



Energy retrofit and passive cooling: overheating and air quality in primary schools

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ABSTRACT

While building stock modelling has been used previously to investigate the space heating demand implications of national energy efficiency retrofitting, there are also implications for indoor overheating and air quality, particularly in schools, with highly intermittent occupancy patterns. This paper assesses indoor overheating risk and air quality within an English classroom stock model containing 111 archetypes, based on the analysis of the nationwide Property Data Survey Programme (PDSP) containing 9629 primary school buildings in England. Metrics for indoor temperatures, heating demand and concentrations of three contaminants (CO₂, NO₂, PM_{2.5}) were estimated in naturally ventilated classrooms, while exploring future climate projections, retrofit and overheating mitigation scenarios to analyse school stock resilience. Classrooms with a south-east orientation experience around four to six times the overheating-hours compared with those with a northern orientation. Post-1976 archetypes are most susceptible to overheating, indicative of the conflict between better insulated and airtight classrooms and overheating prevention. A range of retrofit and passive cooling measures can mitigate against overheating alone, although mechanically driven cooling and filtration may be required towards the 2080s. While no single measure predicted universally positive effects for building performance, night ventilation and overhangs were found to be particularly effective passive overheating mitigation methods across the school stock.

POLICY RELEVANCE

With around 30% of their waking hours spent in classrooms, English schoolchildren experience greater vulnerability to higher indoor temperatures and air pollutants than adults due to limited thermoregulation and immunity, with additional impacts on cognitive

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performance. An increased risk of overheating (due to a warming climate) necessitates the development of future overheating mitigation policies and strategies, which could directly impact separate retrofit strategies required for energy demand reduction. Airflow network modelling has demonstrated how such measures could contribute to school sector carbon emissions. While the granularity of national datasets represents a hurdle to predictive modelling, the orientations, geographical regions and construction eras most vulnerable to overheating risk have been identified. Building stock-level modelling could thus be used to identify sectors of the stock most vulnerable to overheating and poor air quality, leading to strategies with more targeted solutions, including the use of alternative cooling strategies to air-conditioning.

1. INTRODUCTION

School buildings can be considered an important national asset, indicative of future wellbeing, since an entire generation of school-age children spend around 30% of their waking hours there, 70% of which is in classrooms (Csobod *et al.* 2014). Within classroom environments, highly dynamic occupancy (Sekki *et al.* 2015) and building service usage (Pegg *et al.* 2007) on a daily basis can lead to large differentials not just in operational energy demand, but also in indoor environmental conditions (Becker *et al.* 2007; Shrubsole *et al.* 2019). To evaluate this, indoor environmental quality (IEQ) incorporates several features (Chatzidiakou *et al.* 2014; Korsavi *et al.* 2020), including indoor thermal conditions and air quality, which are strongly linked through ventilation practices (Montazami *et al.* 2012).

Indoor overheating is of particular concern since measured data show it is likely to become more prevalent in future in school settings (Jenkins *et al.* 2009; Montazami *et al.* 2012). In addition, with the UK legislating for net zero emissions by 2050 (UK Parliament 2019), the UK school stock must be considered dynamically in terms of ongoing retrofit work, rather than as a snapshot in time. Recent studies have investigated policies to achieve necessary energy savings (Oliveira *et al.* 2017) and subsequent impacts on IEQ (Jain *et al.* 2019). However, improvements to building fabric airtightness and thermal insulation of the stock may exacerbate indoor overheating (Jenkins *et al.* 2009) and lead to greater indoor concentration of pollutants (Shrubsole *et al.* 2019), hence they have been highlighted as worthy of further investigation.

Monitored temperature and CO₂ levels in classrooms have been used to show direct effects of ventilation on school pupils' performance of mental tasks (Bakó-Biró *et al.* 2012). Additionally, it has been demonstrated that children experience detrimental effects to health (Kim 2004) and attainment (Wargocki *et al.* 2020) when exposed to air contaminants, such as NO₂ and particulate matter <2.5 microns (PM_{2.5}), introduced through indoor (Ferguson *et al.* 2020) or outdoor (Taylor *et al.* 2014) sources. Controlling pollutants such as NO₂ and PM_{2.5} through ventilation can conflict with the requirement to prevent high CO₂ concentrations and overheating through natural ventilation (Montazami *et al.* 2012; Chatzidiakou *et al.* 2014).

Recent studies have shown disparity in exposure to indoor pollutants based on socio-economic groups (Ferguson *et al.* 2020), highlighting the importance of investigating overheating and air contaminant concentrations across different building types and settings, rather than isolated examples. In terms of scaling an approach to the nationwide level, building stock modelling has recently been used to autogenerate individual, archetype-based school building models that evaluate energy demand and indoor air quality (IAQ) (Schwartz *et al.* 2021a). National datasets of building geometry and fabric characteristics have been used to achieve top-down coverage, representing the statistical prevalence of different types of archetypes across the UK. Combined with the bottom-up use of physics-based models to model classrooms' internal gains from, a hybrid form of stock modelling has recently become possible, able to model entire sectors of the school stock through archetypes (Bull *et al.* 2014), reflective of different construction era buildings.

Previous examples of scenario modelling of retrofit work driven by energy efficiency in the UK are summarised in **Table 1**. For school buildings, remits have included quantifying potential carbon emissions reductions (Smith et al. 2013) and overall life cycle carbon footprint (Bull et al. 2014). While modelling studies linking energy efficiency retrofitting with IEQ have been carried out previously using building stock modelling in UK residential buildings (Hamilton et al. 2015; Taylor et al. 2015) and care homes (Oikonomou et al. 2020), such modelling has not yet been applied to a classroom setting, although much of the ventilation and overheating methodology is transferrable. Anticipated changes in climate and carbon emissions reduction strategies must also be included in models, in addition to building stock transformations; this should ultimately enhance the understanding of future interactions between climate change adaptation strategies and IEQ.

Table 1: Remit of previous studies investigating retrofit measures using stock models.

STUDY	BUILDINGS USED IN THE STUDY	RETROFIT OPTIONS	REMIT OF MODELLING	KEY FINDING RELEVANT FOR THE PRESENT STUDY
Taylor et al. (2015)	Eight residential archetypes in one location (Plymouth)	Improved U-values (wall, floor, roof), glazing and airtightness	Modelling of indoor and outdoor contaminants under retrofit and future climate	Quantifying contaminant ratios and overheating risk. Use of stock level data in models and future weather files
Hamilton et al. (2015)	896 separate archetypes based on the English Household Survey (EHS)	Three fabric and ventilation scenarios based on the level of regulatory compliance	Health impacts due to exposure to contaminants/temperature	Investigation of conflict between ventilation practices and energy efficiency
Oikonomou et al. (2020)	Five London care homes	Individual and combined: insulation, thermal mass, shading, ventilation	Impact of retrofits on overheating during a heatwave	Optimising a combination of range of retrofit measures
Smith et al. (2013)	Two buildings within a London secondary school campus, scaled up to represent the stock	Individual measures: insulation, glazing, heating controls, mechanical ventilation	Emissions reduction	Discussion of model complexity versus limitations of oversimplification
Bull et al. (2014)	Four different age school archetypes representative of different-era UK buildings	Individual measures: boiler, air tightness, insulation, glazing	Life-cycle analysis of carbon footprint	Use of archetypes to represent sectors of stock

The key aim of the research presented in this paper is:

To evaluate the impact of energy retrofit and passive cooling strategies, as an alternative to mechanically driven cooling, on overheating and IAQ across the English school building stock.

This paper reports on modelling work that combines energy, thermal and IAQ considerations to measure the effectiveness of low carbon building design and operational strategies in English primary schools. Following on from a statistical analysis of the Department for Education’s (DfE) Property Data Survey Programme (PDSP) (EFA 2012), used to construct representative building archetype models of the English school stock (Schwartz et al. 2021a), the present paper develops sophisticated airflow network models using EnergyPlus. These models allow the role of ventilation in the balance of indoor temperatures, and internally and externally generated indoor contaminants, to be modelled for a variety of future retrofit and climate scenarios, for various classroom typologies.

The research aim has been addressed through the following objectives shown in **Figure 1**:

- Quantification of the impact of terrain, geographical location, construction era, classroom glazing, and orientation on indoor overheating and CO₂ concentration levels across the entire school stock.
- Determination of the resilience offered by three selected examples within the stock to future climate scenarios, by comparing base-case assumptions to energy retrofit and overheating mitigation strategies, and simulation of metrics of indoor overheating, winter space heating energy demand and indoor concentration of key contaminants (CO₂, NO₂, PM_{2.5}).

