Modelling UK school performance by coupling building simulation and multi-criteria decision analysis

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SUMMARY

Meeting indoor environment quality (IEQ) standards, incorporating air quality and thermal comfort, is critical for children's health and learning within classrooms. While building simulation provides indicative IEQ outputs, educational and construction stakeholders may require broader criteria, such as attainment, health and healthcare costs, to assess UK school building stock performance.

To investigate the provision of such metrics, a Data dRiven Engine for Archetype Models of Schools (DREAMS) EnergyPlus-based stock-modelling framework was developed, modelling different classroom typologies. Dynamic IEQ simulation has demonstrated that the influence of construction era on learning performance metrics may be stronger in hotter regions, which are increasingly reliant on ventilation to counter higher temperatures and maintain IEQ.

This framework includes creating retrofit scenarios to evaluate school building energy efficiency interventions and coupling with multi-criteria decision analysis (MCDA). This integration of modelled impacts with stakeholder-derived health and educational attainment weightings could provide a basis for future interventions.

KEYWORDS

Building simulation, decision analysis, indoor air quality, thermal comfort, cognitive performance, school buildings.

1 INTRODUCTION

The use of building stock modelling in assessing school indoor air quality

School classrooms are where UK school age children spend around 30% of their waking hours (Csobod, 2014). Hence, it is important to understand the influence of building performance on the educational attainment and health of school children in order to optimise educational and health outcomes (Chatzidiakou et al., 2014). Evidence of the influence of indoor environmental factors such as excessive internal temperature and low ventilation rates on educational attainment and health of school children has been collated and analysed (Chatzidiakou et al., 2014), leading to development of exposure-response type relationships (Wargocki et al., 2020). However, it is also imperative to identify and investigate the indirect influence of factors such as building fabric and operation of building services on educational attainment and children's health via indoor environment quality (IEQ), incorporating indoor air quality and overheating, demonstrated previously in UK care settings (Oikonomou et al., 2020) and residential sectors (Taylor et al., 2014) in order to provide effective mitigation strategies, Post occupancy evaluation (Pegg et al., 2007) has previously been established as a means of evaluating energy performance and sources of energy inefficiency in individual schools. Extending the use of building simulation to schools for the purposes of IEQ evaluation has been a recent development (Jain et al., 2019). Integrating stock level coverage with physics based modelling, the Data dRiven Engine for Archetype Models of Schools (DREAMS) stock modelling framework (Schwartz, Korolija, Dong, et al., 2021) was developed to account for floor area, glazing ratio and external weather conditions of different construction era and geographical region archetypes across the UK, in addition to their abundance within surveys.

The relevance of building simulation tools such as DREAMS to policymakers fills a critical gap in knowledge in relation to the impact of IEQ within school classrooms. For model outputs to be informative to stakeholders in the education and construction sectors and to support decision making in those sectors, the outputs should be translated into metrics which have practical relevance to stakeholders (Willan et al., 2020). Once these metrics are evaluated, multi-criteria data analysis (MCDA) (Neves et al., 2009) is used to integrate the values of these metrics (or impacts) with preferences elicited from the stakeholders on the criteria within a single tool to address a range of stakeholder's aims and objectives. While previous studies have surveyed the views of school building users (Grassie et al., 2021) and construction professionals (Willan et al., 2020) separately on their key drivers and interpretations of building performance, these surveys tended to focus on the individual rather than collective needs of different groups of stakeholders.

As a final point, the performance of the school stock cannot be considered to be time-invariant due to external (climate and external air) (Jain et al., 2019) and building related (energy efficiency retrofit and IEQ mitigation) (Oikonomou et al., 2020) factors, which are expected to impact on building performance. Energy efficiency adaptations and IEQ improvement strategies of the building envelope will therefore be examined in future iterations of this model. However the effect of warming climate and spatial variation across the UK stock are also critical in demonstrating current and future robustness of different typologies across the building stock and are the subject of this research.

Research design

The overarching research aim, addressed by the work presented below is as follows:
To explore how an MCDA-based IEQ evaluation framework could:
(i) incorporate the influences of building fabric, heating and ventilation operation from building simulation on children's health and educational attainment, and
(ii) evaluate and compare the impact of energy efficiency interventions and their variation across the UK primary school building stock.

