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Climatic, energy retro-fit and IEQ mitigation scenario modelling of the English classroom stock model

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Abstract: Health and cognitive performance in UK school classrooms is dependent on building fabric performance as well as heating and ventilation system operation in maintaining Indoor Environmental Quality (IEQ), comprising thermal comfort and air quality. While archetype models can be used to simulate IEQ for different stock-wide location and construction eras, a predictive approach also necessitates the use of longitudinal scenarios. As a key component of the UK's decarbonisation strategy, these scenarios should account for fabric retro-fit adaptations to reduce carbon emissions, and changes in operation of the building for overheating mitigation as well as changes in external climatic conditions.

The IEQ of three representative classroom archetypes, representing the stock of 18,000 English schools, have been analysed for 24 pair-wise retro-fit and operational scenarios across three climatic scenarios. Retro-fitting, while effective in reducing energy demand, may risk compromising indoor air by requiring ventilation at times of the day when external conditions are least conducive to air quality and overheating. Additionally, while North facing classrooms can tackle overheating through single effective IEQ mitigation measures, South facing and 2080 climates will necessitate cumulative effects of multiple measures to be realised. Future work involves incorporating educational and construction stakeholder preferences through multi-criteria decision analysis, to derive suitable metrics.

Keywords: UK school building stock modelling, indoor environmental quality, building simulation

1. Introduction

British children spend 30% of their lives at school on average, and around 70% of that time spent within a classroom environment (Csobod, 2014). Within such environments, linkage has been demonstrated between Indoor Environment Quality (IEQ), comprising not only air quality and thermal comfort, but also health (Chatzidiakou et al., 2014) and attainment (Wargocki et al., 2020) of children. Within the building IEQ also interacts with heating loads, ventilation and management of internal gains (Becker et al., 2007) within the building envelope. Hence the importance of determining operational IEQ performance of the school building envelope in defining health and attainment outcomes of school pupils in different settings.

As public buildings, schools are required to meet standards in overheating through Building Bulletin 101 (Education and Skills Funding Agency (ESFA), 2018) and nitrogen dioxide (NO_2) and particulates smaller than 2.5 microns ($PM_{2.5}$) through the World Health Organisation (World Health Organisation, 2021). As non-domestic buildings, schools are subject to additional constraints, as the UK has legislated to meet net zero carbon emissions by 2050 (UK Committee on Climate Change, 2019) and non-domestic buildings contribute 18% of total emissions (Carbon Trust, 2009). In spite of these multiple objectives, monitoring campaigns exploring the dynamic behaviour of the ingress of NO_2 and $PM_{2.5}$ contaminants (Stamp et al., 2022) and susceptibility to overheating (Mohamed et al., 2021) necessarily investigate these phenomena separately from post occupancy evaluation of energy use in schools (Pegg et al., 2007), although there has been a drive to consider them in parallel due to their co-dependence (Becker et al., 2007; Cabovská et al., 2021). Subsequently, when such work has been scaled up to include a wider portfolio of UK school buildings using statistical or physics-based models, the need to address each objective separately has been retained.

1.1. UK building stock modelling

Recent stock-level energy models of the non-domestic building stock (Steadman et al., 2020) have been able to integrate top-down statistical characteristics from large-scale dis-aggregated national datasets (Hong et al., 2021) with bottom-up, causal, physics-based modelling of individual buildings (Kavgic et al., 2010). For UK schools, stock modelling through the Data dRiven Engine for Archetype Models of Schools (DREAMS) framework (Schwartz, Korolija, Dong, et al., 2021) has facilitated the use of archetypes to define era and geographical region, demonstrating a reasonable match with measured Display Energy Certificate (DEC) data. This modelling has been further developed to incorporate classroom-level orientation (Schwartz, Korolija, Symonds, et al., 2021), rather than whole-building level modelling and additionally airflow network modelling (Grassie, Schwartz, et al., 2022), demonstrating the interactions between external air and heat flows with the windows and walls that the weather is incident upon.

An additional step is required to ensure that the outputs of simulation modelling can be translated into appropriate outcomes (Grassie, Karakas, et al., 2022) for policymakers to act upon. However such an approach also requires scenario modelling to demonstrate longitudinal changes, to demonstrate that these outcomes are also appropriate outside of an individual snapshot in time. In the case of the UK school building stock, these longitudinal scenarios should incorporate three separate effects:

- Energy efficiency retro-fitting: improvements in heat transfer and building energy efficiency required to meet net zero carbon emissions.
- Classroom operational changes: mitigating against overheating and indoor air quality by preventing ingress of heat or improving ventilation characteristics.
- External changes in climate and contaminants: impacting ventilation and heating requirements to maintain an acceptable learning environment.

Isolating the effects of each individual measure as a snapshot is only meaningful over a short time-frame due to the dynamic nature of the stock (Tian & De Wilde, 2011), hence a methodology is required for combining these effects into scenario modelling of the UK school building stock.

1.2. Research question

The previous section described the need for future building simulation tools to account for the effects of future energy efficiency retro-fit on IEQ. These simulation tools could be used by policymakers to inform decisions on different sectors of the UK school stock based on both the predicted effectiveness of energy improvements through retro-fit and mitigation subsequent IEQ issues, while accounting for anthropogenically driven changes in climate. Hence the research question addressed in this paper is as follows:

What is the predicted optimal pairwise combination of retro-fit energy efficiency measure and operational strategy in terms of health and attainment metrics derived for three archetypal UK classrooms, and do these strategies remain suitably robust for future climatic periods?

This question has been addressed by splitting the work into the following research objectives:

1. To generate building simulation models of three base archetypes which are representative of the UK school building stock.

2. To develop pair-wise scenarios incorporating energy efficiency retro-fit and building service operational measures, while addressing dynamic climatic conditions within modelling.

3. To determine performance of a number of key health and attainment metrics and discuss performance of the various pairwise combinations of energy efficiency and operational scenarios for different climatic scenarios.

To address these objectives, the next two sections describe the incorporation of retro-fit, IEQ and climatic scenarios into previous school building stock models and a three stage methodology of generating simulation models, development of scenarios and simulation and post-processing. Results of this analysis are presented in Section 4, prior to a discussion of the significance of the findings and future adaptations and applications of these models. The paper concludes in Section 6 by summarising the main findings from a policy-maker perspective.