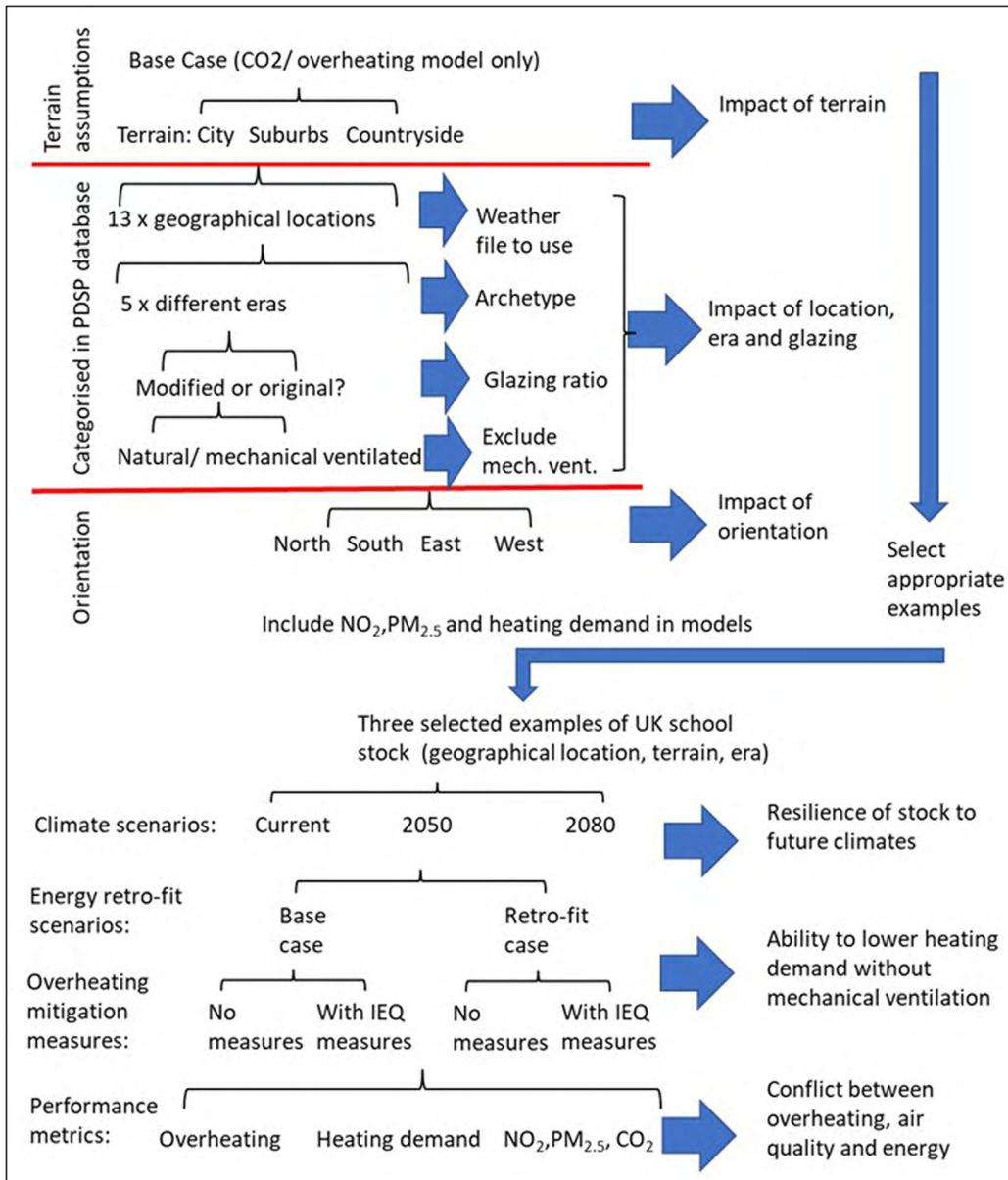


Figure 1: Structure of the analysis.

2. METHODS

2.1 RESEARCH DESIGN

The methods used to generate simulation models for this study are summarised below. Further details of the auto-generation process are presented in Section 2.3.1.

- An analysis of the PDSP national database of school building stock level data was carried out to quantify the propensity for different geographical locations and building typologies within non-mechanically ventilated classrooms from the English stock of 9629 primary schools. Building form, fenestration and building fabric characteristics associated with various construction eras were defined for each of these combinations at the stock level and used as the basis for auto-generating individual thermal classroom models representing sectors of the stock.
- Base-case classroom simulation models were constructed with the EnergyPlus (US Department of Energy 2021) dynamic building simulation software using the Data dRiven Engine for Archetype Models of Schools (DREAMS) modelling framework (Schwartz et al. 2021a). This method uses 168 building archetypes to represent the primary school building stock in England for energy modelling purposes. Omitting 57 mechanically ventilated school archetypes for the current project, 111 similar archetypes containing four different

classroom orientations were auto-generated from geometric seed models to incorporate 12 geographical locations, five different construction era archetypes and modification status of the original building. Classroom models were set up to provide specific metrics for overheating, three separate contaminants (CO₂, NO₂, PM_{2.5}) and space heating demand over a simulation year.

- EnergyPlus base-case models were updated to reflect an additional retrofit scenario, comprising future structural adaptations in the building fabric to improve energy efficiency and reduce carbon emissions.
- Both the EnergyPlus base-case and retrofit scenario were updated to include a programme of measures, including increasing flow through windows and internal shading, for the purposes of mitigating overheating risk.
- Simulations were carried out to investigate the variation of overheating, air quality and carbon emissions metrics reflecting the two objectives, first, across the entire stock under current conditions, before following up with modelling current and future retrofit and overheating mitigation scenarios for a smaller subset of buildings under different climate change scenarios.

2.2 ANALYSIS OF BUILDING STOCK-LEVEL DATA

A statistical analysis previously carried out on an English school dataset (Schwartz *et al.* 2021a) was recently updated to include additional operational characteristics (Hong *et al.* 2022) by linking the following two national datasets:

- Property Data Survey Programme (PDSP) dataset (EFA 2012), containing physical properties of more than 18,000 establishments, or 85% of the English school stock.
- Display Energy Certificate (DEC) dataset based on the Chartered Institution of Building Services' (CIBSE) (2008) benchmarking of annual measured energy use.

The combined dataset was used to classify the stock of 9629 primary schools, after removing secondary schools and other establishments (Hong *et al.* 2022), by the following criteria:

- Geographical location: weather files are available for 10 locations across England (CIBSE 2016), with differing uses for the purpose of overheating described in further detail in Section 2.6. These were allocated to the 12 degree-day regions given by CIBSE in TM46 (CIBSE 2008), used to split schools into geographical regions, as shown in **Figure S1** in the supplemental data online.
- Building construction era: five archetypes were defined based on construction age, as detailed in Section 2.3.1. While different eras, particularly post-1976, contain a variety of contrasting construction types (Pegg *et al.* 2007), to characterise these further would require data on propensity of construction types, which are unavailable in the existing PDSP dataset, but potentially derivable from the more recent Condition Data Collection (CDC) (ESFA 2017).
- Modification status: whether the building has been modified previously (e.g. through the addition of an extension) or remains in its original form.

Fenestration size was accounted for by averaging the window-to-wall ratios (WWR), detailed within the PDSP, of each primary school building within each separate classification of the school stock.

2.3 CONSTRUCTION OF BASE-CASE SIMULATION MODELS

2.3.1 Building geometry and fabric

EnergyPlus (US Department of Energy 2021), a widely tested and validated software, has been used to simulate energy demand and annual exposures to overheating and air contaminants by calculating heating loads and ventilation requirements based upon external conditions. It

has the advantages of not only being widely used and open source, allowing access for a wide range of stakeholders, but also has the ability to introduce modules, such as airflow networks and contaminant models described below, to add increased complexity where required for a particular application.

Geometric classroom models were constructed for the English primary school stock within EnergyPlus version 9.5, with geometries as shown in **Figure 2** using the OpenStudio graphical user interface (GUI) (Guglielmetti et al. 2011), based on an approach devised previously (Schwartz et al. 2021b). These consist of north-, south-, west- and east-facing classrooms, each with three adiabatic walls, an adiabatic floor and ceiling, representing adjacent classrooms with similar heating loads and occupancies, and a single external wall customised for different construction eras and fenestration areas. For their construction details, see **Table S1** in the supplemental data online.