This aim is achieved through two distinct research objectives, the first of which will be addressed through the work described in this paper:

- To develop performance metrics based on building simulation and IEQ modelling, which can be used as key performance indicators of several criteria including health and educational attainment across the school building stock under different climate scenarios.
- To elicit preferences from a wide range of school stakeholders on the relative importance of the performance criteria for use in an MCDA tool.

In terms of building simulation of classrooms, previous work has been carried out to demonstrate the performance of different variants of building form and construction of classrooms through simulation modelling (Schwartz, Korolija, Symonds, et al., 2021), however linkage of the simulation outputs to the objectives of schools' stakeholders is an additional potential key benefit of the current research. A couple of work packages have hence been proposed as shown in Figure 1 in order to formulate this linkage.

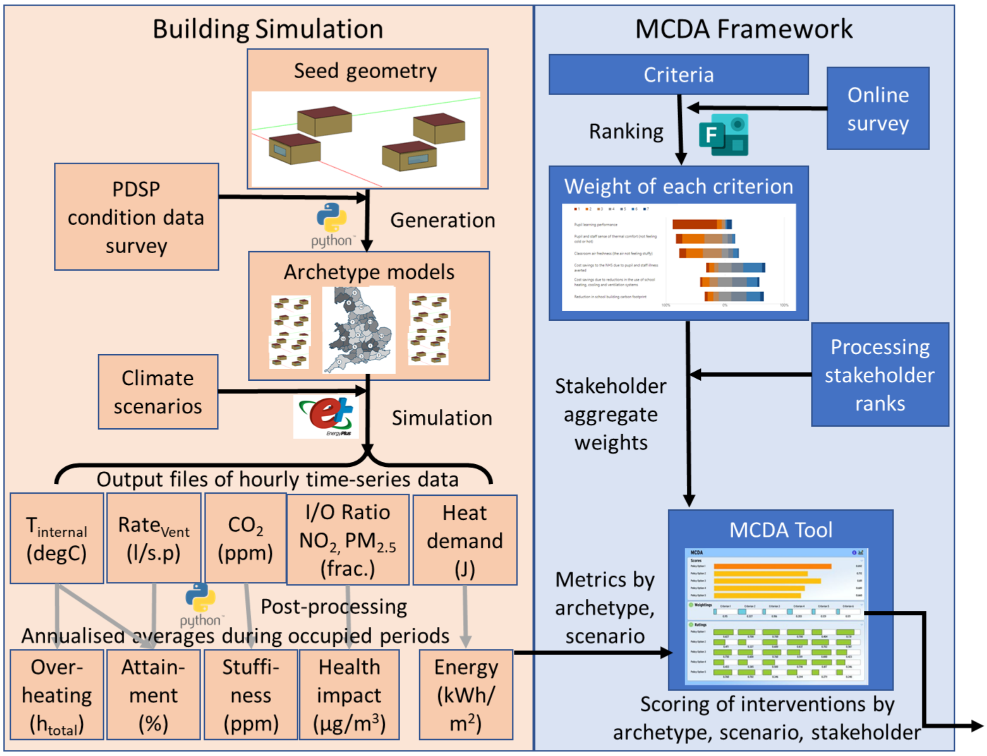


Figure 1. Proposed integration of building simulation and MCDA processes

2 METHODS

Generation of archetype models

Geometric "seed" models containing UK primary school classrooms were constructed from 5 different era constructions, with U-values as shown in Table 1, using EnergyPlus Version 9.5 (US Department of Energy, 2015) as described previously in the DREAMS methodology (Schwartz, Korolija, Dong, et al., 2021). These models contained classrooms in 4 different orientations with North, South, East and West facing windows on one side and adiabatic surfaces on all other walls, ceilings and roof to represent a classroom within a larger building, as shown in Figure 2.