2. Literature review

2.1. The use of building stock modelling to derive health and attainment metrics

Building stock modelling has already been widely established for generating predictive energy demand profiles for domestic and non-domestic buildings, through the auto-generation of simulation models from national level datasets (Kavgic et al., 2010; Steadman et al., 2020). While the use of building simulation to derive IEQ measures across a sector of the stock has been carried out previously in the UK residential sector (Symonds et al., 2016), a greater heterogeneity of available data sources for fabric (Bruhns et al., 2006) for different sub-sectors of the non-domestic stock, have required bespoke methods to categorise and characterise buildings. For example, for energy demand within the school sector, it has been possible to construct archetypes by era (Bull et al., 2014) which have then been fitted to different era buildings described across the stock within the Property Data Survey Programme (PDSP) (Education Funding Agency (EFA), 2012) dataset (Schwartz, Korolija, Dong, et al., 2021) to calculate annual heating load.

Due to functionality within a modelling platform for schools (Schwartz et al., 2019) for individualised geometries based on laser imaging, detection and ranging (LIDaR) acquired polygons, archetypes have also been developed for different era geometries (Schwartz, Korolija, Dong, et al., 2021). However for calculations of IEQ rather than energy, a data-driven whole building approach would account only for known geometric differences, including height of ceiling, number of storeys and glazing ratio, when calculating heating and ventilation requirements across the stock. The lack of key data on orientation and location of classrooms and occupants within the building would affect the calculation of solar gains and ventilation within classroom areas. This could lead to over- or under-prediction of internal temperatures within specific zones where classes are taught when coupled with airflow network models (Grassie, Schwartz, et al., 2022; Symonds et al., 2016), which are dependent on external weather conditions.

In terms of occupancy and building service operation, the National Calculation Methodology (NCM) (Communities and Local Government, 2013) provides a set of rules for calculating energy asset ratings for the non-domestic stock, including definition of daily and annual school occupancy to aid the comparison of similar buildings. However there is a conflict when overheating is a required metric, since overheating calculations within UK school building models defined in Building Bulletin 101 (BB101) (Education and Skills Funding Agency (ESFA), 2018), consider summer utilisation of school buildings to derive overheating metrics. Since IEQ metrics are the dominant feature of such modelling, the year-round BB101 approach has been preferred for this research to explore the full extent of cooling as well as heating seasons.

2.2. Retro-fit and operational scenario modelling within the non-domestic sector

Looking outside the scope of building stock modelling to the domain of individual buildings, a number of research projects have defined resilience of buildings using scenarios in different sub-sectors of the non-domestic stock:

- The Climacare project (Oikonomou et al., 2020) investigated a range of hard (structural) and soft (non-structural) measures across the UK care-home sector, a number of which have been referenced for the operational scenarios given in the methodology section, considering these measures individually and cumulatively rather than exhaustive combinations of hard and soft.
- A sensitivity analysis of annual heating and cooling loads for a Plymouth-based higher education building (Tian & De Wilde, 2011) under different climatic conditions, included wall and window U-values and infiltration within a matrix of cases to be simulated. While demonstrating ideal loads for both heating and cooling seasons is useful for design of future ventilation and air conditioning systems, performance of window airflows are likely to be of particular interest in the school stock, where more than 95% of buildings are still naturally ventilated (Grassie, Karakas, et al., 2022).
- An analysis of overheating avoidance in existing German school buildings (Camacho-Montano et al., 2020) provided commentary on cognitive performance and capital costs and effectiveness of a number of passive measures such as night ventilation and window opening options for summer months only. While the minimisation of “hours of discomfort” was used in optimisation, it was unclear how robust this snapshot alone would be in the face of changing climatic conditions.

While methods of testing robustness of the stock to various retro-fit and operational measures have been demomstrated, there is also a need to incorporate climate resilience into analysis of IEQ and energy simulation in UK school buildings (Department for Education (DfE), 2021).

2.3. Accounting for climate resilience within the non-domestic sector

The use of Chartered Institute of Building Services Engineers (CIBSE) weather files based on future projections of greenhouse gases (CIBSE, 2016) in the sensitivity analysis of higher educational buildings (Tian & De Wilde, 2011) demonstrated how resilience of educational buildings to changes in climate could be determined. In addition to climate, external contaminants are also known to have varied over time. The projections on which the CIBSE weather files are based define the UK’s Clean Air Strategy (Department for Environment Food & Rural Affairs, 2019) to reducing external NO_2 and $PM_{2.5}$.

Summarising, the incorporation of IEQ into building stock models adapted from energy demand modelling has demonstrated a need to understand in more granular detail how occupancy patterns and classroom orientations affect airflow impacting both overheating and ingress of contaminants. When such details have been included in more focussed studies, retro-fit and operational scenarios have often been applied as a series of individualised measures, rather than a matrix of independent retro-fit and operational scenarios. Hence the research explored by this work is the use of pairwise combinations of retro-fit and operational scenarios to determine resilience of UK school building stock to changes in climate.

3. Methodology

3.1. Generation and selection of archetype models

A base model geometry for the investigation of IEQ across the UK school building incorporating four classroom orientations has been defined previously (Schwartz, Korolija, Symonds, et al., 2021) using the open-source EnergyPlus building simulation software (US Department of Energy, 2015). A series of modifications has been made to the single external wall to facilitate airflow network modelling of ventilation (Grassie, Schwartz, et al., 2022) and the OpenStudio (Guglielmetti et al., 2011) representation of this façade is shown below in Figure 1, together with the base model geometry.