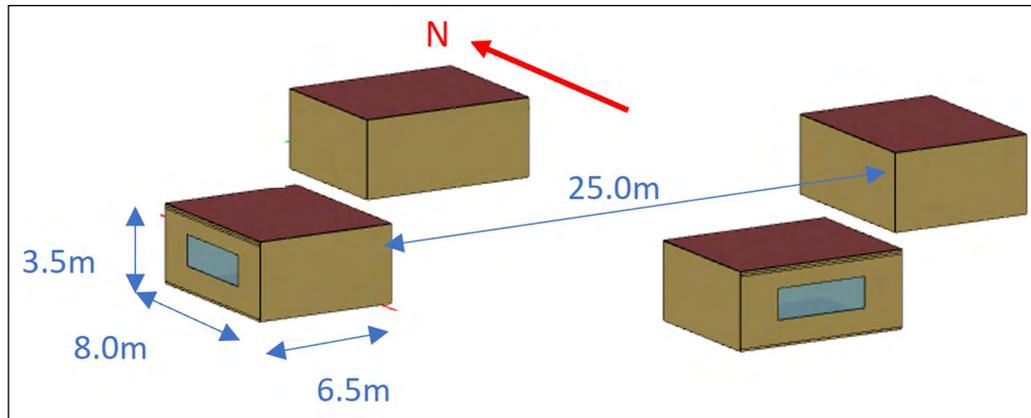


Figure 2: Geometry of the classroom model.

For each external wall, five different construction eras were allocated the features and U -values given in **Table 2** based on a previous analysis of the PDSP dataset (Schwartz et al. 2021a). Despite identical external walls, the same era archetypes from different geographical regions will still have different thermal properties since the glazing ratios as described in Section 2.2 will vary. Although an identical classroom geometry has been assigned to each era, this is a base assumption and differentiation of geometry by era may be updated based on future iterations of the PDSP analysis, as was done previously for buildings themselves in an energy context (Schwartz et al. 2021a).

ERA	PRE-1919	INTER-WAR	1945–66	1967–76	POST-1976
U -value (W/m^2K)	1.916	1.916	1.370	1.370	0.735
Outer layers	Brick 225 mm	Brick 225 mm	Plaster	Plaster	Brick 125 mm
			Brick 125 mm	Brick 125 mm	Air gap 10 mm
			Air gap 10 mm	Air gap 10 mm	Brick 100 mm
			Brick 100 mm	Brick 100 mm	Stone wool 25 mm
Inner layers	Plasterboard	Plasterboard	Plasterboard	Plasterboard	Plasterboard
	Plaster	Plaster	Plaster	Plaster	Plaster

Table 2: Composition of external walls for different eras.

Across the entire stock, primary school classroom models were auto-generated for each individual set of classification of geographical region, era and modification status across England using the EPPY 0.5.56 scripting package (EPPY 2021) in Python 3.9.2 programming language (Python 2021). After excluding 19 combinations that had no schools allocated to them in the PDSP database, 111 EnergyPlus models were constructed in total. As part of pre-processing, 6 mm thickness single-glazed windows were auto-generated on each external surface in each model with the following characteristics:

- Window sill at 1.05 m above the floor, 1.4 m in height for <30% WWR, 2 m for $\geq 30\%$ WWR.
- Width calculated for each archetype to maintain symmetry of the window on the surface while achieving the WWR defined for each category.

EnergyPlus requires the user to specify a terrain type, which can be ‘city’, ‘suburbs’ or ‘country’, although a suitable means of defining this for each school included in the PDSP has not yet been identified. **Table S2** in the supplemental data online lists the variables used to adjust wind speed measured at a weather station for different terrain types, based on model terrain type. Since the definition of terrain affects airflow and therefore natural ventilation, each of the three options was included in the analysis, as described in Section 2.1.

2.3.2 Heating loads, building operation and occupancy for all models

Table S3 in the supplemental data online gives a summary of the internal loads defined within all models used in the study, noting the following points:

- Weekday occupancy schedules of 09.00 to 16.00 hours, including holiday periods, correspond to those used in *Building Bulletin 101* (BB101) (ESFA 2018) overheating calculations, as described in Section 2.3.3.3. Equipment and lighting have also followed this schedule for consistency.
- Heating schedule also follows occupancy, except in accounting for school holidays to prevent overprediction of heating demand, starting at 08.30 hours on occupied weekdays to allow a setpoint to be reached when the classroom is occupied at 09.00 hours.
- No artificial cooling mechanism was provided within models since the only airflow permitted through vents and windows is from natural ventilation.
- Occupied and setback heating setpoint temperatures as well as occupancy, equipment and lighting power densities are derived from the National Calculation Methodology (NCM) modelling guide (Communities and Local Government 2013) based on *CIBSE Guide A* (CIBSE 2015).

Despite compliance with overheating, modelling and environmental design guidance, follow-up surveys are required to check the validity of the assumed internal loads in operation across the school stock, since the guidance offers a one-size-fits-all approach for design purposes only.

2.3.3. Air-flow modelling

The following pollutant sources were simulated in this study:

- Internal transfer of NO_2 and $\text{PM}_{2.5}$ contaminants in the classroom from *external* sources.
- Concentrations of CO_2 in the classroom from internal and external sources.

To facilitate this, the following systems were modelled within EnergyPlus:

- Ventilation was modelled using the air flow network (AFN) model to allow demand-controlled window opening in response to high internal temperatures. Previously these models have been run using a fixed ventilation rate.
- Air pollutant transfer was modelled using the generic contaminant model to calculate the subsequent influx of external contaminants through ventilation and infiltration, and their removal through deposition on internal surfaces.

2.3.3.1. Ventilation modelling

While previous iterations of the UK school stock model (Schwartz et al. 2021b) have used fixed ventilation rates based on a design allowance of 8 l/s/person (Bakó-Biró et al. 2012), AFN modelling was adopted as in the housing stock model (Taylor et al. 2014) to demonstrate weather-driven ventilation behaviour in practice. An advantage of the AFN model is that wind speeds and directions from different regions are accounted for when windows are opened for ventilation, hence ventilation

as well as heat gain from illumination are dependent on classroom orientation. Although double-sided, stack or more complex ventilation arrangements could also be modelled, within the scope of this research the AFN model was set up for single-sided ventilation, approximating a classroom surrounded by an access corridor opposite the external wall and adjacent classrooms on the two other sides, using the layout on the external facade shown in **Figure 3**.

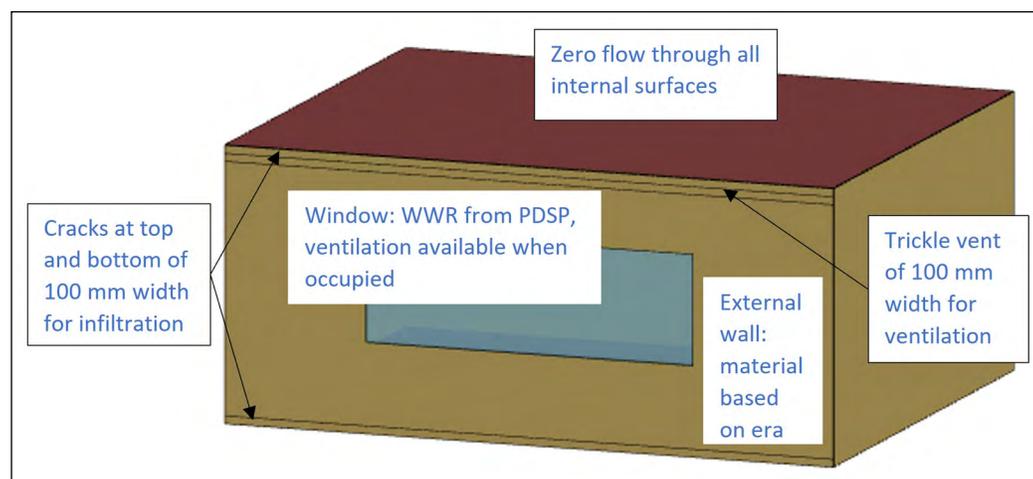


Figure 3: Description of the external facade.

Table S4 in the supplemental data online describes the ventilation parameters for window openings and trickle vents at 3.3–3.4 m, and the infiltration system represented by cracks at 0–0.1 m, and 3.4–3.5 m height. EnergyPlus calculates airflows using these parameters coupled with the internal pressure based on wind velocity, v_z at height z , dependent on the orientation of the classroom and wind direction. Infiltration surfaces were placed at the top and bottom of the external surface to model airflow based on differences in wind pressure at different heights rather than assume a single height. Although trickle vents are mostly features of modern school buildings, they were included in the base case as well. Setting air permeability at $9 \text{ m}^3/\text{h}/\text{m}^2$ @ 50 Pa indicative of a ‘typical school’ (ATTMA 2010) is a key base-case assumption that has been updated in the retrofit cases to improve airtightness. Methods employed in previous work on residential buildings (Taylor et al. 2014) were followed with respect to inputs of flow coefficients and leakage areas, with the discharge coefficient of the window of 0.5 and opening schedules as the key parameters, which are adjusted for the IEQ mitigation scenario in Section 2.5.

