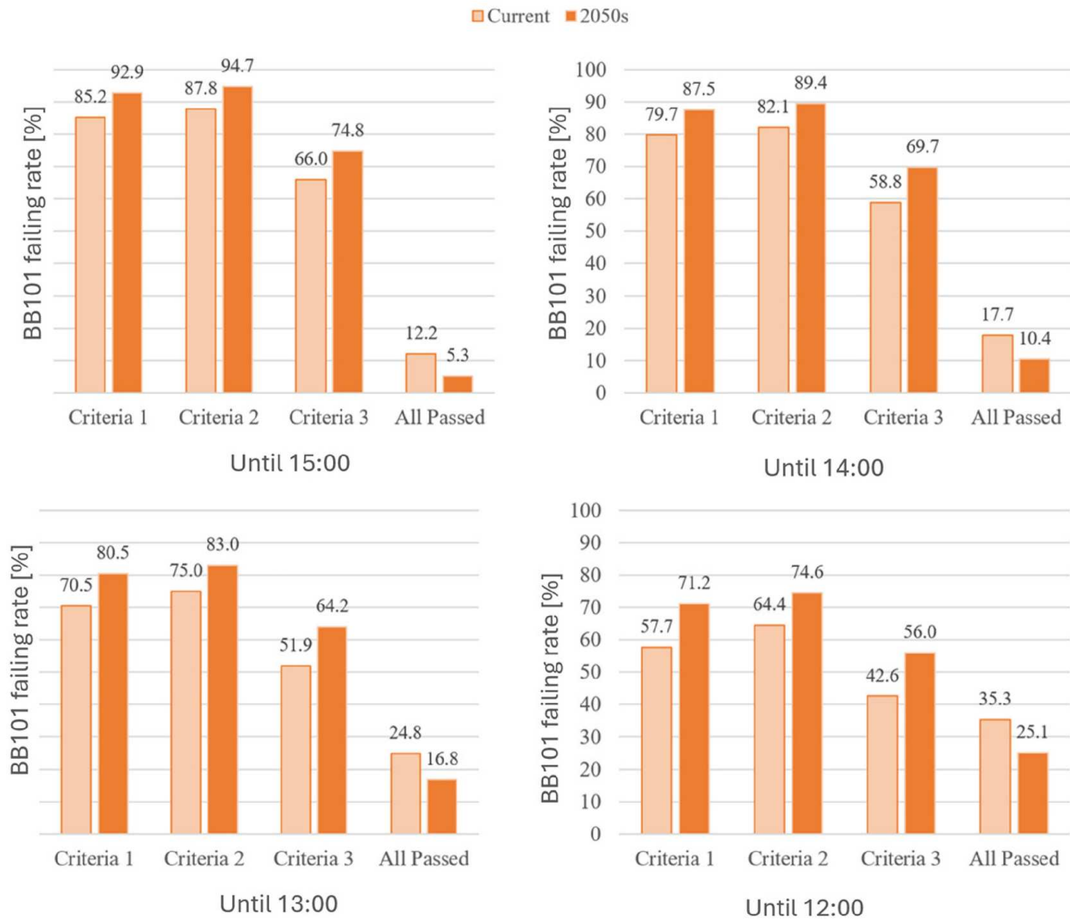


Figure 16. The impact of school-day length on failing BB101.

been developed (Figure 17). This model can help in predicting future overheating risks of individual spaces (number of hours of failing Criterion 1), based on current failure rates. Figure 17 shows a quadratic relationship which can be expressed using the following formula (coefficient of determination =

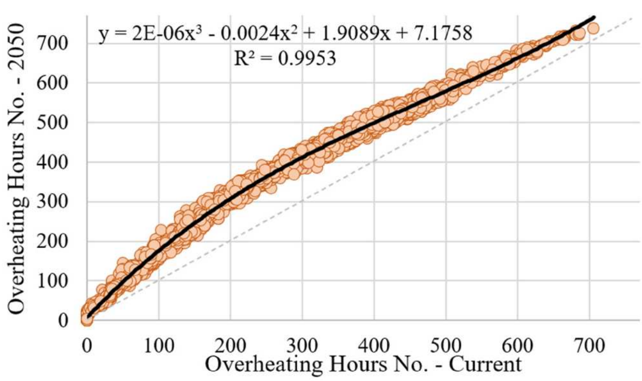


Figure 17. The relationship between the number of hours of Criterion 1 failure under current and future climates scenarios.