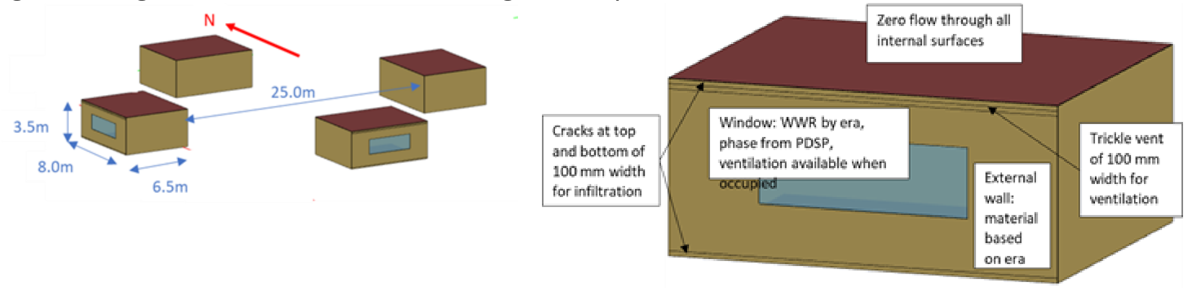

Figure 1. Schematic of classrooms and description of infiltration and ventilation

Table 1 contains a summary of how internal gains and various systems are operated within the building. As described previously, although the NCM (Communities and Local Government, 2013) provides a suitable set of rules for energy calculations, the values in the table have been sourced from BB101 (Education and Skills Funding Agency (ESFA), 2018), due to the need to apply overheating calculations on simulation output.

Table 1: Input values and schedules used in seed model

Parameter	Value / Setpoint	Schedule
Occupancy	Density: 0.55 student/m^2 Internal gains: 70 W CO_2 generation: 3.82 e^{-8} m^3/s/W	100% 09-16 every weekday of the year, otherwise 0%
Lighting	7.2 W/m^2	100% 07-18 every weekday of the year, otherwise 0%
Equipment	4.7 W/m^2	100% 07-21 every weekday of the year, otherwise 5%
Heating	Applied when internal temperature < 20 °C for 07-18 every weekday of the year 12 °C for remainder of the year	
Window	Open 10 minutes at beginning of each hour, otherwise opens when internal temperature >23 °C 9-16 every weekday of the year, closed for remainder of year	

Preceding research demonstrated the auto-generation of archetypes for all combinations of geographical region, era and ventilation combinations contained within the Property Data Survey Programme (PDSP) dataset (Schwartz, Korolija, Dong, et al., 2021). Python scripting (Python 3.9.2, 2021), utilising the EPPY set of libraries (EPPY 0.5.56, 2021) for creating and selectively altering EnergyPlus files, has been used to generate similar archetypes based on those present in the PDSP distinguished by:

- Phase (primary/secondary) – 70 W/student (primary) and 90 W/student (secondary) result in different internal gain and CO_2 output profiles within the classroom, as well as different occupancy patterns.
- Ventilation (natural/mechanical) – As discussed earlier, the vast majority (95%) of schools can be considered to be naturally ventilated, based on an analysis of the PDSP.
- Geographical regions – 13 regions across England and Wales have been defined based on different CIBSE degree-day regions (CIBSE, 2008) and have been allocated the following:
    - Hourly CIBSE weather files (CIBSE, 2016) used for simulating ventilation and heating loads for an entire simulation, discussed further in Section 3.3.
    - Hourly contaminant NO_2 and $PM_{2.5}$ concentrations from UK-wide monitoring sites (Department for Environment Food and Rural Affairs, 2021), collated and averaged over each geographical region
- Era of construction – Five different eras (Pre-1918, Inter-war, 1945-1967, 1967-1976 and Post-1976) have been allocated floor to ceiling height based upon the Department for Education's Resilient School Building Design (Department for Education (DfE), 2021) and differing wall constructions (Grassie, Schwartz, et al., 2022).

In order to examine through scenario modelling the consequences of various fabric and operational decisions, it is necessary to consolidate the number of archetypes under investigation. Hence naturally ventilated primary schools were selected for the following three regions and eras, given in Table 2, which covers a full range of construction eras and regions.

Table 2. Base case description of archetypes selected

Primary school	Geographical Region	Construction era, U-value ($W/m^2.K$)	Floor to ceiling height (m)	Glazing (% Glazing ratio), U-value ($W/m^2.K$)
P1	London	Pre-1919, 1.92	4.5m	Single (25%), 5.8
P2	West Midlands	1945-1967, 1.37	2.7m	Single (25%), 5.8
P3	NE England	Post-1976, 0.74	3.6m	Double with Air (27%), 3.1

3.2. Development of scenarios

Figure 2 shows 24 pair-wise combinations of retro-fit and operational scenarios, analysed longitudinally with three separate climatic scenarios. While Table 3 demonstrates the progressive implementation of external wall, glazing U-values and permeability or air tightness from base case through to EnerPHIt standard, each of the six operational scenarios can be considered in terms of four individual operational measures.

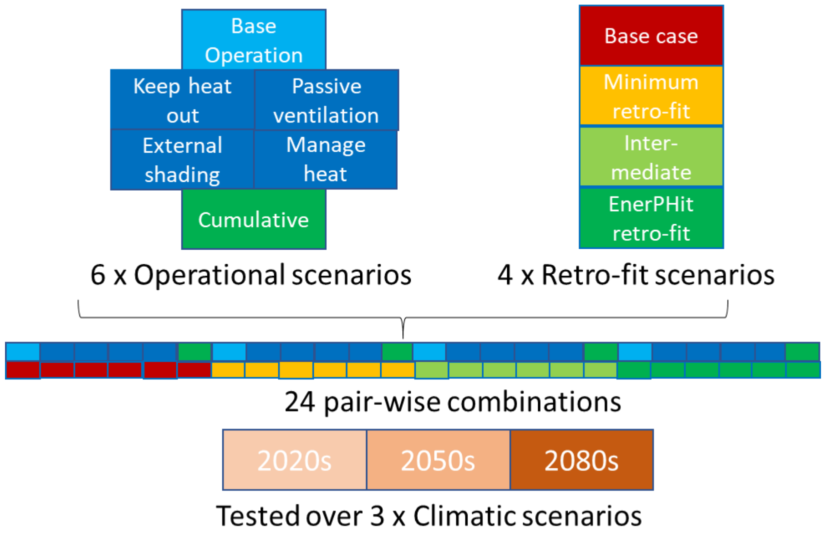

Figure 2. Combination of climatic, retro-fit and operational scenarios

Table 3. Description of energy efficiency retro-fit scenarios

	Base case	Minimum standard	Intermediate	EnerPHIt
Abbreviation	**Base**	**MinR**	**IntR**	**EnPH**
Description (based upon)	As defined in previous section	Building regulations (HM Government, 2021)	Bespoke description used previously (Grassie, Schwartz, et al., 2022)	Criteria required for EnerPHit retro-fit (Institute, 2016)
External wall	Cavity wall (era-dependent)	External expanded polystyrene added	External expanded polystyrene added	External 150mm of EPS insulation added
U-value ($W/m^2.K$)	0.74-1.92	0.34	0.34	0.19
Permeability ($m^3/h.m^2$ @50Pa)	9	8	3	0.89
Glazing	Single/double with air	Double with air + low emissivity glass	Double with argon + low emissivity glass	Triple with argon + low emissivity glass
U-value ($W/m^2.K$)	5.80/3.09	1.79	1.22	0.75