2.3.3.2. Air pollutant modelling within EnergyPlus

The role of the EnergyPlus generic contaminant model, previously verified against a CONTAM model (Taylor et al. 2014), was to model internal air temperatures, CO_2 concentration levels and indoor/outdoor (I/O) ratios of NO_2 and $\text{PM}_{2.5}$ contaminants at hourly intervals based on internal loads and ventilation for an entire year.

External CO_2 concentration was set at 415 ppm, based on 2021 atmospheric measurements (NASA 2021), static over the 2020s, 2050s and 2080s climate scenarios, while recognising that this figure is increasing to different extents under different climate scenarios. As detailed in **Table S3** in the supplemental data online, occupants provide an internal source of CO_2 , based upon a density of 0.55 children/ m^2 (Communities and Local Government 2013), metabolic rate per child of 110 W (representing 80% of the 145 W attributed to secondary age children in a classroom environment; Communities and Local Government 2013) and CO_2 generation rate of $3.82/\text{e}^8 \text{ m}^3/\text{s}/\text{W}$ (Schwartz et al. 2021b).

There were no assumed internal sources of NO_2 and $\text{PM}_{2.5}$, which is a necessary stock modelling oversimplification, since it is unknown if there are catering activities adjacent to or carpets installed within the classrooms. In addition, external concentrations are location dependent, hence I/O ratios were exported from the model and internal concentrations were calculated in the post-processing of EnergyPlus outputs described in Section 2.3.3.3.

Within EnergyPlus, external contaminants are modelled using experimental deposition rates of 0.87/h (Emmerich & Persily 1996) and 0.19/h (Long et al. 2001) for NO₂ and PM_{2.5}, respectively, applied to each available surface comprising the building envelope to give a deposition velocity. A penetration factor of 80% was then applied for PM_{2.5} contaminants from October to April inclusive in post-processing to account for the building fabric, potentially filtering out one-fifth of particles because they infiltrate the classroom in the absence of ventilation. The significant degree of uncertainty of these values due to the need to estimate values empirically is acknowledged. The I/O ratio (C_{in}/C_{out}) of both NO₂ and PM_{2.5} contaminants is calculated based on inputted deposition velocity, k , penetration factor, P , and air exchange rate, a (/h) (Long et al. 2001):

$$\frac{C_{in}}{C_{out}} = \frac{Pa}{a+k}$$

2.3.3.3. Processing of EnergyPlus outputs

A Python script was used to process time-series output from the EnergyPlus classroom stock model to allow the relative comparison of different typologies and geographical location through the following metrics:

- Prediction of overheating: the most recent criteria available for overheating in UK schools comes from BB101 (ESFA 2018), following on from CIBSE *Guide A* (CIBSE 2015). Hence, three overheating metrics, detailed in Section 2 in the supplemental data online, were defined for each model based on total hours and degree of exceedance (rounded) derived from hourly internal temperature and daily external dry bulb temperatures during occupied hours. For clarity, the first metric (number of hours exceeding the threshold temperature based on a weighted average of daily external temperatures) was used in the plots in Section 3.
- Reduction in heating demand: the benchmarking of measured fossil fuel energy demand of individual schools (CIBSE 2008) has been an annual requirement for most English school buildings through the DEC scheme. In the classroom models it was assumed that all heating comes from fossil fuels and the energy intensity (kWh/m²) was calculated for each classroom by normalising annual space heating demand in kWh by the available floorspace of 52 m². It is important to note that since such modelling necessarily omits the heating of hot water and other uses of fossil fuels, the calculated values cannot be compared against total benchmark energy consumption values from other databases.
- Prediction of indoor contaminant concentrations: the World Health Organisation (WHO) has recently updated its recommended annual targets for exposure to NO₂ and PM_{2.5} (WHO 2021) from 2005 figures (WHO 2005) to:
 - 10 µg/m³ annual mean for exposure to NO₂ (down from 40 µg/m³); and
 - 5 µg/m³ annual mean for exposure to PM_{2.5} (down from 10 µg/m³).
- CO₂ concentration guidelines were derived from BB101 (ESFA 2018), which suggests high, normal and acceptable moderate levels of 1765, 1215 and 965 ppm internal CO₂ given an outdoor concentration of 415 ppm, maintained for all three climate scenarios.

Indoor concentrations of CO₂ (ppm) and I/O ratios of NO₂ and PM_{2.5} were averaged over an entire year at hourly intervals during occupied periods. To convert NO₂ and PM_{2.5} into indoor concentrations (µg/m³), annual figures of NO₂ and monthly figures of PM_{2.5} concentration were previously extrapolated for the London, West Pennines and Portsmouth regions (Schwartz et al. 2021b), as shown in **Table S5** in the supplemental data online. These figures were also used in this study, with the Portsmouth figures used as an analogue for East Anglia in terms of being a similar region with an urban/rural setting. Converse to external CO₂, it is expected that the external contaminants will decrease in future 2050s and 2080s scenarios (WHO 2021). However, since this has not been quantified, the current contaminant levels were maintained for the future scenarios.

2.4 CREATION OF AN ENERGY EFFICIENCY RETROFIT SCENARIO

The ClimaCare study on overheating prevention in care homes (Oikonomou et al. 2020) presented a combination of ‘hard’ and ‘soft’ strategies, defined in the study as structural alterations to the fabric and non-structural occupant behavioural measures, respectively. Climate resilience can encompass both substantial upgrades in the building fabric and services covered in this section as well as adaptive capacity through options available to occupants to maintain reasonable IEQ covered in the following section. A retrofit scenario combining three separate potential improvements to the building envelope is presented in **Table 3**, which supplements the base-case scenario described in Sections 2.2 and 2.3.

RETROFIT MEASURE	DESCRIPTION OF UPDATE	DESCRIPTION OF UPDATED MODEL INPUTS	EFFECT OF UPDATE ON BUILDING PROPERTIES
Upgraded external wall insulation	Expanded polystyrene fitted to the outside of the building, air permeability decreased to 3 m ³ /h/m ² @ 50 Pa (ATTMA 2010) for ‘best practice’	Polystyrene properties: <ul style="list-style-type: none"> • Conductivity = 0.027 W/m/K • Density = 40 kg/m³ • Specific heat = 1200 J/kg/K 	Decreases heat transfer through the fabric (<i>U</i> -value decrease of 1.916 to 0.337 W/m ² /K for pre-1919 buildings)
Double-glazed window	Replace windows in all classrooms	Windows upgraded to: <ul style="list-style-type: none"> • Glass pane = 6 mm • Argon = 10 mm • Glass pane = 6 mm • No changes to the linear thermal junction of glass panes with walls 	Decreases heat transfer through the closed window: <i>U</i> -value = decrease of 5.8 to 2.6 W/m ² /K Solar heat gain coefficient = decrease of 0.82 to 0.70
External shading—overhang	Add external shading element to every window	Opaque overhang: <ul style="list-style-type: none"> • 50 mm above the window • 800 mm extension in the horizontal plane 	Decreases radiative heat transfer through windows from direct sunlight: <ul style="list-style-type: none"> • Highest effect = 98% reduction for south-facing classrooms at noon in mid-summer • Lowest effect = 1–7% for all orientations in mid-winter 09.00 and 15.00 hours

Table 3: Summary of the measures comprising the retrofit scenario.

The positioning of the additional insulation for the wall insulation measure has an impact on the thermal mass and hence the thermal capacitance and heating requirements of the classroom. In this case, the insulation was placed on the outside of the building to minimise the additional heating load required and to prevent overheating due to the decoupling of the wall thermal mass with the interior.

2.5 CREATION OF AN IEQ BEHAVIOURAL MEASURES SCENARIO

As described in the previous section, both base and retrofit cases were additionally simulated for ‘soft’ behavioural measures, such as night-time cooling, which could be provided in a complementary fashion to more intensive changes in fabric to improve IEQ. **Table 4** contains details of the ‘soft’ overheating mitigation measures applied to both base and retrofit cases to create four different combinations for the three metrics of overheating, contaminant concentration and heating demand.

Table 4: Summary of the measures comprising the overheating mitigation scenario.