0.9953):

$$C1_{2050} = 2E - 06xC1^3_{current} - 0.0024xC1^2_{current} + 1.9089xC1_{current} + 7.1758$$

This model shows that schools that overheat now will generally overheat even more in the future. The model could be useful in quantifying the risk of overheating in London school spaces in the future, and might help policy makers and stakeholders in decision making mitigation measures.

5. Conclusions

This study explored the risk of overheating of the school building stock in London, both under current and future (2050s) DSY files, following the BB101 overheating assessment criteria for risk assessment.

The results of this study were used to create a benchmark for overheating risk in schools in London. The study found that:

- Schools are at the higher risk of overheating during the period between June – August, and particularly in July. Simulation results have shown that the average maximum indoor temperature across the stock is almost 36.5°C under the current climate and will rise to almost 38°C in the 2050s.
- While a shorter school year only has a minimal impact on overheating risk, shorter school days during the overheating season could significantly reduce the risk of overheating. This is mainly because overheating in schools takes place at later times during the day – once external temperatures are high, and when internal temperatures had built up due to internal gains and steady occupancy levels.

The findings of this study can be useful for both policy-makers and stakeholders involved in the provision and operation of school buildings:

- The study has demonstrated that a 'one-by-one' Modelling Platform for Schools (MPS) can offer an opportunity to support: (1) evidence-based policy making by aggregating data at the national stock level, (2) development of action plans at regional/local authority levels, and (3) provide insights to head-teachers and governors on overheating risks in their schools.

The study has emphasised the relationship between the risk of overheating and school operation schedule. National educational activities (e.g. national exams) should be scheduled considering the overheating risk on monthly and daily basis. The study highlights that the risk of overheating increases through the day, i.e. the lowest risk for overheating is in early morning (9:00) and the highest risk is in the afternoon (16:00). A potential recommendation would be considering an early finish for school days, as is done in some Mediterranean countries, as shorter school days can help reducing the risk of overheating (as described by BB101).

5.1. Future work

Since the development of the MPS school model is ongoing, it is important to note that plans for further analysis of the stock are in place. Further research activities could include:

- The MPS Model/predictor for future overheating risk: This study developed a model that can predict the number of failed Criterion 1 h in the 2050s, given the number of failed hours under the current climate. While this model is currently developed for schools in London only, the characteristics of the London school stock as well as the local climate are not representative of the national stock, and so plans are in place to expand this analysis to cover all English primary & secondary schools. The model could help both individual schools and local authorities understanding how severe overheating in their schools might be in 2050, without needing any further modelling. Future work for London could also include an investigation into the impact of urban heat island effect in different urban settings. This can be done by splitting the London stock model by geo-location and using the corresponding London DSY weatherfile, where the impacts of the UHI are incorporated. For example, using the London Weather Centre (LWC) DSY1 weatherfile for inner-city schools or London Gatwick (GTW) DSY1 for rural locations, instead of using London Heathrow (LHR) for when simulating all schools across London. This might assist in understanding the risk of overheating in school locations across the city.

- While this study used the BB101 overheating protocol and its modelling assumptions, it is acknowledged that these assumptions do not accurately represent actual school operations. Future work for evaluating overheating risk assessment would need to use actual school operation patterns during high temperature periods.
- While this work recommends looking into adaptation measures for coping with the school overheating risk, the broader implications of the examined measures should be considered. These include impact such as students' mental wellbeing, learning and curriculum, economic impacts. Furthermore, work is also needed to explore mitigation measures – e.g. retrofitting by adjusting the buildings' physical properties (e.g. shading devices, mechanical ventilation, active cooling system etc.) to help coping with the increased heating stress during the overheating season.
- Expanding the MPS model, to make use of more of the data collected in the CDC surveys could also be beneficial; improving the accuracy of the modelling and enabling different issues to be explored. For example, integrating the data on the types and condition of HVAC plant could be used in the assessment of the potential decarbonisation of the stock. This would require more information (such as to translate the CDC heating plant data into efficiency values for modelling), and potentially the use of new modelling & analytical techniques such as using machine learning or computer vision in processing the underlying data and producing the models.
- Exploring the risk of overheating in schools using weather files describing climate in 13 other climate regions across the country. This could assist in prioritising mitigation of overheating risk in certain geographic regions, which may be more prone to overheating, compared to other areas.