A description of the four individual operational measures which comprise the six operational scenarios is given below. The base operation (abbreviated to BaseOp) and cumulative (Cumtve) operational scenarios contain none and all of the below measures respectively.

- Keep heat out (KpHtOt): Wall albedo updated from 0.7 to 0.1 solar and visible absorbances. Internal window blinds with shading control added with setpoint of 120W.
- External shading (ExtSha): External overhang added above all windows at 90 degrees, 50mm thick (in vertical direction) and 800mm depth (projecting out from the wall), above the horizontal length of the window.
- Manage heat (Manage): 50mm thickness of cast concrete added to internal walls as thermal mass

- Passive ventilation (PasVen): Availability of school-day ventilation increased to 24 hours/day, and flow increased through ventilation by increasing the height factor of the opening from 0.1 to 0.3 and start height factor from 0.9 to 0.7

The climatic scenarios are derived from CIBSE weather files incorporating the UKCIP09 climate change scenarios (Mylona, 2012) for weather stations within the three separate geographical regions. For the 2020s, 2050s and 2080s climate scenarios, the weather files selected represent P50 conditions for an A1B medium emissions scenario (Intergovernmental Panel on Climate Change (IPCC), 2000). For each region and each climate scenario, a hybrid approach to account for both heating and cooling seasons has been utilised by merging weather data from October 1st to April 30th from Test Reference Year (TRY) files, with Design Summer Year (DSY1) files, representing a moderately warm summer from May 1st to September 30th.

Ambient external CO_2, set as constant over a simulation year, has been updated across climatic scenarios to reflect projected trends. For 2020s, the figure of 435 ppm is based on 2021 measurement of 415 ppm (NASA, 2021) plus a 20 ppm urban uplift effect (Mitchell et al., 2018). For 2050s and 2080s, external CO_2 concentrations of 532 ppm and 649 ppm, based on the A1B projection (Intergovernmental Panel on Climate Change (IPCC), 2000), are also uplifted by 20 ppm to 552 ppm and 669 ppm. Although external NO_2 and $PM_{2.5}$ may be expected to decrease in line with the Clean Air Strategy (Department for Environment Food & Rural Affairs, 2019), they have conservatively been held constant.

3.3. Simulation and Post-processing

Each individual archetype and scenario combination has been simulated over a simulation year using UCL's Myriad high performance computing (HPC) cluster to simulate the large number of different models and weather file combinations. Since EnergyPlus calculates one contaminant at a time, separate runs are required to calculate internal CO_2 and Indoor/Outdoor ratios of NO_2 and $PM_{2.5}$ over a simulation year. Both NO_2 and $PM_{2.5}$, external hourly data was acquired for 2019 for all monitoring sites (Department for Environment Food and Rural Affairs, 2021) and multiplied at each time step by the Indoor/Outdoor ratio to give internal concentrations.

Metrics have been calculated for five separate criteria for occupied periods only, with Table 4 providing the linkage between model outputs via post-processing to each criterion, using Python and EPPY scripting.

Table 4. Description and derivation of health and attainment metrics used for evaluating performance.

Criterion	Short label	Hourly data from annual EnergyPlus simulation	After processing
Pupil learning performance	Attainment	Internal temperature (t)	Annual average (%) by multiplying the following two factors (Dong et al., 2020; Wargocki et al., 2020) : $y = 0.2269*t^2 - 13.441*t + 277.84$
		Ventilation rate (V_R)	$y = 0.0086*V_R + 0.9368$
Pupil and staff sense of thermal comfort	Overheating	Operative temperature	Total overheating hours based on "Annual hours of exceedance" metric from BB101 (Education and Skills Funding Agency (ESFA), 2018)
		External temperature	
Classroom air	Stuffiness	CO_2 concentration	Annual average CO_2 concentration (ppm)

freshness			(occupied hours only)
Cost savings to due to pupil/staff illness averted	Health	NO_2 concentration PM2.5 concentration	Annual averages of NO_2 and $PM_{2.5}$ ($\mu g/m^3$) (occupied periods only)
Cost savings from reduction in heating	Heating	Energy use (J) of: baseboard heating	Annual total heating energy normalised by floorspace (kWh/m^2)

4. Results

4.1. Performance of all possible different pair-wise combinations of scenarios

Table 5, Table 6 and Table 7 show the five criteria described in the previous section by column (omitting $PM_{2.5}$) for the three selected archetypes by row for South-facing classrooms in 2020s climate, South-facing classrooms in 2080s and North-facing classrooms in 2080s respectively. For each archetype and criterion, all 24 pair-wise combinations of retro-fit scenario (by column) and operational scenario (by row) are displayed, with green and red colour coding indicative of improved and reduced performance respectively.