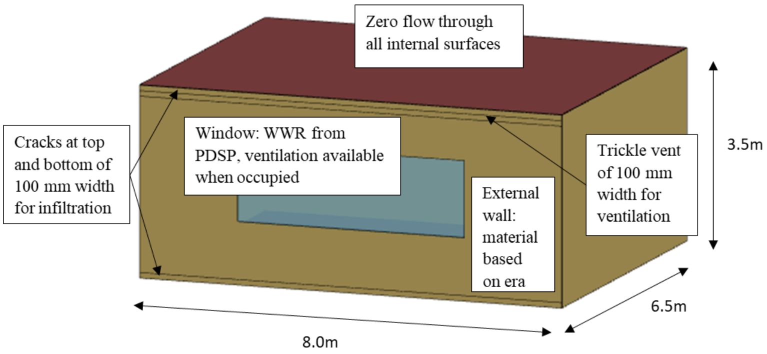
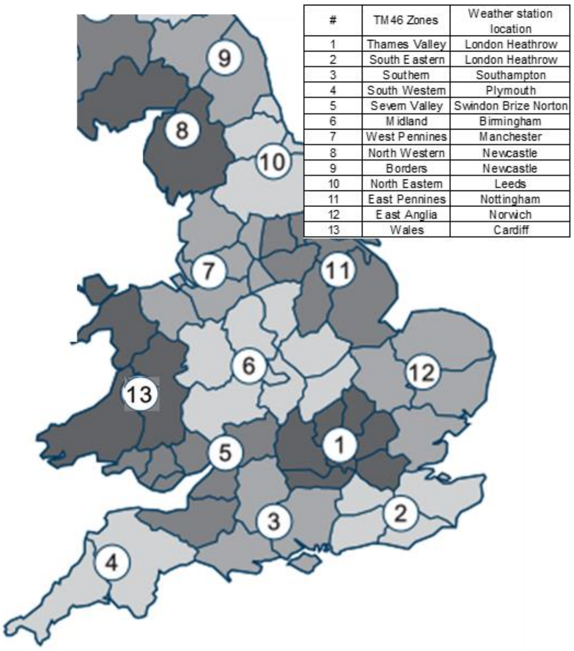


Figure 2. Geometric "seed" model and associated ventilation

Table 1. U-values for different construction era archetypes

Era	Pre-1919	Inter-war	1945 to 1966	1967 to 1976	Post-1976
U-value (W/m^2.K)	1.916	1.916	1.37	1.37	0.735

111 different combinations of naturally ventilated schools, representing 5 eras of constructions, 13 geographical regions by CIBSE degree day, illustrated in Figure 3, and whether the original building had been modified, were derived through an analysis of the Property Data Survey Programme (PDSP) dataset of UK school buildings (Schwartz, Korolija, Dong, et al., 2021). These 111 separate archetypes were then generated from the seed models using Python scripts (Python 3.9.2, 2021) utilising the EPPY package (EPPY 0.5.56, 2021) for communicating with EnergyPlus. For each archetype, the glazing ratio used was based on the mean average of the glazing ratio within the PDSP dataset for all primary schools of that archetype type.



#	TM46 Zones	Weather station location
1	Thames Valley	London Heathrow
2	South Eastern	London Heathrow
3	Southern	Southampton
4	South Western	Plymouth
5	Severn Valley	Swindon Brize Norton
6	Midland	Birmingham
7	West Pennines	Manchester
8	North Western	Newcastle
9	Borders	Newcastle
10	North Eastern	Leeds
11	East Pennines	Nottingham
12	East Anglia	Norwich
13	Wales	Cardiff

Figure 3. Locations of 13 CIBSE degree day regions (CIBSE, 2008) and weather stations

Weekday occupancy schedules of 9am to 4pm, ignoring holiday periods, have been applied in the simulation in line with Building Bulletin 101 (BB101) overheating calculations (Education and Skills Funding Agency (ESFA), 2018) with both heating and ventilation availability following these schedules. Heating setpoints (<20 °C when occupied, <12 °C unoccupied), ventilation availability (>23 °C occupied) and internal gains (pupils (60.5 W/m^2)), lighting (5.1 W/ m^2), and electrical equipment (3.35 W/m^2) when occupied) were defined by the UK's National Calculation Methodology (NCM) (Communities and Local Government, 2008) modelling guide. A constant external CO2 concentration of 415ppm has been assumed in the models based on current atmospheric levels, although this is rising annually (NASA, 2021).