5.2. Limitations

The authors acknowledge that validating the outputs of the overheating assessment is an important next step, particularly if the outputs of this study might be used in policy development. Unfortunately, at present, the authors are not aware of any publicly available dataset on overheating for comparison purposes. However, some validation of energy usage in school buildings was carried, using a similar modelling mechanism (Schwartz et al. 2021a), where modelling outputs were compared against energy use intensities from Display Energy Certificates (DECs). While the specifics of the models involved may have been different, the underlying model remains essentially the same (relying on PDSP or CDC data and using EnergyPlus to assess overheating). It is also noted that the MPS model generation process was tested and discussed extensively in a previous publication (Schwartz et al. 2022), and that the thermal simulation tool used for estimating thermal performance in this study (EnergyPlus) is regarded as highly reliable.

An additional layer of validation could involve assessing BB101's capacity to predict overheating. However, similarly to the previous point, the lack of an overheating dataset makes this assessment challenging. Nonetheless, despite the shortcomings in the BB101 methodology, it is currently the official method for evaluating overheating in schools nationwide.

As this study used a 'one-by-one' stock modelling method, to assess the risk of overheating in schools in England, it is noted that in developing the school stock model, it is not possible to represent 100% of the schools. The generation of the school stock is highly dependent on data quality. Work has been done on the school database – the Department for Education is currently undertaking new CDC surveys, which will improve and update the data that is used in MPS for models generation.

Furthermore, it is noted that some modelling assumptions, describing internal gains, ventilation rates, use patterns and build-ups were used. Improvements to the CDC database, but also to the way that MPS interprets school buildings build-ups are expected to reduce uncertainties around this. Future plans for MPS are to incorporate building assemblies, where such data is available, into the thermal model generation process.

It is important to recognise that the chosen BB101 criteria for assessing overheating represent industry-standard protocols. As such, the results presented in this study are framed within the boundaries and constraints outlined by the BB101 protocol, which includes the use of specific DSY weather files and occupancy profiles. It is also noted that the assumed 0.5 ach to all schools in the stock is most probably not an accurate representation of air infiltration across the stock, however the study relied on inputs from the BB101 guide for assumed air change rates. Future work would correlate ACH with windows quality and construction age. Additionally, it is noted that this study focused on a limited set of scenarios, such as using a single climate change weather file for assessing future overheating risk and exploring only a few mitigation scenarios related to school day schedules. Different outcomes may arise through employing alternative (e.g. more spatially disaggregated) weather files or exploring additional scenarios.

Lastly, the work on MPS is part of long-term research into the performance of the school stock. Development of the platform is ongoing, with work being carried out both to improve the models existing algorithms, as well as to expand the types of analyses that it can undertake. Future developments include further validation of the model, alongside other improvements such as updating the underlying data, refining the data processing steps to widen the model coverage, and expanding MPS capabilities to evaluate tasks such as assessing the impact of retrofits, performance under future climate scenarios or net zero potential.

Acknowledgments

This study was undertaken as part of the School Buildings Adaptation, Resilience and Impacts on Decarbonisation in a Changing Climate (ARID) project, funded by the Natural Environmental Research Council (NERC), project reference NE/V01000X/1, and supported by the Department for Education.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Dr. Yair Schwartz is a Lecturer in Engineering and Architectural Design at UCL's Institute for Environmental Design and Engineering (IEDE), part of the Bartlett Faculty of the Built Environment. He leads the Life Cycle Analysis & Circular Economy research theme at IEDE and plays a key role in school stock modeling research. Yair was instrumental in developing both the archetype school stock model and the 'one-by-one' school stock model, which assess the performance of schools in England and Wales. These platforms have enabled research collaborations with organisations like the Met Office, Department for Education, and others.

Dr. Ivan Korolija is an Associate Professor of Building Systems Modelling at the UCL Institute for Environmental Design and Engineering. Ivan's main research interest is in the energy performance of buildings with a particular focus on HVAC systems, data-driven building operation and control optimisation, and urban scale and stock-level building energy modelling and simulation. His pivotal contribution to the building stock modelling field is being the SimStock academic lead. SimStock, a modelling platform which combines data from multiple sources to create 'one-by-one' building models, has been used in many stock-level research projects dealing with schools, university campuses, non-domestic buildings, mixed-use premises as well as segments of the domestic stock.