Table 5: Performance criteria for archetypes based on a matrix of retro-fit and operational scenarios: South facing classrooms for 2020s climate scenario

CO2 (ppm)	801	1136	1999
Overheating (h)	79	581	763
Attainment (%)	82.7	79.5	75.9
Heating (kWh/m2)	0	0.46	16.3
NO2 (ug/m)	9.06	20.6	26.2

		Average CO2 (ppm)				Annual overheating (h)				Average attainment (%)				Annual heating (kWh/m2)				Average NO2 (ug/m3)			
		Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH
Archetype P1	BaseOp	935	838	811	802	482	593	680	686	81.8	80.4	80	79.7	11.3	1.78	0.78	0.47	22.9	24.6	25.2	25.6
	ExtSha	979	867	840	826	299	418	515	531	82.1	80.7	80.1	79.8	12.9	2.04	0.89	0.56	22.2	24	24.7	25.2
	KpHtOt	1009	859	834	807	262	469	572	659	82.5	80.6	80.1	79.8	16.2	2.4	0.96	0.52	21.7	24.1	24.7	25.5
	Manage	960	840	811	801	496	642	706	705	81.8	80.3	79.9	79.6	9.24	1.48	0.78	0.46	22.5	24.6	25.3	25.6
	PasVen	1271	1108	1106	1114	518	553	616	575	80.2	78.3	77.9	77.6	7.26	0.11	0.01	0	18.5	21.4	21.8	22
	Cumtve	1532	1162	1151	1145	79	192	268	319	81.5	78.5	77.8	77.4	10.7	0.12	0	0	15.8	20.7	21.3	21.9
Archetype P2	BaseOp	1058	946	918	908	513	697	742	750	80.5	79.4	79	78.7	4.1	0.35	0.16	0.11	21.5	23.1	23.6	23.9
	ExtSha	1104	968	938	924	357	569	699	729	80.8	79.6	79.1	78.8	4.64	0.41	0.19	0.12	21.1	22.9	23.4	23.7
	KpHtOt	1147	967	937	912	316	593	705	743	81	79.7	79.2	78.7	6.12	0.47	0.21	0.11	20.6	22.9	23.3	23.8
	Manage	1082	946	916	907	536	718	759	763	80.5	79.4	78.9	78.6	2.11	0.31	0.16	0.1	21.4	23.2	23.6	23.9
	PasVen	1534	1430	1445	1460	547	617	663	644	78	76.6	76.4	76.2	1.93	0	0	0	17.8	19.6	19.7	19.7
	Cumtve	1726	1470	1484	1487	121	361	473	541	79	76.8	76.4	76.1	2.1	0	0	0	16.4	19.4	19.5	19.7
Archetype P3	BaseOp	904	872	840	831	497	528	625	634	81	80.6	80	79.8	4.49	1.67	0.84	0.59	12.1	12.4	12.7	12.9
	ExtSha	947	901	866	851	318	383	496	513	81.6	81	80.3	80.1	4.78	1.87	0.97	0.67	11.8	12.2	12.5	12.7
	KpHtOt	949	895	862	837	317	417	530	599	81.5	80.9	80.3	79.8	6.73	2.26	1.03	0.64	11.7	12.2	12.5	12.8
	Manage	917	874	841	830	503	548	688	688	81	80.5	79.9	79.7	2.94	1.4	0.8	0.58	11.9	12.4	12.7	12.9
	PasVen	1225	1187	1185	1192	505	494	547	503	78.4	77.8	77.4	77.2	1.7	0.14	0	0	10.2	10.8	11	11
	Cumtve	1331	1229	1221	1218	115	171	249	278	79.3	78.3	77.7	77.3	1.79	0.05	0	0	9.53	10.5	10.8	11

Table 6: Performance criteria for archetypes based on a matrix of retro-fit and operational scenarios: South facing classrooms for 2080s climate scenario

		Average CO2 (ppm)				Annual overheating (h)				Average attainment (%)				Annual heating (kWh/m2)				Average NO2 (ug/m3)			
		Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH
Archetype P1	BaseOp	1133	1044	1021	1015	574	686	726	730	81.3	80.1	80	79.6	6.85	0.74	0.31	0.18	23.5	25.3	25.9	26.2
	ExtSha	1172	1071	1047	1037	433	554	663	671	81.1	79.9	79.5	79.3	7.79	0.93	0.36	0.2	22.8	24.8	25.4	25.8
	KpHtOt	1200	1064	1041	1019	391	599	686	714	81.4	80.1	79.8	79.6	10.4	1	0.39	0.19	22.3	24.8	25.4	26.1
	Manage	1146	1045	1020	1015	604	710	742	743	81.2	80	79.8	79.5	5.2	0.65	0.31	0.17	23.2	25.3	25.9	26.2
	PasVen	1451	1337	1344	1359	588	649	685	659	80.2	78.3	78.1	77.6	4.39	0.02	0	0	19.3	21.9	22.2	22.3
	Cumtve	1680	1386	1390	1391	206	375	466	508	80.2	77.8	77.4	77	6.31	0.02	0	0	16.7	21.3	21.7	22
Archetype P2	BaseOp	1247	1158	1136	1131	621	745	763	763	79.9	78.9	78.7	78.4	2.43	0.14	0.06	0.03	22.1	23.5	23.9	24.1
	ExtSha	1286	1178	1155	1146	483	697	743	755	79.8	78.9	78.5	78.2	2.77	0.17	0.07	0.04	21.7	23.3	23.7	23.9
	KpHtOt	1320	1176	1153	1135	445	708	748	763	80.1	79	78.7	78.4	3.79	0.2	0.08	0.03	21.3	23.3	23.6	24
	Manage	1263	1156	1134	1130	663	757	763	763	79.8	78.8	78.6	78.3	1.01	0.13	0.06	0.03	21.9	23.6	23.9	24.1
	PasVen	1748	1680	1697	1715	637	685	716	707	77.8	76.5	76.4	76.1	1.14	0	0	0	18.3	19.7	19.7	19.7
	Cumtve	1897	1723	1740	1745	249	516	606	649	78.1	76.3	76	75.9	1.07	0	0	0	17.1	19.5	19.6	19.6
Archetype P3	BaseOp	1108	1080	1052	1046	588	629	717	718	80.2	79.8	79.4	79.2	2.48	0.8	0.4	0.25	12.3	12.7	12.9	13.1
	ExtSha	1142	1103	1075	1065	443	505	614	647	80.4	79.9	79.4	79.2	2.98	0.95	0.45	0.29	12.1	12.5	12.8	13
	KpHtOt	1150	1099	1070	1051	446	532	645	698	80.5	80	79.5	79.2	4.03	1.12	0.49	0.28	12	12.5	12.8	13.1
	Manage	1115	1081	1051	1045	620	687	746	744	80.1	79.7	79.3	79	1.49	0.68	0.37	0.25	12.2	12.7	13	13.1
	PasVen	1445	1419	1424	1438	593	579	629	593	78	77.4	77.1	76.8	0.95	0.03	0	0	10.5	10.9	11.1	11.1
	Cumtve	1534	1460	1463	1466	224	296	378	411	78.4	77.5	77	76.7	0.85	0.01	0	0	9.93	10.8	11	11.1