OVERHEATING MITIGATION MEASURE	DESCRIPTION OF UPDATE	DESCRIPTION OF UPDATED MODEL INPUTS	EFFECT OF UPDATE ON BUILDING OPERATION
Increased window-opening angle leading to lower the resistance of flow	Update discharge coefficient for all ‘detailed opening’ objects	Discharge coefficient for fully open window updated from 0.5 to 0.625	Increases volume of air able to flow through the window by 25%
Curtains used for internal shading (need for lighting has been ignored)	Add ‘interior shading’ object with availability schedule	Drapes 4 mm always available while occupied to cover windows	Decreases solar gains into the classroom incident on all windows
Night-time cooling by opening windows permitted	Update window-opening availability schedule	Window opening allowed 24 h/day during weekdays	Improved ability to reduce internal temperature overnight

Test Reference Year (TRY) and Design Summer Year (DSY) annual weather data files (CIBSE 2009), representing typical weather conditions and warmer conditions for the purposes of overheating assessment calculations, respectively, were updated by CIBSE (2016) for both current and future climates. These include high, medium and low ranges (10th, 50th and 90th percentile scenarios) of climate change prediction for the 2020s, 2050s and 2080s (CIBSE 2016) based on the UK's Climate Projections from 2009 (UKCP09) (The Met Office 2009). For the initial analysis of impact of typology and location on overheating and indoor CO₂ across the entire stock, the unaltered current TRY files were used to represent a typical year. However, for the determination of resilience to future scenarios, hybrid weather files were created combining the following:

- From 1 October to 30 April, the 50th percentile TRY for 2020s high and 2050s and 2080s medium climate change scenarios representing a typical heating season.
- For 1 May to 30 September, the 50th percentile DSY1 for 2020s high and 2050s and 2080s medium climate change scenarios representing a 'moderately warm summer' (CIBSE 2016).

2.7 MODEL VALIDATION

Energy data generated by the DREAMS building stock were validated against DEC data (Schwartz et al. 2021a) and showed agreement within 4–12% by construction era. IAQ predictions for classroom models were also validated (Schwartz et al. 2021b), falling within the range of PM_{2.5} (5.2–11.4 µg/m³) and on the high side of NO₂ (7.3–23.3 µg/m³) of internal concentrations provided by residential models (Taylor et al. 2014). The addition of AFN modelling to these fixed ventilation models offers similar ranges for the three separate contaminants, although slightly more dispersed due to the additional simulation of scenarios (see [Table S6](#) in the supplemental data online for more details). For overheating prediction, the use of BB101 with hybrid DSY/TRY weather files prevents a direct comparison with previous uses of the DREAMS stock modelling, which used CIBSE (2015).

Further validation is possible by comparing the ventilation rates and internal temperatures predicted by modelling with monitored data and recommended rates. [Figure 4](#) shows the modelled ventilation rates and internal temperatures for all four scenarios simulated of a west-facing London classroom run with the 2020s hybrid weather file, for the warmest week with respect to overheating-hours. The two scenarios containing the IEQ overheating mitigation use night ventilation, available overnight during weekdays, to reduce temperatures to the threshold of 22°C given in [Table S4](#) in the supplemental data online.

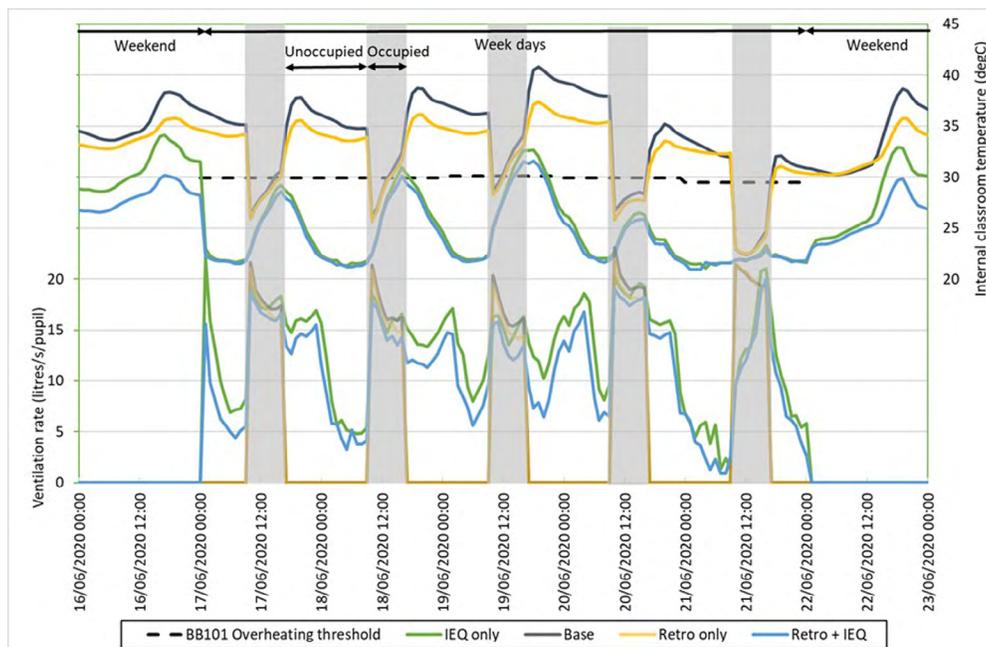


Figure 4: Ventilation rate and internal temperatures for the warmest week under different retrofit and indoor environmental quality (IEQ) scenarios (west-facing London classroom, 2020s climate).

The peak temperature experienced for the base case while occupied of 30–33°C is consistent with measured peak temperatures of 30°C previously measured in Western European classrooms from the Schools Indoor Pollution and Health Observatory Network in Europe (SINPHONIE) (Csobod et al. 2014). The natural ventilation rate of 15–20 l/s/person while occupied represents a high calculated airflow when compared with recommendations of 8–9 l/s/person for maintaining internal CO₂ around 1000 ppm (ESFA 2018) and measured rates of 13.33 l/s/person (Csobod et al. 2014). However, it is consistent with evidence that ventilation rates up to 15 l/s/person could be beneficial due to incremental improvements in attainment (Chatzidiakou et al. 2014).

3. RESULTS

3.1 ANALYSIS OF THE MODELLING APPROACH AND IMPACT OF TYPOLOGY ACROSS THE ENTIRE SCHOOL BUILDING STOCK

3.1.1 Database analysis

Figure 5 shows the number of primary schools for each category within each geographical region by typology. Fewer than 3% of primary schools have mechanical ventilation (omitted from the modelling study), even within post-1976 primary schools, where it is slightly more prevalent. A total of 83% of schools contain multiple-age buildings, highlighting the complexity of assuming a building fabric based on construction era, with London, Midlands (Birmingham) and West Pennines (Manchester) containing, by far, the largest concentrations of all eras of schools. In terms of trends between construction era and geographical regions, there are above-average proportions of East Anglian schools, which are post-1976 buildings (30%) compared with all other geographical regions (18%), with pre-1919 London schools (22%) and 1967–76 Midlands schools (28%) also reasonably prevalent.

Figure 5: Number of primary schools in each geographical region for various categories.

Note: Green shading denotes number of schools within each archetype category.

	Pre-1919				Inter-War				From 1945-1966				From 1967-1976				Post 1976			
	Natural		Mechanical		Natural		Mechanical		Natural		Mechanical		Natural		Mechanical		Natural		Mechanical	
	Single	Multi	Single	Multi	Single	Multi	Single	Multi	Single	Multi	Single	Multi	Single	Multi	Single	Multi	Single	Multi	Single	Multi
Thames Valley	34	443	3	8	26	207	2	5	84	427	2	16	98	445	2	14	120	238	17	15
South-Eastern	25	112			10	31			43	102			34	85		2	48	62	5	5
Southern	12	54		1	3	23		2	18	49		2	36	57	2	2	36	43	7	3
South Western	25	56			3	9			10	29	1		16	36		2	45	30	4	3
Severn Valley	26	89	1	8	7	14		3	36	72	3	5	34	79	3	9	51	55	10	4
Midland		325		4		114		1		317		5		368		6		186		7
West Pennines	2	353		3		121				302		8		494		12		228		
North Western		40				9				32				37				17		
Borders	18	26			13	11			22	36	1		34	40	1		26	8	2	
North Eastern	28	83			18	15			24	72		2	46	90	2	5	39	37	3	2
East Pennines	55	237		3	16	66			56	242		4	56	235	1	9	49	82		2
East Anglia	36	149	1	6	10	48			36	104		8	38	160		7	87	168	2	

3.1.2 Definition of terrain

The relationship between orientation and CO₂ and overheating was examined by clustering points of the same orientation indicated by shaded zones in Figure 6, which includes all three terrain types. The widest contrast is between south-facing orientations, experiencing the greatest range of overheating due to direct sunlight but the lowest CO₂ concentration due to increased ventilation and north-facing orientations, with a wider range of CO₂ concentration, but markedly cooler conditions. However, there is some reasonably visible overlapping west and east clustering of points between both these groups.