Daniel Godoy-Shimizu is a Research Fellow in Building Physics Modelling at the UCL Energy Institute. His research focusses on understanding the energy use and decarbonisation potential of the building stock. His recent projects have included explorations of the pathways towards Net Zero within London's social housing stock and examining the accuracy of the EPC process. On the Modelling Platform for Schools (MPS) project, he is one of the developers, carrying out the analyses and processing of the large-scale buildings data to feed into the schools simulation models.

Dr. Sung Min Hong is an Associate Professor of Building Performance Analysis at the UCL Institute for Environmental Design and Engineering. As a building scientist, his research focusses on leveraging big data to improve energy efficiency and decarbonisation of buildings. Sung Min's research provided a knowledge base for development of the English school stock model. Over the past decade, he has worked closely with the Department of Education informing development and implementation of policies aimed at improving energy performance of English schools. He is a member of the CIBSE Knowledge Generation Panel.

Anna Mavrogianni is Professor of Sustainable and Healthy Built Environment at the UCL Institute for Environmental Design and Engineering. With a background in architectural engineering, Anna is an expert in building indoor environmental quality, and climate change adaptation of the built environment sector. Anna led the EPSRC-funded project 'Advancing School Performance: Indoor environmental quality, Resilience and Educational outcomes' (ASPIRE), and is a member of the CIBSE Knowledge Management Committee.

Dejan Mumovic is Professor of Building Performance Analysis, and the Director of the UCL Institute for Environmental Design and Engineering. He was a co-founder of CIBSE School Design Group and currently serves as the Scientific Advisor for Climate Change at the Department for Education. He has led over 30 projects focusing on modelling and monitoring aspects of school building performance analysis in the context of energy, health, comfort and cognitive performance. This includes both the industry (CIBSE TM57 Integrated School Design, 2015, 2025), and policy (Greater London Authority, the UK Government and European Commission) focused outputs.

ORCID

Ivan Korolija http://orcid.org/0000-0003-3153-6070

References

Altan, Hasim, and Bertug Ozarisoy. 2022. "An Analysis of the Development of Modular Building Design Elements to Improve Thermal Performance of a Representative High Rise Residential Estate in the Coastline City Of Famagusta, Cyprus." *Sustainability* 14:4065. https://doi.org/10.3390/su14074065.

Ballarini, Ilaria, Vincenzo Corrado, Francesco Madonna, Simona Paduos, and Franco Ravasio. 2017. "Energy Refurbishment of the Italian Residential Building Stock: Energy and Cost Analysis Through the Application of the Building Typology." *Energy Policy* 105 (January): 148–160. https://doi.org/10.1016/j.enpol.2017.02.026.

Becker, Rachel, Itamar Goldberger, and Monica Paciuk. 2007. "Improving Energy Performance of School Buildings While Ensuring Indoor Air Quality Ventilation." *Building and Environment* 42 (9): 3261–3276. https://doi.org/10.1016/j.buildenv.2006.08.016.

Betti, G., F. Tartarini, C. Nguyen, and S. Schiavon. 2024. "CBE Clima Tool: A Free and Open-Source web Application for Climate Analysis Tailored to Sustainable Building Design." *Building Simulation* 17: 493–508. https://doi.org/10.1007/s12273-023-1090-5.

Brøgger, Morten, and Kim Bjarne Wittchen. 2018. "Estimating the Energy-Saving Potential in National Building Stocks – A Methodology Review." *Renewable and Sustainable Energy Reviews* 82 (July 2017): 1489–1496. https://doi.org/10.1016/j.rser.2017.05.239.

CIBSE. 2016. "Current and Future Weather Files. Chartered Institution of Building Services Engineers (CIBSE)." 2016. https://www.cibse.org/weatherdatasets.

Csobod, Eva, Isabella Annesi-Maseano, Paolo Carrer, Stylianos Kephalopoulos, Joana Madureira, and Peter Rudnai. 2014. *Schools Indoor Pollution and Health Observatory Network in Europe*. Luxembourg: European Union. https://doi.org/10.2788/99220.

Department for Communities and Local Government. 2015. "Improving the Energy Efficiency of Our Buildings: A Guide to Display Energy Certificates and Advisory Reports for Public Buildings," no. July: 1–37.

Department for Education. 2018. "BB101 Guidelines on Ventilation Therma Comfort and Indoor Air Quality in Schools".

Department for Education. 2022. "Get Information about Schools." 2022. https://www.gov.uk/guidance/get-information-about-schools.