Table 7: Performance criteria for archetypes based on a matrix of retro-fit and operational scenarios: North facing classrooms for 2080s climate scenario

		Average CO2 (ppm)				Annual overheating (h)				Average attainment (%)				Annual heating (kWh/m2)				Average NO2 (ug/m3)			
		Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH	Base	MinR	IntR	EnPH
Archetype P1	BaseOp	1263	1116	1092	1067	354	512	648	688	81.8	80.3	80	79.6	12.2	1.4	0.59	0.29	21.4	23.8	24.3	25.1
	ExtSha	1274	1126	1103	1074	314	455	583	650	81.9	80.4	80	79.6	13	1.51	0.62	0.31	21.2	23.6	24.1	24.9
	KpHtOt	1274	1121	1098	1067	256	439	566	671	81.9	80.3	80	79.6	13.1	1.52	0.62	0.3	21.2	23.6	24.2	25.1
	Manage	1297	1119	1093	1067	321	524	680	704	82.1	80.2	79.9	79.5	10.5	1.13	0.52	0.29	20.8	23.8	24.4	25.1
	PasVen	1634	1404	1403	1403	364	450	521	510	80.4	78.4	78	77.5	8.64	0.26	0	0	16.8	20.6	21	21.5
	Cumtve	1772	1425	1421	1415	186	308	389	433	81	78.4	77.9	77.5	8.55	0.05	0	0	15.7	20.5	20.9	21.5
Archetype P2	BaseOp	1378	1216	1189	1167	427	708	752	763	80.3	79.3	79	78.6	4.75	0.32	0.15	0.08	20.5	22.7	23.2	23.6
	ExtSha	1397	1223	1196	1172	375	672	740	754	80.4	79.3	79	78.6	5.02	0.34	0.15	0.08	20.3	22.7	23.1	23.6
	KpHtOt	1399	1221	1195	1168	324	654	736	759	80.4	79.3	79	78.6	4.86	0.32	0.15	0.08	20.4	22.7	23.1	23.6
	Manage	1415	1215	1187	1166	431	728	762	763	80.4	79.2	78.9	78.6	3.16	0.25	0.13	0.07	20.2	22.8	23.2	23.6
	PasVen	1905	1727	1741	1751	436	581	631	633	78.4	76.7	76.5	76.2	2.66	0.01	0	0	16.7	19.2	19.3	19.4
	Cumtve	1999	1744	1760	1764	232	483	571	617	78.6	76.7	76.4	76.2	1.63	0	0	0	16.2	19.2	19.3	19.4
Archetype P3	BaseOp	1215	1154	1122	1097	388	464	591	640	80.9	80.4	80	79.7	5.99	1.72	0.89	0.51	11.4	12	12.3	12.7
	ExtSha	1231	1163	1132	1104	324	417	539	598	81.1	80.5	80.1	79.7	6.33	1.8	0.92	0.53	11.4	11.9	12.2	12.6
	KpHtOt	1226	1160	1127	1097	294	410	533	620	81	80.5	80	79.7	6.16	1.74	0.92	0.52	11.4	12	12.3	12.7
	Manage	1244	1159	1125	1096	376	474	628	675	81	80.4	79.9	79.6	3.87	1.32	0.8	0.49	11.2	12	12.3	12.7
	PasVen	1572	1484	1480	1478	374	400	453	431	78.8	78	77.6	77.3	2.68	0.36	0.02	0	9.58	10.4	10.6	10.8
	Cumtve	1628	1502	1496	1491	193	254	326	349	79.1	78.1	77.6	77.3	1.7	0.04	0	0	9.27	10.4	10.6	10.9

The following observations persist across different orientations and climatic scenarios:

- In terms of IEQ, exposure to overheating and NO_2 concentrations are lowest and attainment highest for non-retrofitted classrooms due to the lower internal temperatures achieved through greater air and heat leakage during cooler nights. Consequently the heating requirements of base case retro-fit classrooms are highest, although more modern constructions (Archetypes P2 and P3) have considerably lower heating loads than Archetype P1. Figure 3 demonstrates the steeper night-time heat leakage of non-retrofitted cases and how during the warmest week, this functions in a similar manner to passive ventilation to reduce overheating (where operative temperature > dotted back BB101 threshold temperature line).