Figure 6 also contains a single indicative line plot of overheating CO₂ concentration results for each orientation, using the same archetype, but spanning the three different terrains. In all cases, the city sites experience greater overheating but lower CO₂ than the suburbs site and then countryside site, respectively, due to a larger reduction to the windspeed incident on the external surface. However, the impact of terrain on overheating varies significantly between each trend line, as indicated by the slope, possibly since overheating-hours are determined by exceeding thresholds, with terrain having a higher impact on overheating closer to the acceptable limit of 40 h. In the case of the east example, lack of data of the school's surroundings introduces an uncertainty range of 32–39 h, which for warmer future climates could be the difference between passing or failing the BB101 overheating criteria.

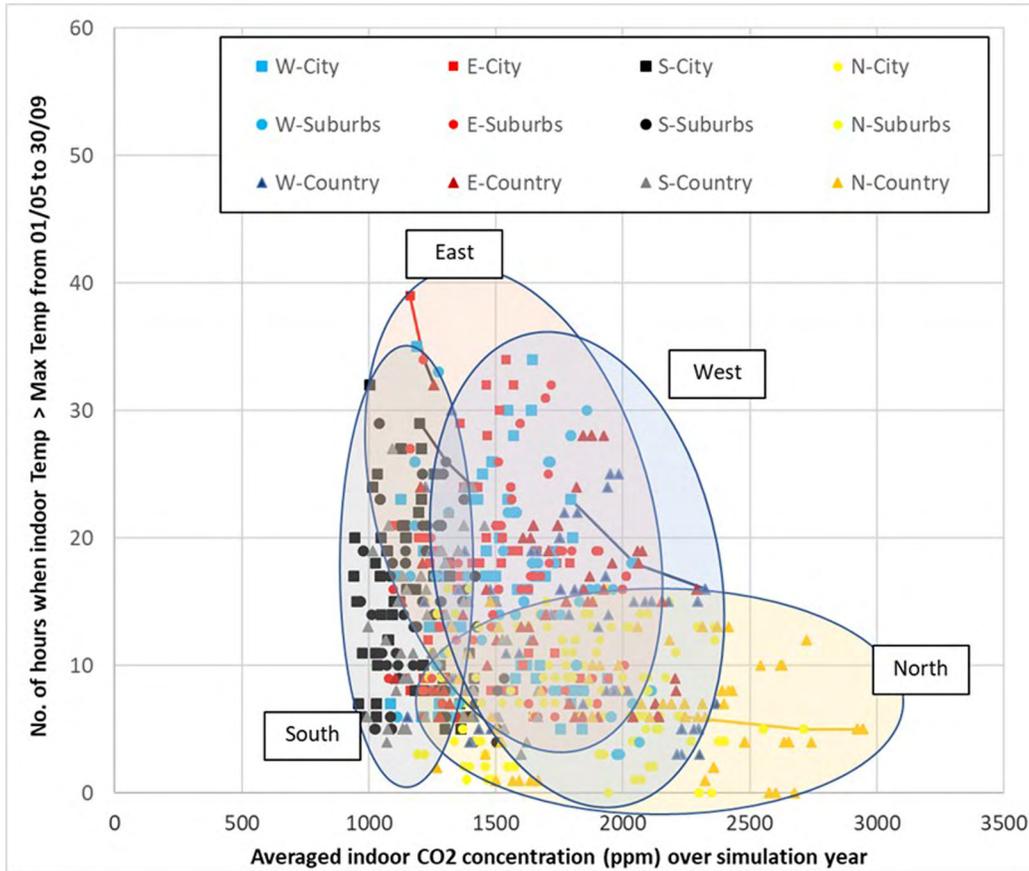


Figure 6: Cross-plot of average indoor CO₂ concentration versus overheating-hours for different terrains and orientations across all region and era archetypes.

3.1.3 Comparison of geographical location/era archetypes

Figures 7 and 8 demonstrate the variation across geographical regions and archetypes for average indoor CO₂ concentration and overheating-hours, respectively, for west-facing classrooms in suburban terrain. The following trends can be observed:

- Geographical: south-eastern locations appear more susceptible to higher degrees of overheating throughout the year. Northern locations tend to have higher average CO₂ concentrations, possibly as a result of less hours when the window opening setpoint of 22°C.
- Construction eras: overheating is considerably more prevalent for the post-1976 archetype than for other eras, indicating the potential for conflict between the need to better insulate classrooms to reduce heating demand, and overheating prevention.

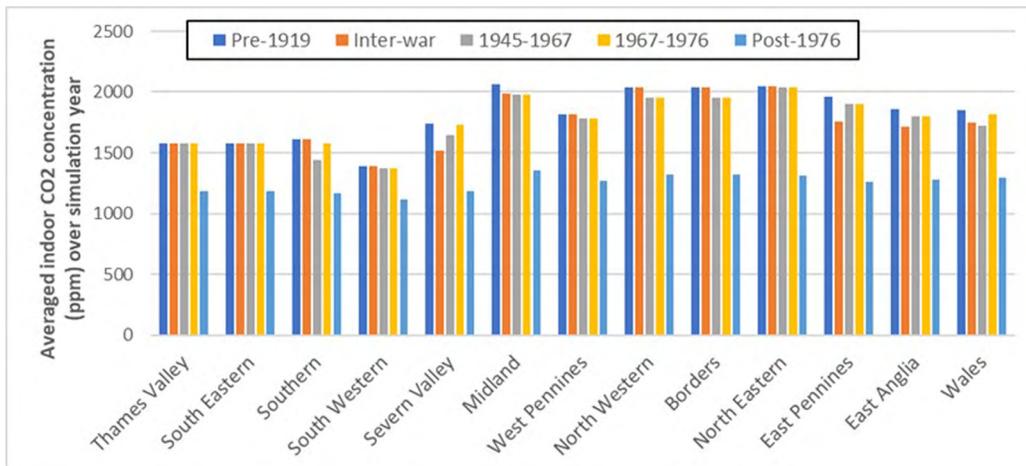


Figure 7: Indoor CO₂ concentration for west-facing suburban classrooms.

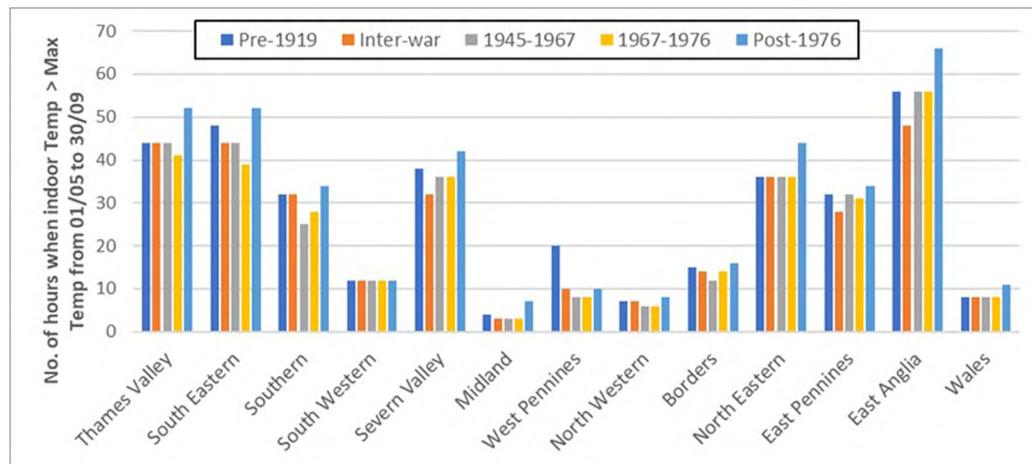


Figure 8: Overheating-hours for west-facing suburban classrooms.

3.1.4 Selection of three examples

Based on the above analysis, **Table 5** lists three selected examples, based on their relative propensity as derived in Section 3.1.1, combined with dominant terrain types based on location.