Department of Energy and Climate Change. 2015. "Guidance on Preventing Overheating in the Home," no. June: 1–10.

DoE. 2020. "DoE, U., EnergyPlus Energy Simulation Software v. 3-1-0. US DoE EERE".

Dong, Jie, Yair Schwartz, Ivan Korolija, Anna Mavrogianni, and Dejan Mumovic. 2021. "London School Building Stock Model for Cognitive Performance Assessment." BSO20 - Building Simulation and Optimization Conference, Loughborough, UK, September 21–22, 2020.

Education and Skills Funding Agency. 2017. "Condition Data Collection (CDC): Programme Guide," no. July.

EFA. 2015. *Property Data Survey Programme: Summary Report*. London, UK: Education Funding Agency.

Escandón, Rocío, Rafael Suárez, Alicia Alonso, and Gerardo Maria Mauro. 2022. "Is Indoor Overheating an Upcoming Risk in Southern Spain Social Housing Stocks? Predictive Assessment Under a Climate Change Scenario." *Building and Environment* 207. https://doi.org/10.1016/j.buildenv.2021.108482.

Famuyibo, A. A., A. Duffy, and P. Strachan. 2013. "Achieving a Holistic View of the Life Cycle Performance of Existing Dwellings." *Building and Environment* 70 (2): 90–101. https://doi.org/10.1016/j.buildenv.2013.08.016.

Geraldi, Matheus Soares,, and Enedir Ghisi. 2020. "Building-Level and Stock-Level in Contrast: A Literature Review of the Energy Performance of Buildings During the Operational Stage." *Energy and Buildings* 211:109810. https://doi.org/10.1016/j.enbuild.2020.109810.

Grassie, Duncan, Yair Schwartz, Phil Symonds, Ivan Korolija, Anna Mavrogianni, and Dejan Mumovic. 2022. "Energy Retrofit and Passive Cooling: Overheating and Air Quality in Primary Schools." *Buildings and Cities* 3 (1): 204–225. https://doi.org/10.5334/bc.159.

Hong, Sung Min, Greig Paterson, Dejan Mumovic, and Philip Steadman. 2014. "Improved Benchmarking Comparability for Energy Consumption in Schools." *Building Research and Information* 42 (1): 47–61. https://doi.org/10.1080/09613218.2013.814746.

Intergovernmental Panel on Climate Change (IPCC). 2019. *Foreword Technical and Preface. Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*.

Jenkins, D. P., A. D. Peacock, and P. F. G. Banfill. 2009. "Will Future Low-Carbon Schools in the UK Have an Overheating Problem?" *Building and Environment* 44 (3): 490–501. https://doi.org/10.1016/j.buildenv.2008.04.012.

Kavgic, M., A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, and M. Djurovic-Petrovic. 2010. "A Review of Bottom-up Building Stock Models for Energy Consumption in the Residential Sector." *Building and Environment* 45 (7): 1683–1697. https://doi.org/10.1016/j.buildenv.2010.01.021.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel. 2006. "World Map of the Köppen-Geiger Climate Classification Updated." *MetZ* 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Li, Wenliang, Yuyu Zhou, Kristen Cetin, Jiyong Eom, Yu Wang, Gang Chen, and Xuesong Zhang. 2017. "Modeling Urban Building Energy Use: A Review of Modeling Approaches and Procedures." *Energy* 141:2445–2457. https://doi.org/10.1016/j.energy.2017.11.071.

Mastrucci, Alessio, Antonino Marvuglia, Ulrich Leopold, and Enrico Benetto. 2017. "Life Cycle Assessment of Building Stocks from Urban to Transnational Scales: A Review." *Renewable and Sustainable Energy Reviews* 74 (December 2016): 316–332. https://doi.org/10.1016/j.rser.2017.02.060.

Mavrogianni, Anna, Mike Davies, Konathon Taylor, Zaid Chalabi, Phil Biddulph, Eleni Oikonomou, and Ben. Jones. 2014. "The Impact of Occupancy Patterns, Occupant-Controlled Ventilation and Shading on Indoor Overheating Risk in Domestic Environments." *Building and Environment* 78:183–198. https://doi.org/10.1016/j.buildenv.2014.04.008.