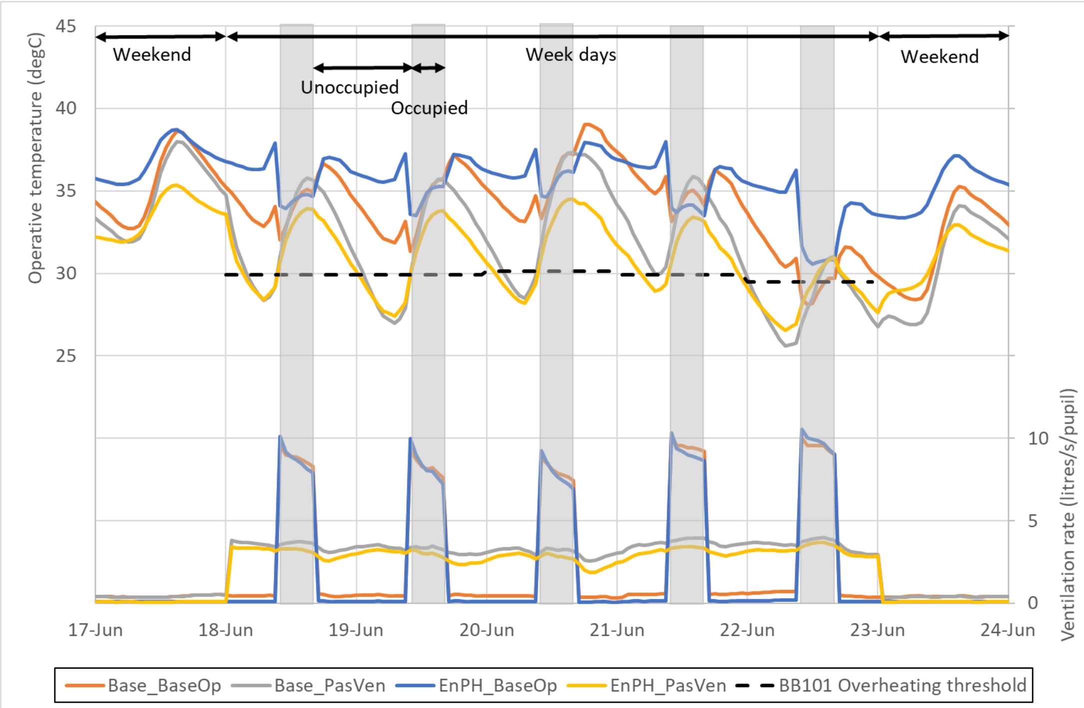

Figure 3: Internal temperatures and ventilation rates during hottest week of year for Archetype P1 base and EnerPHIt scenarios showing impact of night-time ventilation

- Although operational measures of keeping heat out through shading control and albedo are generally effective in mitigating overheating, other individual operational measures except external shading are not universally effective, dependent on the level of retro-fit, era of construction and orientation. For example, passive ventilation is most effective for any level of retro-fit, but not effective at all for base case scenarios, worsening for older, leakier fabric. Managing heat using thermal mass, while effective as a heating reduction, only improves overheating in a couple of North facing cases. However cumulatively, the combination of measures significantly reduces overheating in all cases, as shown in Figure 4, since the dotted threshold line representing overheating can be very sensitive to small changes in operative temperature.
- While NO_2 concentration is driven largely by location, passive ventilation is an effective measure, even in the more polluted London region (P1), due to more ventilation being shifted to less polluted night-time hours. An unintended consequence is that the lower required ventilation rates during occupied hours, shown in Figure 3, also lower the perceived attainment for passive ventilated and cumulative cases.
- P2 is most susceptible of the three archetypes to overheating and stuffiness; this is a function of both lower floor to ceiling heights of the 1945-1967 era and warmer West Midlands climate.

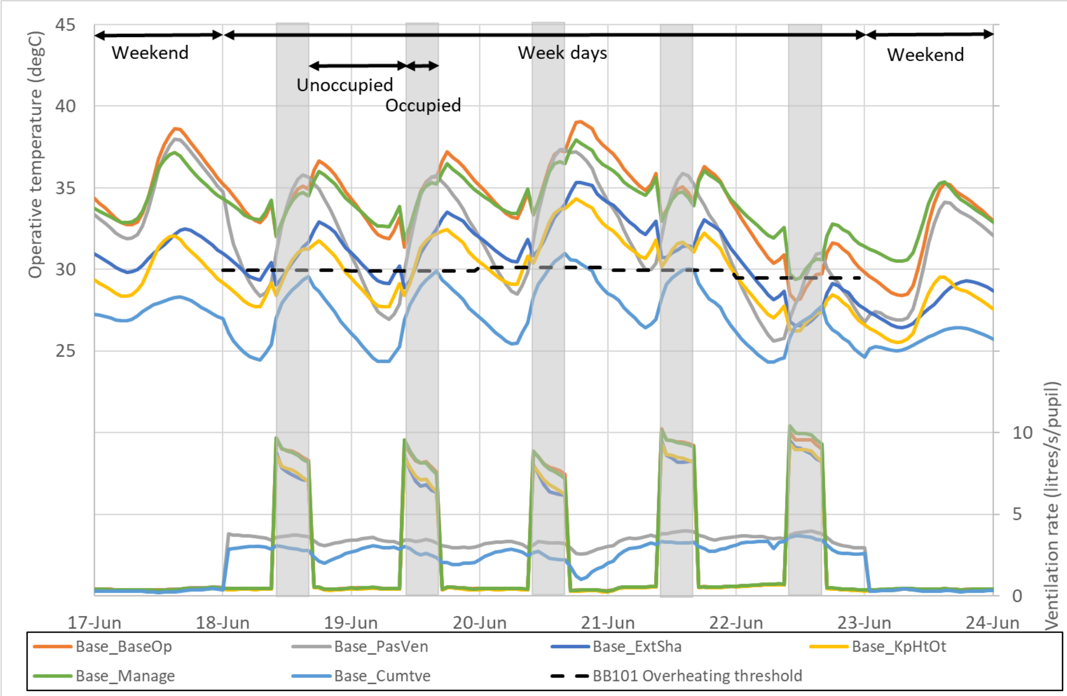

Figure 4: Internal temperatures and ventilation rates during hottest week of year for Archetype P1 base retro-fit showing individual and cumulative operational scenarios

Comparing the 2020s and warmer 2080s climatic scenario in Table 5 and Table 6, there is little change in attainment since higher internal temperatures are off-set by higher required ingress of air. However, these effects negatively impact overheating and contaminant ingress respectively, narrowing the ability of base operational cases to mitigate IEQ. With orientations, North-facing classrooms in Table 7, while decreasing overheating hours by around 30-40% for the Base-BaseOp case, have limited impact (<10%) for both greater retro-fitted cases and use of operational measures.

4.2. Summary of best performing pair-wise scenarios

Figure 5 shows the best performing pair-wise retro-fit and operational scenarios for the 5 metrics separately for a range of climate scenarios and orientations, with a couple of caveats:

- For heating demand, a number of combinations indicate zero annual demand (where internal gains are sufficient to maintain occupied temperature above 18 ^{o}C), hence the least stringent retro-fit and operational scenarios to deliver these conditions are indicated.
- For stuffiness and attainment, across orientations and climates, there is little to differentiate between the three individual operational changes (Manage heat, Keeping heat out and External shading). All three individual measures offer an improvement over base operation and are not penalised by including night ventilation, which impacts stuffiness and attainment by bringing in a greater proportion of fresh air at night, resulting in lower required ventilation during occupied hours.