Table 2. Key parameters for EnergyPlus AFN model

AFN feature	EnergyPlus inputs	Role within EnergyPlus
Infiltration: Cracks at top and bottom	Placed at 0-0.1 m and 3.4-3.5 m on external wall Air mass flow exponent, n = 0.5 (turbulent) Air mass flow coefficient, $c_Q = 4.368e^{-4}$ kg/s based on permeability of 9 m^3/h/m^2 @50Pa for a "normal school" (ATTMA, 2010)	Provides infiltration, q based on: $q \alpha c_Q*(\Delta P)^n$ accounting for pressure differences at heights
Ventilation: Trickle vent	Placed at 3.3-3.4 m on external wall Discharge coefficient, $C_d = 0.62$ @ ΔP of 1Pa	Provides flow based on area, C_d, density and ΔP
Ventilation: window	Open: Horizontal pivot: Top 1/3 available Discharge coefficient = 0.5 (Taylor et al., 2014)	Infiltration when closed, ventilation when open

Additional features included in the current research, supplementing previous work (Schwartz, Korolija, Symonds, et al., 2021) are:

- Ventilation/Infiltration – EnergyPlus's internal Airflow Network (AFN) model was for modelling airflow through windows and cracks as illustrated in Figure 2. The parameters used in this modelling are given in Table 2.
- Air contaminant modelling – the study has been scaled up to include external nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$) data for all 13 geographical regions. For each CIBSE degree-day area, all available hourly annual data for the year 2019 was collated from available monitoring sites (Department for Environment Food and Rural Affairs, 2021). Examining all

time-series data across the year for each geographical data, monitoring data from a single location was selected as being representative of that geographical region.

Simulation of EnergyPlus models

Annualised hybrid weather files, representing 2020s, 2050s and 2080s future climates were created for each of the 13 geographical regions in Figure 3 from 11 weather stations locations, combining two types of annualised weather files (CIBSE, 2009). Design summer year (DSY) data used for overheating calculations from 1st May to 30th September were combined with test reference year (TRY) data from 1st October to 30th April, representing a typical year. Each of the 111 archetype models was simulated for each of the three climate periods.

Post-processing of EnergyPlus outputs

Table 3 shows the linkage between 5 performance criteria identified for each individual archetype in the first two columns and hourly data from each simulation in third column.

Table 3. Post-processing of EnergyPlus outputs into suitable metrics for MCDA

Criterion	Short label	Hourly data from EnergyPlus simulation	After processing
Pupil learning performance	Educational attainment	Internal temperature (t) Ventilation rate (VR)	Multiply the two factors (Dong et al., 2020; Wargocki et al., 2020) : $y = 0.2269*t^2 - 13.441*t + 277.84$ $y = 0.0086*VR + 0.9368$
Pupil and staff sense of thermal comfort	Overheating	Internal temperature External temperature	Calculated based on “Annual hours of exceedance” metric from Building Bulletin 101 (BB101) (Education and Skills Funding Agency (ESFA), 2018))
Classroom air freshness	Stuffiness	CO_2 concentration	Annual average CO_2 concentration (occupied hours only)
Pupil/staff illness averted	Health	NO_2 concentration $PM_{2.5}$ concentration	Annual averages of NO_2 and $PM_{2.5}$ (occupied only)
Reductions in heating,	Energy	Energy use (J) of: baseboard heating.	Annual total energy normalised by floorspace (kWh/m^2)

The final column indicates the calculation methodology used within the Python script used to process EnergyPlus output files for each metric, whilst noting the following:

- The World Health Organisation (WHO) has recently published recommended annual NO_2 (10 $\mu g/m^3$) and $PM_{2.5}$ (5 $\mu g/m^3$) exposure targets (World Health Organisation, 2021), which post-processing averages over occupied periods only within the models.
- Building Bulletin 101 (BB101) (Education and Skills Funding Agency (ESFA), 2018) provides three metrics for determining degree of overheating. The first has been adopted for this research and involves summing the number of occupied hours between May 1st and September 30th when temperature exceeds a daily calculated threshold based on weighted external temperature from the previous 7 days. For CO_2 concentration, BB101 suggests baseline + 800 ppm represents “normal” levels. While a more complete definition of “stuffiness” would incorporate parameters such as relative humidity, combining these into a single metric as for attainment could complicate interpretability relative to such guidelines.
- % relative cognitive performance (a proxy for educational attainment) is calculated for each occupied hour based on the formula given in Table 3 where a maximum 100% attainment is only achieved at internal temperatures < 20 °C and ventilation rate > 7.35 l/s.person.
- No specific targets for reduction in heating at classroom level have been provided although fossil fuel and electricity benchmarks exist at building level (CIBSE, 2008).

3 RESULTS

Variation of cognitive performance across different locations and construction eras

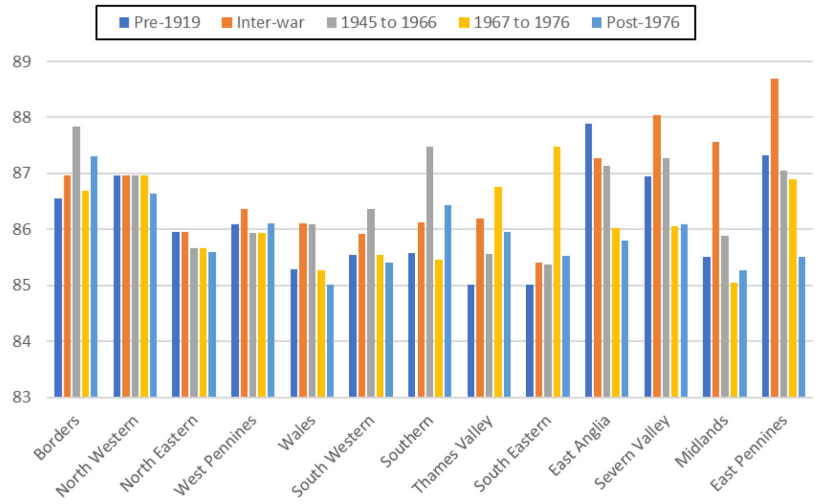


Figure 4. Variation of % relative cognitive performance with location and era (2020 climate, averaged by archetype)

Figure 4 demonstrates that archetype performance in terms of average cognitive performance appears to fit in a narrow 85-88% range for all cases, without an obvious direct relationship with either location or era. However, for the cooler Wales, North Western, North Eastern, West Pennine and Border regions, there is less variation in performance across different era buildings than for warmer Southernly and Eastern locations. This demonstrates a complex interplay between conflicting factors of ventilation and high internal temperatures for locations which are more susceptible to higher temperatures leading to a larger variation in performance.

Comparison of conflicting metrics

The two plots shown in Figure 5 demonstrate minima, maxima, quartiles and averages of all 6 different metrics across different climates and different orientations. The data was averaged during occupied periods only from hourly time-series data for each simulation, and compiled across all region-era archetypes to produce each box plot. Some key findings are as follows:

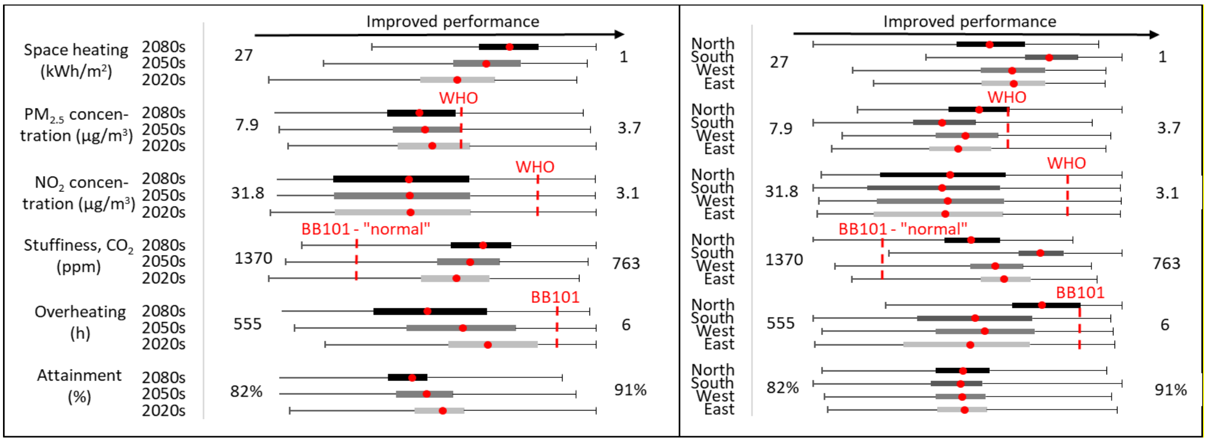


Figure 5. Variation of metrics across (a) climate scenarios, (b) different classroom orientations

- Cognitive performance (a proxy for attainment) is fairly uniform across class orientations, as warmer temperatures in non-North facing classrooms are compensated for by increased ventilation. However, it decreases markedly as climate warms, due to decreased effectiveness of natural ventilation. This is also seen in the increasing issue of overheating and decrease in stuffiness as warmer winters mean increased all year-round ventilation, negating the effect of lack of ventilation during winter months.
- Increased ventilation for warmer orientations and climate does not markedly worsen the influx of external NO_2 into the classroom when compared against WHO targets.

- All classrooms are expected to have significant issues with overheating in years with extremely hot summers both currently and in the future.
- While ventilation of 15-20 l/s.person (8.5-11.3 ac/h) required to maintain internal temperature below 32 ^{o}C during the hottest week exceed the recommended 8 l/s.person (4.5 ac/h) in BB101 to maintain CO_2 at 1000 ppm, these are consistent with heatwave measurements from the SINPHONIE project (Csobod, 2014).

4 DISCUSSION

The results of the building simulation demonstrate a need to adjust the effectiveness of natural ventilation in order for higher energy mechanical ventilation with air purifying solutions to be avoided. This could involve ventilating the building when external NO_2 levels are low due to traffic at night time and providing hybrid options for when external air is too warm and contaminated by $PM_{2.5}$. In terms of sources of poor IEQ, more comprehensive study of school IEQ should include internal sources of $PM_{2.5,}$ however such data sources do not form part of the PDSP dataset and hence cannot be included in stock modelling. Also, better understanding of NO_2 variation spatially across geographical regions and year to year is necessary. While setpoints are useful for predicting the requirement of ventilation to counteract overheating, more sophisticated mitigation strategies, such as optimising ventilation rate and schedule is required for metrics on overheating to be more indicative of conditions during a hot summer. The next stages will expand the current limited set of input conditions, outputs and scenarios to include:

- Definition of different era archetypes to include floor-to-soffit heights and permeability features. The broad Post-1976 archetype could also be split into more diverse archetypes, indicative of geographical and building programmes, requiring additional data analysis of more descriptive national building condition datasets following on from the PDSP.
- Simulation outputs and additional energy based metrics incorporating cooling and mechanical ventilation, by adding mechanically ventilated schools to the study.
- Development of policy option scenarios, incorporating building envelope alterations, accounting for energy efficiency retrofits and IEQ and overheating mitigation.
- Integration of metrics described in this research with weights assigned against criteria elicited from an online survey sent to groups of stakeholders as part of a formalised MCDA framework. This will explore the implications of the outputs of building simulation and implications of low carbon design and operational strategies on health and educational attainment impacts relating to IEQ. The preferences of different groups of stakeholders in terms of the relative importance they assign to the criteria are taken into consideration in the MCDA framework.

5 CONCLUSIONS

A framework was demonstrated for adapting building simulation modelling of the UK school stock, originally used for energy modelling, to account for specific indicators of health and learning. Testing the conversion of model outputs into stakeholder attainment and health metrics for this framework has demonstrated a requirement to better understand the diminishing effectiveness of ventilation for overheated classrooms in future climates. Evaluating ventilation-overheating interactions of different regions and eras could play a major role in the selection and definition of future IEQ mitigation strategies across the UK school stock.

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