Mavrogianni, Anna, Paul Wilkinson, Michael Davies, Phillip Biddulph, and Eleni Oikonomou. 2012. “Building Characteristics as Determinants of Propensity to High Indoor Summer Temperatures in London Dwellings.” *Building and Environment* 55:117–130. https://doi.org/10.1016/j.buildenv.2011.12.003.

Montazami, Azadeh, Mark Gaterell, and Fergus Nicol. 2015. “A Comprehensive Review of Environmental Design in UK Schools: History, Conflicts and Solutions.” *Renewable and Sustainable Energy Reviews* 46:249–264. https://doi.org/10.1016/j.rser.2015.02.012.

NCM. 2016. “National Calculation Methodology (NCM) Modelling Guide (for Buildings Other than Dwellings in England).”.

Oikonomou, Eleni, Michael Davies, Anna Mavrogianni, Phillip Biddulph, Paul Wilkinson, and Maria Kolokotroni. 2012. “Modelling the Relative Importance of the Urban Heat Island and the Thermal Quality of Dwellings for Overheating in London.” *Building and Environment* 57:223–238. https://doi.org/10.1016/j.buildenv.2012.04.002.

Ordanance Survey. 2021a. “Code-Point with Polygons | UK Postcode Shape Mapping | Vector Map Data.”.

Ordnance Survey. 2021b. “OS MasterMap Topography Layer | Great Britain’s Landscape | Vector Map Data.”.

Ozarisoy, Bretug, and Hasim Altan. 2022. “Bridging the Energy Performance gap of Social Housing Stock in South-Eastern Mediterranean Europe: Climate Change and Mitigation.” *Energy and Buildings* 258: 1–47. https://doi.org/10.1016/j.enbuild.2021.111687.

Schwartz, Yair, I. Korolija, J. Dong, S. M. Hong, A. Mavrogianni, and D. Mumovic. 2021a. “Energy & Buildings. Developing a Data-Driven School Building Stock Energy and Indoor Environmental Quality Modelling Method.” *Energy & Buildings* 249:111249. https://doi.org/10.1016/j.enbuild.2021.111249.

Schwartz, Yair, Ivan Korolija, Daniel Godoy-Shimizu, Sung Min Hong, Jie Dong, Duncan Grassie, Anna Mavrogianni, and Dejan Mumovic. 2022. “Modelling Platform for Schools (MPS): The Development of an Automated One-By-One Framework for the Generation of Dynamic Thermal Simulation Models of Schools.” *Energy and Buildings* 254:111566. https://doi.org/10.1016/j.enbuild.2021.111566.

Schwartz, Yair., I. Korolija, P. Symonds, D. Godoy-Shimizu, J. Dong, S. M. Hong, A. Mavrogianni, D. Grassie, and D. Mumovic. 2021b. “Indoor Air Quality and Overheating in UK Classrooms - An Archetype Stock Modelling Approach.” *Journal of Physics: Conference Series* 2069 (1): 1–8. https://doi.org/10.1088/1742-6596/2069/1/012175.

Swan, Lukas G., and V. Ismet Ugursal. 2009. “Modeling of End-Use Energy Consumption in the Residential Sector: A Review of Modeling Techniques.” *Renewable and Sustainable Energy Reviews* 13 (8): 1819–1835. https://doi.org/10.1016/j.rser.2008.09.033.

Taylor, J., M. Davies, A. Mavrogianni, Z. Chalabi, P. Biddulph, E. Oikonomou, P. Das, and B. Jones. 2014. “The Relative Importance of Input Weather Data for Indoor Overheating Risk Assessment in Dwellings.” *Building and Environment* 76:81–91. https://doi.org/10.1016/j.buildenv.2014.03.010.

UKCP. 2018. “UK Climate Change Projections 2018.” https://www.daera-ni.gov.uk/articles/uk-climate-change-projections#toc-0.

UK Parliament. 2008. “Climate Change Act 2008,” 1–103. https://doi.org/10.1136/bmj.39469.569815.47.

Wang, Haojie, and Qingyan Chen. 2014. “Impact of Climate Change Heating and Cooling Energy Use in Buildings in the United States.” *Energy and Buildings* 82:428–436. https://doi.org/10.1016/j.enbuild.2014.07.034.

Xu, Peng, Yu Joe Huang, Norman Miller, Nicole Schlegel, and Pengyuan Shen. 2012. “Impacts of Climate Change on Building Heating and Cooling Energy Patterns in California.” *Energy* 44 (1): 792–804. https://doi.org/10.1016/j.energy.2012.05.013.