EXAMPLE	GEOGRAPHICAL LOCATION	TERRAIN	ERA	MODIFIED?	GLAZING RATIO (%)
A	London	City	Pre-1919	Yes	27%
B	Midlands	Suburbs	1967–76	Yes	23%
C	East Anglia	Country	Post-1976	Yes	26%

Table 5: Selected examples for further analysis

3.2 ANALYSIS OF OVERHEATING, HEATING DEMAND AND IEQ FOR THREE EXAMPLES

3.2.1 Effect of individual retrofit and IEQ measures

Figure 9 demonstrates, for example A (London pre-1919) under the current climate, the incremental effect of changes to the base case to create the retrofit scenario and then includes overheating mitigation across the five performance metrics. Not one individual change has wholly positive or negative effects across the range of metrics, indicating that changes in internal temperatures through altering insulative properties can have a complex relationship with IEQ practices through ventilation and heating constraints. For example, adding external wall insulation (and decreasing air permeability) in the model requires window-opening throughout the year to reduce overheating, lowering average indoor CO₂ but increasing ingress of external contaminant of PM_{2.5} and NO₂ slightly, and reducing the benefit of greater energy efficiency on lower heating demand. This result is indicative of a need to optimise opening size and heating load to prevent heating overshoot when applying ventilation and space heating in models balancing IEQ and energy efficiency.

3.2.2 Performance of three examples under different scenarios

Figure 10 summarises each scenario run on each case by averaging the results over all four orientations. **Table S7** in the supplemental data online is an expanded version showing orientations with the minimum and maximum for each metric. **Figure 10** demonstrates that no single case performs entirely satisfactorily under all five metrics, as indicated by colour coding, requiring a trade-off, for example:

- Scenarios without retrofit or IEQ mitigation, particularly in London and East Anglia, demonstrate significant overheating issues, exceeding the BB101 target of 40 h for the 2020s, 2050s and 2080s by increasing extents, for all but 2020s north orientations.

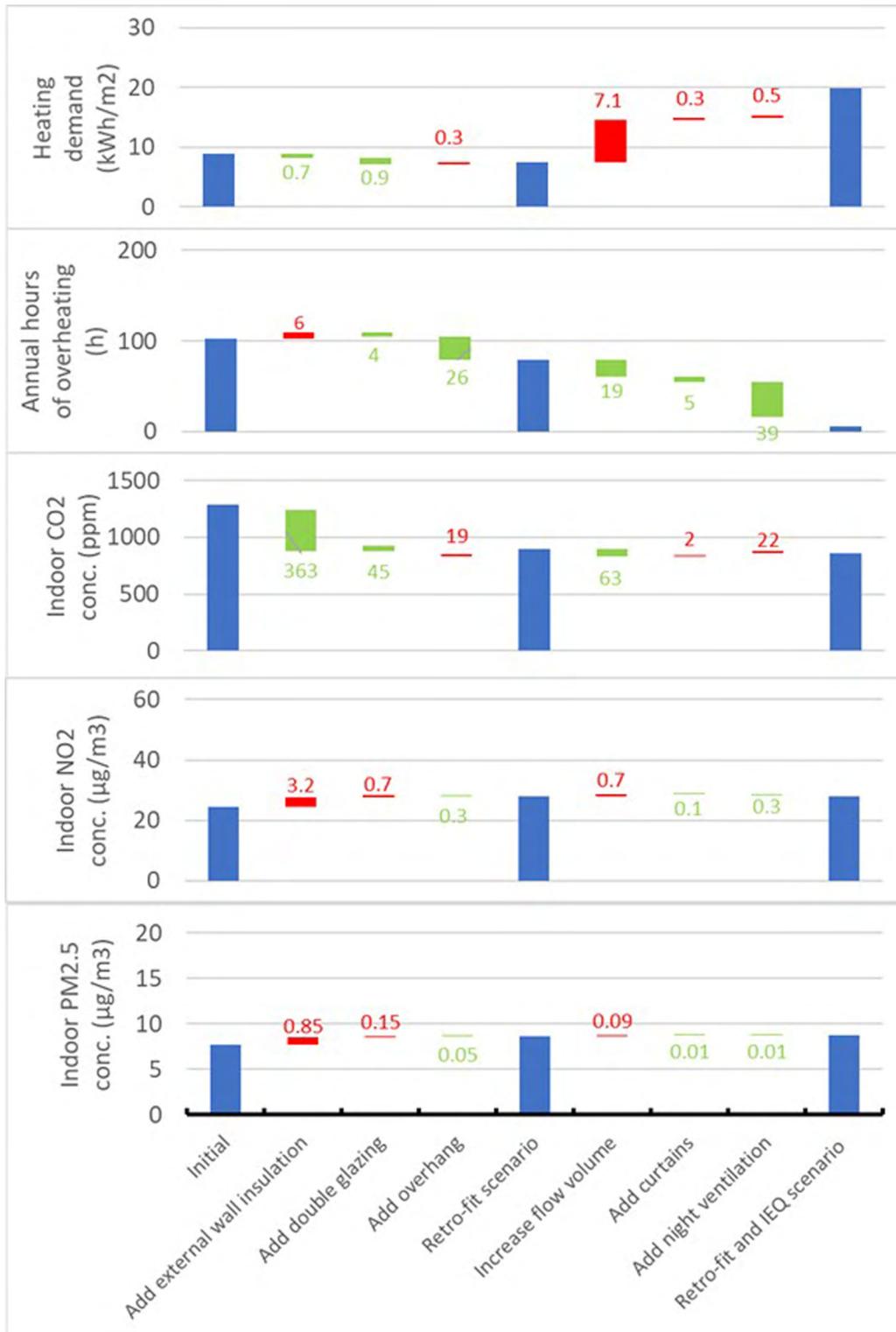


Figure 9: Change in heating demand, overheating and contaminant concentration for incremental retrofit and indoor environmental quality (IEQ) measures.

- Shading and insulation measures reduce the number of overheating-hours, while still breaching the target of 40 h for the 2050s and 2080s scenarios and non-north orientations. Additionally, elevated internal concentrations of PM_{2.5} and NO₂ arise through increased demand for ventilation due to improved airtightness of the fabric, although these are very small and are within the error margins of the external data in **Table S5** in the supplemental data online. However, naturally ventilated classrooms will increasingly become constrained in addressing overheating due to the tightening of WHO targets as external climate warms, unless I/O ratios are reduced by other means or reduction of ambient air pollution is achieved. For example, wider adoption of electric vehicles, leading to a reduction in NO₂.

- Where IEQ mitigation measures were added, overheating-hours were reduced below the 40 h threshold for most orientations, even for the Midlands and East Anglia 2080s scenario. However, there is a large subsequent increase in heating demand of around 60–120% depending on if retrofitting has also been applied.
- Geographically, the more northerly Midlands school experiences greater issues with CO₂, exceeding BB101 guidelines, which could be improved by IEQ measures, again with the penalty of increasing heating demand.
- While the vulnerability of north-facing classrooms to high CO₂ concentrations and south-facing to higher NO₂ and PM_{2.5} is again seen respectively, there is no discernible annual trend between orientation and high and low heating demand and overheating.

Figure 10: Summary of annual overheating hours, heating use and average contaminant concentration for three cases under various retrofit and climate scenarios, averaged over four orientations.

Note: IEQ = indoor environmental quality.

Cases	Case	A: London City				B: Midland Suburbs				C: East Anglia Country			
	Retrofit scenario	Base		Retro-fit		Base		Retro-fit		Base		Retro-fit	
	IEQ scenario	Base	Mitigate	Base	Mitigate	Base	Mitigate	Base	Mitigate	Base	Mitigate	Base	Mitigate
CO ₂ conc. (ppm)	2020	1273	1242	894	855	1399	1400	930	886	1123	1097	941	900
	2050	1170	1134	877	847	1294	1253	908	869	1069	1031	916	885
	2080	1095	1058	860	848	1201	1173	892	861	1019	991	896	887
Over-heating (h)	2020	113	38	75	13	55	14	38	7	65	23	47	16
	2050	159	62	108	36	87	27	62	15	87	31	67	23
	2080	216	86	152	57	118	42	93	24	110	42	85	31
Heating (kwh/m ²)	2020	8.9	14.5	8.0	15.9	12.0	17.3	12.6	22.4	10.8	20.2	9.8	18.7
	2050	7.0	11.9	5.9	12.3	9.8	17.8	9.8	19.0	8.8	16.9	7.9	14.7
	2080	5.5	9.4	4.2	9.0	8.0	15.0	7.5	15.0	6.8	12.8	5.9	11.6
PM _{2.5} conc. (µg/m ³)	2020	7.8	7.9	8.6	8.7	7.0	7.1	7.5	7.9	6.5	6.6	6.7	7.1
	2050	8.1	8.2	8.7	8.8	7.2	7.2	7.6	7.9	6.6	6.7	6.8	7.1
	2080	8.0	8.1	8.6	8.8	6.9	6.9	7.4	7.8	6.7	6.8	6.9	7.1
NO ₂ conc. (µg/m ³)	2020	24.8	25.2	28.1	28.6	9.9	10.0	11.2	11.4	13.8	14.1	15.1	15.4
	2050	26.2	26.7	28.5	28.9	10.1	10.3	11.3	11.4	14.2	14.4	15.2	15.5
	2080	25.6	26.0	28.3	28.8	9.6	9.7	11.1	11.3	14.5	14.7	15.4	15.6