			Stuffiness / CO2		Overheating		Attainment		Heating		Health / NO2	
P1	N	2020	EnPH	Manage	Base	Cumtve	Base	Manage	EnPH	Cumtve	Base	Cumtve
		2050	EnPH	BaseOp	Base	Cumtve	Base	Manage	EnPH	PasVen	Base	Cumtve
		2080	EnPH	KpHtOt	Base	Cumtve	Base	Manage	IntR	PasVen	Base	Cumtve
	S	2020	EnPH	Manage	Base	Cumtve	Base	KpHtOt	EnPH	Cumtve	Base	Cumtve
		2050	EnPH	BaseOp	Base	Cumtve	Base	KpHtOt	IntR	PasVen	Base	Cumtve
		2080	EnPH	Manage	Base	Cumtve	Base	KpHtOt	IntR	PasVen	Base	Cumtve
P2	N	2020	EnPH	Manage	Base	Cumtve	Base	KpHtOt	MinR	Cumtve	Base	Cumtve
		2050	EnPH	Manage	Base	Cumtve	Base	ExtSha	MinR	Cumtve	Base	Cumtve
		2080	EnPH	Manage	Base	Cumtve	Base	Manage	MinR	Cumtve	Base	Cumtve
	S	2020	EnPH	Manage	Base	Cumtve	Base	KpHtOt	MinR	Cumtve	Base	Cumtve
		2050	EnPH	Manage	Base	Cumtve	Base	KpHtOt	MinR	Cumtve	Base	Cumtve
		2080	EnPH	Manage	Base	Cumtve	Base	KpHtOt	MinR	PasVen	Base	Cumtve
P3	N	2020	EnPH	BaseOp	Base	Cumtve	Base	KpHtOt	EnPH	Cumtve	Base	Cumtve
		2050	EnPH	KpHtOt	Base	Cumtve	Base	Manage	EnPH	Cumtve	Base	Cumtve
		2080	EnPH	Manage	Base	Cumtve	Base	ExtSha	EnPH	Cumtve	Base	Cumtve
	S	2020	EnPH	Manage	Base	Cumtve	Base	ExtSha	EnPH	Cumtve	Base	Cumtve
		2050	EnPH	Manage	Base	Cumtve	Base	KpHtOt	IntR	PasVen	Base	Cumtve
		2080	EnPH	Manage	Base	Cumtve	Base	KpHtOt	IntR	PasVen	Base	Cumtve

Figure 5: Top performing pair-wise scenarios for 5 separate metrics and different orientations and climate scenarios for 3 archetypes

Figure 5 demonstrates that there are three/four different modes of operation which partially demonstrate degrees of optimal performance across the five metrics:

- For overheating and ingress of pollutants, a low-degree of retrofit, coupled with the cumulative scenario of operational measures is optimum for lowering exposure. Attainment would also be included within this set of metrics, were it not for night ventilation resulting in lower required occupied ventilation rates (as shown in Figure 4), hence impacting the attainment metric calculation.
- For stuffiness, the converse is true: a high-degree of retro-fit coupled with selective use of operational measures mitigates against high CO_2 levels.
- For heating, a high degree of retro-fit is highly desirable although EnerPHIt may not be essential for all scenarios. Some form of night-ventilation, most often as part of a cumulative strategy, minimises heating demand.

While a number of key caveats remain, the summarising of 24 pair-wise scenarios into three or four optimal groupings gives the potential to focus future research onto a smaller sub-set of models within the UK school stock.

5. Discussion

5.1. Implications and validity of results

While the previous section demonstrated a number of feasible pairwise scenarios in response to the research question, a remaining key question arising from Table 5 is around the degree to which it is necessary to retro-fit future buildings. While there is a current focus on provision of net zero carbon buildings (Department for Education (DfE), 2021), there is some indication that improvements towards minimum building regulation standard alone may provide around 60-80% of the required energy efficiency improvements, while preventing the worst of overheating and ingress of contaminants. However, a major issue with the models is the problem of applying rigid heating and ventilation rules, preventing the ad-hoc ‘free-will’ opening of windows to mitigate stuffiness which could give more retro-fitted models greater flexibility in the trade off between energy use and IEQ mitigation.

An interpretation of the acceptable ranges of each criterion is dependent on existing guidelines. BB101 (Education and Skills Funding Agency (ESFA), 2018) targets under 40 annual overheating hours of exceedance and 1500 ppm of annual CO_2 exposure, and World Health Organisation (WHO) annual mean targets for exposure to NO_2 and $PM_{2.5}$ are 10 and 5 μg/m^3 respectively, both of which are heavily exceeded for most cases. While entire-building heating energy use would generally be normalised and benchmarked against a typical school building through CIBSE TM46 (CIBSE, 2008), the classroom models represent a partial use of a school building and as such are only internally comparable between scenarios and archetypes. Similarly attainment percentages are useful for relative rather than absolute comparison outside the scope of this project.

5.2. Future work

Since the ultimate aim of this work is to inform the design of a modelling platform for IEQ in school classrooms across the UK stock to predict effectiveness of retro-fit decisions, considerable calibration of a baseline to monitored data will be required in the future to validate the dynamic trends demonstrated in this work. Additionally, the limitations of operating classroom stock models in isolation have been demonstrated, in terms of their inability to prioritise one output over another without further guidance. Hence, there is a need for modelling to feed into a further tool, which would combine the criterion investigated with weightings based on the priorities of various school sector stake-holders. A survey of over 150 such construction, educational and governmental stake-holders has therefore been carried out, to feed into a multi-criteria decision analysis (MCDA) tool. This would combine criterion with weighting to score individually different retro-fit, operational scenarios as well as different archetypes across the stock, based on the priorities of different groups.

In terms of additional simulation modelling, there may be a benefit in further analysis of some non-ideal cases to fully test resilience outside of future anticipated operating envelopes. Such cases could include archetypes with a lower floor to ceiling height than allowed for in proposed design, additional indoor sources of $PM_{2.5}$, extreme future climate scenarios, or extended school operating hours.

6. Conclusions

The simulation modelling presented in this paper in response to the research question clearly demonstrates that there are around three or four pair-wise retro-fit and operating strategies worthy of further detailed analysis. While, individually, the five criterion presented in the results section provide some indication of the degree to which various scenarios satisfy individual needs for energy demand reduction, IEQ mitigation and boosting attainment, to be an effective tool for policy makers this output should be coupled with weightings and priorities driven by stake-holders themselves.

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