Key:

CO ₂ concentration (ppm)	847	1215	1765	Amber and red thresholds based on 'normal' and 'high' concentrations (BB101)
Over-heating (h)	0	40	216	Amber threshold of 40 hours based on maximum (BB101)
Heating (kwh/m ²)	4.2	10.2	22.4	Amber threshold indicates 50th percentile of all cases
PM _{2.5} concentration (µg/m ³)	N/A	5	10	Amber and red thresholds based on maxima (WHO in 2021, 2005 respectively)
NO ₂ conc. (µg/m ³)	8.9	10	40	Amber and red thresholds based on maxima (WHO in 2021, 2005 respectively)

4.1 POLICY IMPLICATIONS OF FINDINGS

The differing degrees of conflict between simultaneously meeting space heating demand reduction measures, indoor overheating risk mitigation and IAQ targets have been demonstrated for three separate cases in [Figure 10](#). Overheating above the BB101 threshold of 40 h in the current school stock can be reduced through a range of retrofit and overheating mitigation strategies to a certain extent.

In terms of the practicality of the measures suggested, while cost-effectiveness is outside the scope of this research, it is clear that night ventilation for overheating mitigation and overhangs for windows in retrofitting represent examples of lower cost measures alongside more intensive fabric insulation and fenestration upgrades. This study has shown both to be somewhat effective at lowering the hours of overheating, if practical barriers to implementing this, such as security concerns, can be overcome. However, to reduce overheating below 40 h without exceeding WHO-recommended guidelines thresholds of NO_2 and $\text{PM}_{2.5}$ will not be possible for any of the climate scenarios modelled. Hence either a significant improvement in external NO_2 and $\text{PM}_{2.5}$ concentrations through the successful implementation of Clean Air policies and strategies is required, or the widespread use of mechanical ventilation to reduce internal temperatures (Jenkins et al. 2009) or the use of air purifiers (WHO 2021).

Current school ventilation guidance (ESFA 2018) acknowledges that schools ‘in London [...] and polluted areas’ will be required to minimise the ingress of external air and employ mechanical ventilation, although this is not a specific requirement for retrofitted school buildings within the building regulations (HM Government 2013). However, this research indicates without further intervention that a large number of schools throughout England, including the rural and semi-rural locations given in [Table 5](#), will fail to meet the updated WHO guidelines both now and in the future.

More generally, it is important to note that building stock models are not designed to model a single variable in isolation. This study illustrates that a focus on a single goal such as space heating demand reduction through building fabric improvement may miss important implications for IEQ. It may be necessary to revise such models, used in regulatory energy benchmarking calculations through TM46 (CIBSE 2008), to account for whether overheating and air quality targets are met with the recorded regime of energy use.

4.2 MODEL UNCERTAINTY, LIMITATIONS AND FUTURE WORK

An inherent risk of stock modelling is failing to appreciate the narrow margins of internal temperature predictions and I/O ratios within modelling error between meeting or failing overheating and air quality targets, respectively. This is present due to the necessary approximation of features such as glazing and building service operation within archetypes. Since the key output of the stock model is the success or failure of meeting these targets, rather than the raw model data themselves, uncertainties in internal temperature prediction and the effect of ventilation could be amplified when internal temperature approaches the threshold.

In terms of the point of onset of overheating, [Figure 4](#) demonstrates that due to night-time ventilation, the internal temperature of the classroom is 3–4°C lower at the start of the school day (indicated by shading) for IEQ mitigation scenarios. This leads to temperatures that are around 1–2°C lower later in the day, delaying the predicted onset of overheating, as defined by BB101. These cumulative small differences in the onset of overheating lead to a 23% reduction in annual hours of overheating, from 103 to 79 h, and a further 80% reduction to 16 h once retrofitting and IEQ mitigation are added, respectively. The same reasoning applies, given the closeness of revised WHO guidelines to external contaminant levels (see [Table S5](#) in the supplemental data online). Uncertainties in I/O ratio become amplified as internal concentrations approach the target. Hence, the rate of heating dictated by internal gains from humans and equipment is also critical to this prediction, since the rate of heating dictates the rate of temperature increase and requirement for ventilation throughout the day.

AFN modelling, while providing a beneficial linkage of hours of overheating to weather-driven ventilation, dependent on internal and external pressure and temperature differences rather than assumed ventilation, adds additional model uncertainty in the use of a discharge coefficient, adjusted for the IEQ mitigation scenarios. While this could be adjusted for different window types and geometries in the future, this assumption of ventilation performance means that such models will require validation against monitored ventilation data.

There is ample scope to improve the data available on critical elements of the system, within the novel methodology of combining previous work on school stock modelling with airflow network modelling and scenario modelling. In terms of archetypes, greater disaggregation of the post-1976 archetype into smaller groupings such as low carbon schools should be possible based on the next iteration of the PDSP, the CDC (ESFA 2017), providing more detail on construction types, including air permeability. It is also acknowledged that school classrooms are not uniform geometrically, and this should be adapted into future archetypes as for variations in floor area/occupant density which could be critical determinants of overheating and CO₂, and hence heating demand and PM_{2.5} and NO₂ concentrations.

Hence, significant improvements can be made to this methodology in the next decade with the increasing availability of data through future iterations of the PDSP on additional items such as terrain, demonstrated to be an important consideration in [Figure 6](#), and classroom geometry, as well as improving existing items such as investigating the variance of WWR across the stock, as well as the mean.

A key data availability limitation is the granularity of weather and PM_{2.5} and NO₂ concentration data across the UK, making it impossible to correct the performance of the AFN for local weather effects. Lack of model calibration means that models cannot yet be considered predictive of IEQ; however, increased CO₂ and internal temperature monitoring in classrooms could allow these models to be corrected for local conditions.

The next step of this study involves a survey of a wide range of school building professionals to determine the most appropriate use of performance metrics, including the possibility of modelling additional air contaminants. Optimisation of specific details such as window-opening sizes and schedules will be required to meet overheating requirements while minimising the ingress of pollutants and heating energy demand. Additional measures not investigated here, such as internal heat management, thermal mass and increased albedo, may also be useful tools in preventing overheating without resorting to air-conditioning methods; testing these additional scenarios forms part of ongoing work.

5. CONCLUSIONS

A novel approach to simultaneous air flow network (AFN) modelling of overheating, heating demand and indoor environmental quality (IEQ) metrics at the school building stock level for a range of future adaptations and climatic conditions was presented. The main findings of this study are as follows:

- English schools will experience high levels of overheating under future climate scenarios, with those most at risk being the insulated post-1976 buildings, and schools located in the South East of England.
- Although it may be possible to use overheating mitigation strategies, as an alternative to air-conditioning, to dramatically reduce the likelihood of overheating for future climate scenarios, beyond a certain point (e.g. the 2080s) this will not sufficiently meet existing overheating criteria.
- Increased ventilation to combat overheating could lead to a rise in the ingress of externally generated pollutants, such as PM_{2.5} and NO₂. This will be of particular concern for urban settings with schools located in highly polluted areas.

- Complex interactions between ventilation and heating constraints based on calculated internal temperatures can negate small improvements in energy efficiency gained by altering insulative and permeability properties through retrofitting, in some cases doubling heating demand where overheating is fully addressed.
- A case for incorporating terrain definition into models, requiring further analysis of future versions of the national Property Data Survey Programme (PDSP) dataset was made due to impact against *Building Bulletin 101* overheating targets.

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AUTHOR CONTRIBUTIONS

DG, YS, AM and DM devised the project framework and designed the initial study. DG adapted scripting to carry out the study adapted from the methodology developed originally by YS and IK, to incorporate modelling features previously investigated by PS. DG carried out the analysis and wrote the manuscript with guidance from YS, AM and DM, and with technical guidance from PS and IK.

COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

The data that support the findings of this study are openly available in an online repository (see <http://doi.org/10.5522/04/19369694>).

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SUPPLEMENTAL DATA

Supplemental data for this article can be accessed at: <https://doi.org/10.5334/bc.159.s1>.

PUBLISHER’S NOTE

Figure 10 was updated to remove an unintentional highlight over row “Over-heating (h): 2020” on the 11th of April, 2022, however the actual data in the table was not changed.

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